



Review on Virtual Inertia Control Topologies for Improving Frequency Stability of Microgrid

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HIGHLIGHTS

- RESs connected with the inverter have no physical inertia compared with the synchronous generator.
- VSG provides the required inertia under sudden disturbances in a microgrid.
- VSG controller emulates droop controller to decrease the frequency deviation.

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ABSTRACT

Renewable energy sources (RESs), such as solar and wind power, offer new technologies for meeting the world's energy requirements. The distributed generator (DG) based on RESs has no rotational mass and damping effects compared to the traditional power system with synchronous generators (SG). However, the increasing penetration level of DG based on RESs causes low inertia, a dampening effect on the dynamic performance of the grid, and stability. A solution to improve the frequency stability of such a system is to provide virtual inertia by using virtual synchronous generators (VSG), which can be created by using short-term energy storage and a power inverter, and a suitable control mechanism. The VSG control mimics the dynamics of the rotation SG and enhances the power system's stability. This paper presents an overview of various topologies on virtual inertia, VSG concepts, control techniques, and VSG applications. Finally, the VSG challenges and future research will be discussed.

1. Introduction

The supplies of conventional fossil energy have been considerably exhausted and inadequate to satisfy the needs of sustainable human society growth. The benefits of distributed RESs are flexibility, pollution-free and wide distribution. It becomes appropriate energy that complies with the principle of sustainable development [1,2]. Another advantage is its main involvement in supporting the electricity network in remote and rural areas [3]. In recent years, many RES, such as wind farms and photovoltaic (PV), have been integrated into the conventional power system. RES based on power electronic converters (PECs) is expected to have a significant impact on a sizeable power grid in the near future [4,5], as the PEC-based generations would be substituted for the substantive portions of traditional SGs in power systems [4]. The RES-based PECs have no rotating mass and damping effects compared with traditional power with SG. On the other hand, the SG plays an important role in grid stability due to the inherent kinetic energy in rotating mass and damping properties (due to mechanical friction and losses) [6].

Most RES connects to the grid via a power electronic device (Inverter) [7]. Although there are quick responses to the conventional grid-connected inverter, it has almost no moment of inertia, is unable to provide the requisite support for voltage and frequency [8,9], and makes it hard to provide the necessary inertia and to dampen the grid [10,11]. So, the increase in RES will lead to serious stability problems for the power system. As a result, new technology is urgently needed to allow new energy to participate in regulating and modulating the power grid frequency [12,13].

The DGs containing RESs systems can contribute to frequency sustenance by introducing virtual inertia to the grid. In contrast, the SG provides frequency support and decreases the rate of change of frequency (ROCOF) during a disturbance using its rotating mass in conventional power systems [14]. The way to stabilize such a grid is by providing virtual inertia. DGs/RES can generate virtual inertia by combining an energy storage system (ESS) with a power inverter and a

suitable control mechanism. This term is called a virtual synchronous generator (VSG) [6,15] or synchronous virtual machine (VSM) [16]. The units would then work as SG.

The IEEE Working Group initially suggested the VSG idea. Researchers then continued investigating exterior characteristics for analog synchronous engines [17], virtual inertia, and frequency control strategy [18]. However, the VSG is yet in the development stage and must still develop its theoretical framework and practical foundation. The existing literature mainly presents various kinds of control technologies and methods of VSG implementation [19,20]. In [21-25], a basic idea of VSG is introduced, enabling the grid-connected to the inverter to mimic SG's operating properties. However, the current-controlled VSG equates to the current source, so providing the system with voltage and frequency support is difficult. Therefore, a voltage-controlled VSG technique is suggested in [26] to overcome the deficiencies of current-controlled VSG. The essence of voltage-controlled VSG strategies is to mimic SGs in frequency control rotor inertia and system frequency modulation features to increase the system's frequency stability. At the same time, reactive power and voltage control are primarily used to control stable voltage output [27].

Moreover, several techniques in [23,28,29] have been demonstrated that develop a model and a controller to simulate the different dynamics of SG. These model and control strategies accomplish the operation and self-synchronization of SG without a phase-locked loop (PLL). The VSG control is, therefore, still needed to be theoretically and practically mature enough compared to traditional SG.

The rest of the paper is structured as follows: Section 2 introduces different virtual inertia topologies. The concept of VSG is discussed in section 3. In section 4, the VSG control is explained. Section 5 describes the VSG application. The problems and future studies are explained in section 6. Finally, section 7 presents the conclusion of this paper.

2. Virtual Inertia Topologies

VSG is a combination of RESs, control algorithms, ESS, and power electronics that emulate the inertia of SG in a conventional power system [30]. The VSG algorithm is the main component of the system interfacing between different storage units, generation units, and the utility grid.

The VSG concept was presented as a method to tackle the power grid's stability problems, including RESs [30,31]. PV systems interfaced to the grid through DC to AC converters (inverter). This system does not respond to changes in inertia. Much research is also developing many concepts and control methods to mimic the damping and inertia characteristics of an SG. According to the literature, for different topologies, the main model ideas are similar, but the implementation of each model is different from the others. Few topologies use mathematical equations to simulate the SG's behavior (Synchronous generator model-based). In contrast, few topologies copy the erratic SG performance using the swing equation (Swing equation based). In addition, DG units respond in a few topologies to changes in the grid system frequency (Frequency-power response based) [32]. In this section, many essential VSG topologies are discussed.

2.1 Vsync's VSG Topology

Figure 1 shows the VSG control system developed by the VSYNC group (project within the 6th European Research Framework Program) [33-35], where energy sources are connected through an inverter with a filter LCL to the grid. The PLL is used in grid frequency measurement and frequency change rates. In addition, to inertia emulation, PLL also generates the rotating frame of dq reference phase angle for inverter control quantity and reference frequency. The reference current is determined using the control block using the state of charge (SOC) of energy storage, grid voltage, change in frequency, and the reference voltage through the following Equation [34-36].

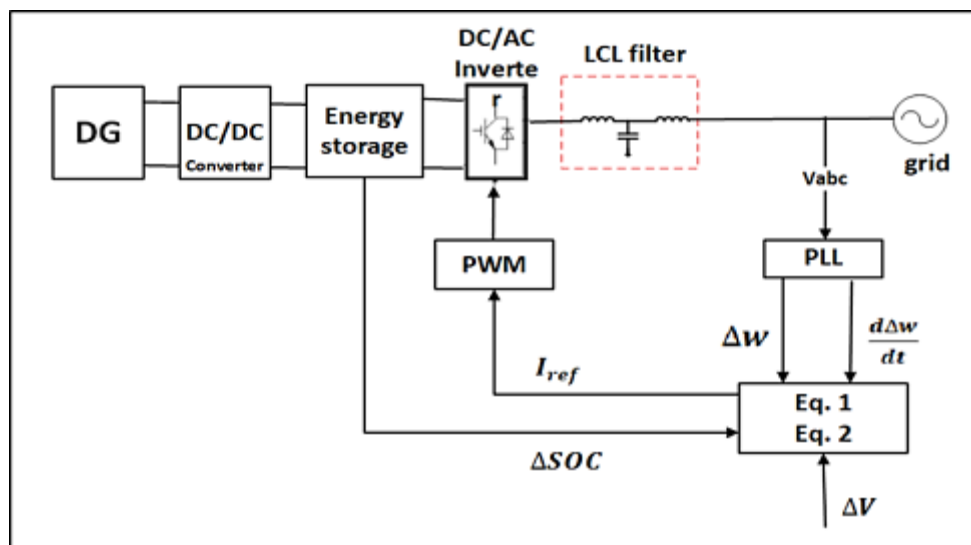


Figure 1: Structure of VSYNC [36]

$$P_{VSG} = k_{soc}\Delta SOC + k_p\Delta w + k_i \frac{d\Delta w}{dt} \tag{1}$$

$$Q = k_v\Delta V \tag{2}$$

2.2 Synchronverters

A synchronverter is equivalent to an SG with a small capacitor bank connected to the stator in parallel [37]. The frequency droop algorithm regulates the output power of the inverter in the same way as it regulates the output power of SG [38]. The structure of a synchronverter is shown in Figure 2. The output voltage and current signals from the inverter solve the differential equation of the controlling unit. In addition, the damping factor and moment of inertia can be configured to meet specific requirements. These parameters, however, are extremely important in terms of system stability [39]. The mechanical equation is given by:

$$J \frac{dw}{dt} = T_m - T_e - D_p w \tag{3}$$

where J is the moment of inertia, T_m and T_e is the mechanical and electromagnetic torque, w is the virtual angular speed and D_p is a damping factor. Electromagnetic torque can be found by [39]:

$$T_e = M_f i_f \langle i, \sin \theta \rangle \tag{4}$$

where M_f is mutual inductance, i_f is DC current, i is the inductor currents, and θ is the virtual angle. The reference generated voltage of the controller is given by

$$e = w M_f i_f \widehat{\sin \theta} \tag{5}$$

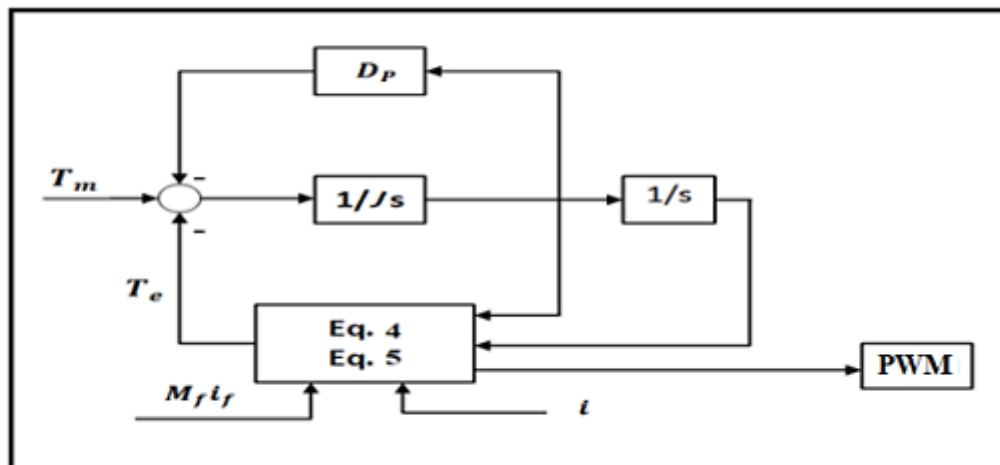


Figure 2: Structure of Synchronverter [32]

2.3 Ise Lab Vsg Topology

Figure 3 illustrates the VSG model produced by Osaka University's ISE lab. The swing equation, expressed as the following equation, was used in this model [40,41].

$$P_{in} - P_{out} = J\Delta w_m \frac{d\Delta w_m}{dt} - D\Delta w_m \tag{6}$$

Where P_{in} is the input power (prime mover), P_{out} is the output power of the VSG, J is the rotor moment of inertia, w_m is the angular speed of the rotor, and D is the damping factor. The frequency and power measurement unit receives the voltage from the common connection point (CCP) and measures the inverter's output current. Then, it calculates the inverter's active output power and utility grid frequency using these values [42,43].

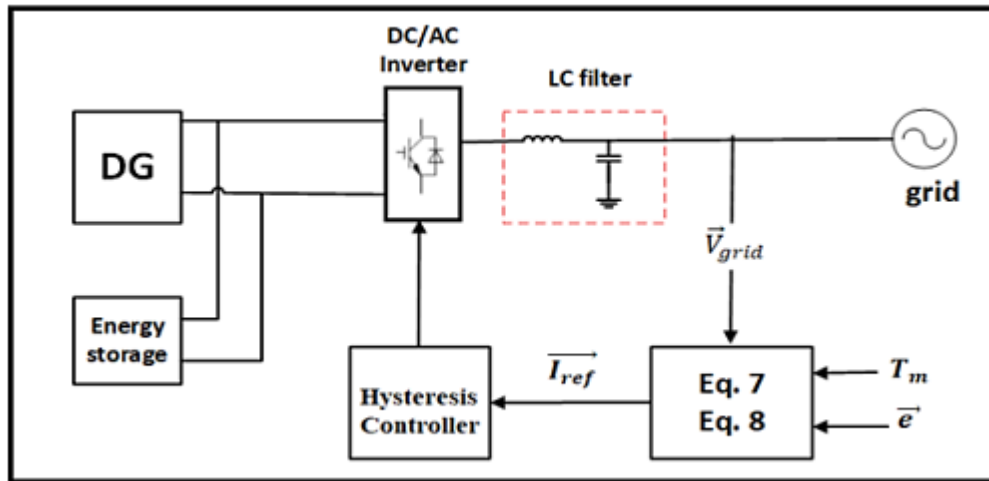


Figure 5: Structure of IEPE control [36]

In addition, the IEPE group developed VISMA-2 [31], which is a new tool. Instead of using grid voltage to feed the SM algorithm, this method produces the reference voltage as an output using grid current. In addition, the hysteresis controller was replaced by a PWM controller to use a constant switching frequency, making it easy to choose the filter circuit. This new technology is extremely effective for asymmetric loads and sharp grid changes.

In Table 1, a comparison between all topologies of virtual inertia is presented. Finally, the advantages and disadvantages of each inertia emulation topology are summarized in Table 2.

Table 1: Comparison of virtual inertia topologies

Control Strategies	control Mechanism	Control Variable	Measurement Variable	PLL Function	Others
VSYNC Topology	PWM control	Phase currents	Grid voltage	Provide frequency, rate of change of frequency ROCOF, and phase of dq transformation	Used with high inertia grid
Synchronverter	PWM control	Phase voltages	Voltage and current	Frequency	Used with low inertia grid
ISE Lab Topology	PWM control	Phase voltages	Voltage and current	Frequency	Used with low inertia grid
KHI Topology	PWMcontrol	Phase currents	Voltage and current	Frequency and phase of dq transformation	Used with high inertia grid
IEPE topologies	PWM control or Hysteresis control	Phase voltages or Phase currents	Voltage or current	Without PLL	Used with low and high inertia grid

Table 2: Highlights advantages and disadvantages of virtual inertia emulation

Control Idea	Control Technique	Advantage	Disadvantage
Synchronous generator model-based	<ul style="list-style-type: none"> Synchronverter IEPE KHI 	<ul style="list-style-type: none"> Exact SG dynamics Replication Not needed for frequency derivative PLL used only for synchronization 	<ul style="list-style-type: none"> Concerns for numerical Instability voltage-source implementation; no over-current protection
Swing equation based	ISE	<ul style="list-style-type: none"> Simpler design than SG-based model Not needed for frequency derivative PLL used only for synchronization 	<ul style="list-style-type: none"> Oscillations in power and frequency voltage-source implementation; no over-current protection
Frequency-power response based	VSYNC Topology	<ul style="list-style-type: none"> Straightforward Implementation current source implementation, essential over-current protection 	<ul style="list-style-type: none"> Instability due to PLL, mainly in weak grids Frequency derivative required; system susceptible to noise

3. VSG Concept

The VSG theorem is based on the inclusion of the advantages of dynamic converter technologies and electromechanical SGs' static and dynamic operating properties [49]. As seen in Figure 6, the basic description of the VSG concept. VSG's three distinct elements include power electronic converters (PECs), ESS (battery, supercapacitor, etc.), and the control system that

controls the amount of power injected or absorbed from the energy storage. This power enables the power system to avoid frequency variations like the SG [50,51].

If the DG and ESS are considered the prime mover input torque, The electromechanical power transformer between the stator and rotor is supposed to be the DC/AC converter. Then the main midpoint voltage component represents VSG's electromotive force. Filter unit resistance and induction represent the stator winding impedance. VSG is usually placed between a DC source and a grid [50]. The DC source to the VSG algorithm operates as SG by providing inertia and damping support to the grid system. This is achieved by successful inverter power control in inverse proportion to the rotor speed.

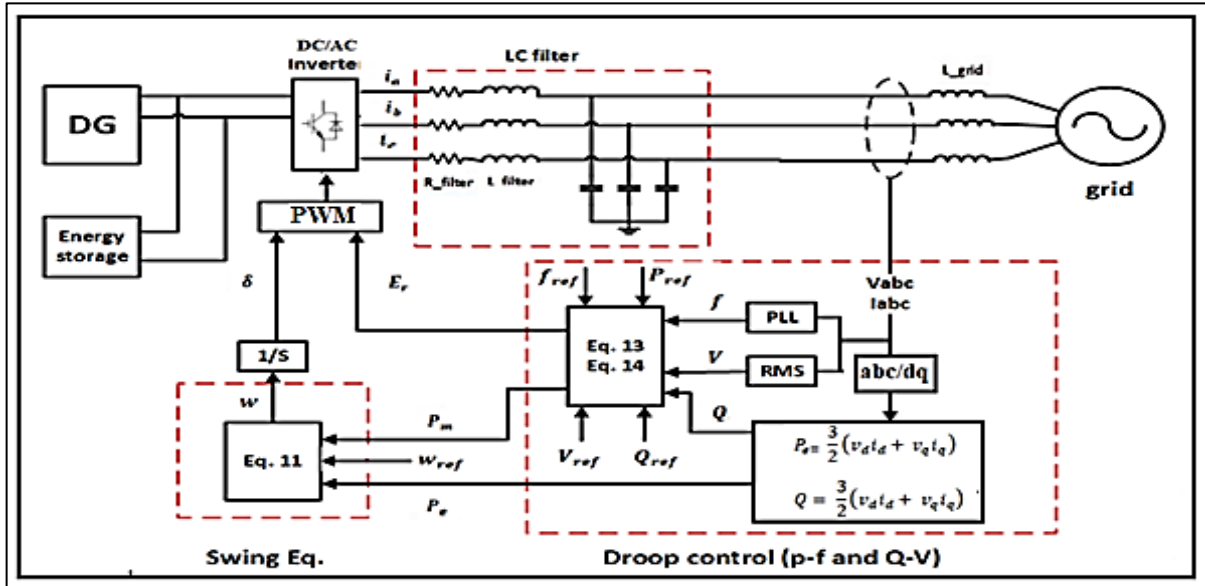


Figure 6: Simple VSG Structure [52]

The VSG can absorb or inject (charge or discharge) power into the system due to the presence of an ESS. The VSG control strategies with the higher or lower order can be developed by small changes to the voltage sources controller control system. While all VSG strategies control active and reactive power, each has its control frame. Furthermore, different VSG control strategies have been introduced to enable the inverter to emulate the properties of an SG [41,52]. As a result, every VSG implementation entails an approximately direct mathematical model of an SG [4]. Many solutions presented in the literature show that selecting any SG model and its parameters primarily depends on a random design choice. However, any VSG implementation mimics electromechanical oscillations' inertial properties and damping characteristics. An SG model's transient and sub-transient dynamics can be included or ignored, depending on the required level of competence and accuracy in replicating the SG dynamics [42].

The basic SG swing equation is a key component of VSG, and it is stated as [52]:

$$J \frac{dw}{dt} = T_m - T_e - D(w - w_{ref}) \frac{d\delta}{dt} = w \tag{9}$$

Where J is rotor inertia. D is the damping factor. T_m is mechanical torque and T_e is electromagnetic torque. w and w_{ref} virtual angular frequency and reference angular frequency, respectively. And δ is the power angle.

Furthermore, to approximate the electromagnetic properties of SG for VSG, the SG's stator equation is usually simulated without considering the electromagnetic relationship between rotor and stator, and this can be expressed as [52]:

$$L_f \frac{di_{abc}}{dt} = e_{abc} - V_{abc} - Ri_{abc} \tag{10}$$

Where L_f and R are the inductance and resistance of the LC filter, V_{abc} and i_{abc} are the voltage and current of the inverter, respectively. The VSG power loop emulates the primary SG frequency modulation, damping, and inertia to determine the reference phase and the modulated signal frequency. And the reactive power simulates the SG's voltage regulation and determines the modular signal's amplitude. The VSG active power mathematical equation, comprising a simple VSG governor, is as follows [52]:

$$J \frac{dw}{dt} = \frac{P_m}{w} - \frac{P_e}{w} - D(w - w_{ref}) \tag{11}$$

where P_m and P_e are the input power and output electrical power of the inverter, respectively. Moreover, the VSG's reactive control loop mathematical Equation is as follows [53]:

$$K \frac{dE_r}{dt} = Q_m - Q_e + k_q(V - V_r) \tag{12}$$

where K is the inertia coefficient of the reactive power loop, E_r is the virtual electromotive force, Q_m and Q_e are the reference and output reactive power, respectively, V and V_r is the output and rated voltage amplitude, respectively. k_q is the Q-V droop coefficient.

4. VSG Control

In the power grid, converter control is a very important factor that affects grid stability. Droop control is the most common control system used now [14]. Droop control is divided into active power with frequency control (P-f) [54,55] and reactive power with voltage control (Q-V) [56,57]. P-f control adjusts the phase angle (δ), and, Q-V adjusts the voltage amplitude (E) of the reference potential in response, where the changes in E adjust the reactive power and changes in δ adjust the active power. VSG's control algorithm can be classified into two groups, as follows.

4.1 P-F Control

VSG's active power control is a copy of SG's governor unit. Figure 7 shows the control diagram. Grid frequency stability is achieved in the power system by active power. The power generated is balanced with load power under normal conditions in the power system. And when the system is disturbed, the active balance is destroyed, and the grid frequency fluctuates. [13]. The general equation for P-f droop is

$$P_m = P_{ref} - k_p(f_r - f) \tag{13}$$

Where: P_m and P_{ref} are the mechanical and active power references of VSG, respectively. f_{ref} and f is the reference and actual frequency of the system and k_p is the P-f droop coefficient.

The output torque of VSG is controlled by the change of power in the active power adjustment control of VSG. So, the active loop mimics SG's primary frequency modulation characteristic, and its output works as the inverter's reference phase angle of voltage [58].

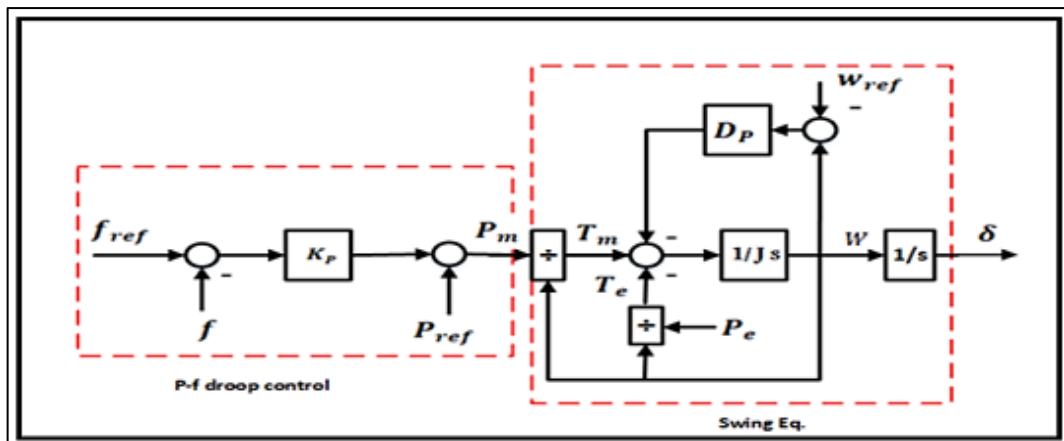


Figure 7: P-f control of VSG [57]

4.2 Q-V Control

As illustrated in Figure 8, a classic droop control method is used for voltage control. The grid voltage is kept stable by the reactive power [33]. Grid voltage will fluctuate if the balance is disrupted. The droop characteristic equation for Q-V is [57]

$$Q = Q_{ref} - k_q(V_r - V) \tag{14}$$

Where: Q and Q_{ref} are the output and reference reactive power of VSG, respectively. V_{ref} and V are the reference and measured voltage of the system and k_p is the Q-V droop coefficient. If the inverter does not provide reactive power support in steady states, Q_{ref} set to zero. The droop coefficient is based on maximum voltage changes and the voltage control features that affect the stability of the power system. [59].

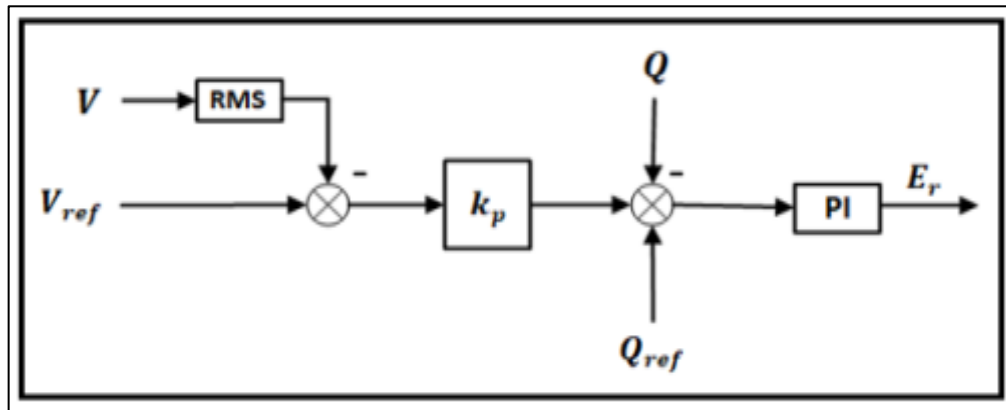


Figure 8: Q-V control of VSG [33]

5. Application of VSG

Because of the inherent features that enable it to participate in frequency stability support, the VSG control method may be used for all types of generation units, such as PV farms, wind farms, electric vehicles, and AC and DC transmission lines.

In the case of PV generation, literature [60,61] presented a PV-VSG technology, which considers the dynamic features of PV power, allowing for many PV units to connect to the grid via VSG. It enables the connect-off-grid operation that is both flexible and reliable, and it is critical to enabling grid-friendly access for distributed PV power generation.

In the case of wind power [62-64]. VSG is used to increase the dynamic performance of the wind turbine on the side of the rotor wind turbine and grid converters.

In the application of independent energy storage units, literature [65-67] proposed an electric vehicle VSG-based battery control technique. Active and reactive power is calculated by the virtual two-phase system, preventing the effect of power oscillation on virtual inertia and contributing to primary frequency modulation for the power grid. In addition, when the grid is disrupted, the island grid can be restored, and the local load can be supplied by the electric vehicle battery.

In the case of the AC and DC transmission side, literature [68-70] offered a VSG-based active voltage feedback control technique for frequency control, irrespective of the communication technology. In addition, the typical synchronizer has been improved, and the VSG can now adjust the secondary frequency independently of the PLL current under fault conditions.

6. Challenges and Further Research

The use of many units of VSGs in power systems presents additional technical problems. As the electrical sector works to use substantial amounts of DGs-based RES in the power grid, a lot of work is needed to accommodate and effectively manage the VSG units already in use. A key aspect is handling topological changes generated by using multiple VSGs as additional network control devices and stabilizing the power grid to employ the potential flexibility of the dispersed VSGs. However, extensive expertise and a thorough analysis of the literature reveal numerous challenges surrounding VSG integration that must be thoroughly investigated.

6.1 Centralized Control for VSG

Because the current power system is developing and integrating a large number of VSG-based DGs, it is necessary to develop a centralized control method that improves the various VSG control methods, including grid connection, voltage and frequency control, active or reactive power control, and parallel circulation control. In addition, it is required to build centralized control on the distributed control properties of VSG to produce more stable centralized control for VSG [71,72].

6.2 Develop VSG Control Algorithms

Various VSGs may need to be more flexible to balance supply and demand on modern power grids. The VSG frequency regulation refers to the ability of these units to regulate their output through effective control methods. In order to achieve this effectively, more active practical algorithms and control methods are required. Further investigations must be performed with traditional SG properties to coordinate kinetic energy discharge time and dimensions.

6.3 Efficient VSG Modeling

By further study of the mathematical derivation of equivalence between the VSG concept and the SG, an effective and robust control system can still be achieved by improving the existing models, where only the preferable parts are used.

6.4 VSG Energy Storage System

Batteries and capacitors are generally employed as power storage systems with VSG-based PV systems. Therefore, the battery and the ultra-capacitors combination is suggested in [73] that suppress high-frequency effects, as ultra-capacitors quickly release stored energies while batteries manage low-frequency effects. This is a better solution for power storage, but

not economical because of the high cost. Therefore, a new and economical ESS must be developed with the characteristics of conventional batteries, ultracapacitors, and small sizes.

A summary of the advancements in virtual inertia topologies discussed above sections is shown in Table 3.

Table 3: Summary of advancements in virtual inertia topologies

Year	Controller Formulation	Controller Strategy	Numerical/ Experimental	Controller Function	System Performance	Ref.
2015	$P_{set}, w, \text{ and } i_{ref}$	VSYNC (Frequency-power response based)	Numerical	Improve the transient stability of PV-hydro microgrid systems	<ul style="list-style-type: none"> Improve the frequency fluctuation and the high ROCOF ESS requirements of the VSG are very low compared to the system size 	[34]
2012	$P_{set}, Q_{set}, \text{ and } V, \theta$	VSYNC (Frequency-power response based)	Numerical	Using an output impedance model for a VSynC-based DFIG to analyze the grid-connected stability in weak grids	<ul style="list-style-type: none"> The instability caused by phase-locked loop (PLL) under the interaction with the weak grid The obtained results show the accuracy and effectiveness of the output impedance in system stability. 	[35]
2020		ISE, VISMA, VSYNC, Synchronverter	Numerical	Perform tests for the main VSG topologies	<ul style="list-style-type: none"> Synchronverter deliver larger capacity of active power to the grid, compared to the other topologies. ISE deliver a larger capacity of reactive power to the grid. VSYNC has a higher voltage oscillation 	[36]
2018	$P_{set}, Q_{set}, \text{ and } V, \theta$	Synchronverter (Synchronous generator Model-based)	Numerical and Experimental	Self-tuning of controllable parameters.	<ul style="list-style-type: none"> The self-tuning method permits the synchronverter to achieve the online change of inertia, and damping depends on grid frequency. In the acceleration period, J needs to increase, and in the deceleration period, J is decreased to the minimum value. 	[38]
2018	$P_{set}, Q_{set}, \text{ and } V, \theta$ (Different for both converters)	Synchronverter (Synchronous generator Model-based)	Numerical	The application of synchronverter to the back-to-back converter is studied.	<ul style="list-style-type: none"> For a rectifier converter, the inertial characteristics of a synchronous motor are used for the synchronverter. In the case of an inverter, a conventional synchronverter is used. 	[39]

Table 3: Continued

2017 2019	$P_{set}, Q_{set},$ and i_{ref}	ISE (Swing equation based)	Numerical and Experimental	To add the inertia emulation feature for the power electronic inverter.	<ul style="list-style-type: none"> The power loop controller is designed in such a way that both the inertia and damping features of SG are to be emulated. The load sharing of inverters with a synchronous power controller is tested. 	[40, 41]
2017 2016	$P_{set}, Q_{set},$ and V_{DC}	ISE (Swing equation based)	Numerical	The functionality of a synchronous power controller with a modular multi-level converter is studied.	<ul style="list-style-type: none"> Inertia, damping, and droop effect are emulated to the modular multi-level converter with the use of a synchronous power controller. Resynchronization of the converter with a synchronous power controller without any power loss is discussed. 	[42, 43]
2017	$P_{set}, Q_{set},$ and i_{ref}	VISMA (Synchronous generator model based)	Numerical and Experimental	A comparison of dynamic or quasi- stationary machine models of a synchronous machine and a VISMA is presented	<ul style="list-style-type: none"> The quasi-stationary VSM implementation is preferable when using SM parameters with low virtual stator resistance for decoupling the active and reactive power control, 	[46]
2016	$P_{set}, Q_{set},$ V_{DC} and i_{ref}	VISMA (Synchronous generator model based)	Numerical and Experimental	converts the battery chargers of an electric vehicle to VSM	<ul style="list-style-type: none"> The electric vehicle charger can contribute to the spinning reserve and regulate the frequency of the power system The proposed system has the inherent capability for feeding local loads in islanded operation 	[48]

7. Conclusion

Continuous development in integrating DGs based on RESs into the power system network has contributed to the imbalance in a traditional power system structure. DGs have little or no inertia and damping property compared to the conventional SGs, which means that the total inertia of the whole system is decreased altogether. The VSG solves the low inertia problem and dampening properties by providing virtual inertia by injecting active power from the VSG for a short time after any disturbance occurs. VSG's development is a convenient and economical solution for the utilization and expansion of RESs. An important measure to allocate RESs optimally is the effective interaction between VSG and SG. In addition, VSG integrates the flexibility of electronic power equipment with the operating mechanism of SG efficiently. This paper gives an overview of several virtual inertia topologies and a detailed description of the VSG structure as the most important topics on the VSG concept. Moreover, VSG control defining P-f and Q-V control is explained in detail. The VSG applications are afterward explained. Finally, the VSG challenges and future research are discussed.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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