Aalborg Universitet

On the Role of Virtual Inertia Units in Modern Power Systems

A Review of Control Strategies, Applications and Recent Developments

Jafari, Mahmood ; Gharehpetian, Gevork B.; Anvari-Moghaddam, Amjad

Published in:
International Journal of Electrical Power & Energy Systems

DOI (link to publication from Publisher):
10.1016/j.ijepes.2024.110067

Creative Commons License
CC BY 4.0

Publication date:
2024

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Jafari, M., Gharehpetian, G. B., & Anvari-Moghaddam, A. (2024). On the Role of Virtual Inertia Units in Modern Power Systems: A Review of Control Strategies, Applications and Recent Developments. *International Journal of Electrical Power & Energy Systems*, *159*, 1-19. Article 110067. https://doi.org/10.1016/j.ijepes.2024.110067

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: August 20, 2025

On the Role of Virtual Inertia Units in Modern Power Systems: A Review of Control Strategies, Applications and Recent Developments

Mahmood Jafari[a], Gevork B. Gharehpetian[a,*], Amjad Anvari-Moghaddam[b]

[a]*Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran*
[b]*Department of Energy (AAU Energy), Aalborg University, 9220 Aalborg, Denmark*

Abstract

The modern power system is progressing from a system based on synchronous generators toward systems with high penetration of renewable energy sources (RESs) such as photovoltaic (PV) and wind power generating units which are connected to the grid through inverters. RES units will represent a significant share of the power generation in near future; therefore, the conventional approach of integrating them into the grid may lead to frequency instability. Many researchers have suggested the use of inverters with virtual inertial control methods to act as synchronous generators in the grid and maintain and increase the frequency stability. This paper presents a comprehensive overview of virtual inertial strategies and current control strategies and makes a comprehensive comparison while describing their characteristics. Then, different types of stability analyses in the presented methods are examined and examples of each are presented. In continuation and in addition to the review studies conducted in this field, methods presented with the aim of improving the virtual inertial control are carefully examined and their characteristics according to the number of resources used, the adaptivity of parameters, the use of optimization methods, the issue of coordination between several resources and the type of communication network are studied. Moreover, a comprehensive review of multiple- virtual synchronous generator (VSG) methods to develop and implement the concept of virtual inertia in weak grids are presented. Finally, a discussion of challenges and research directions is presented, particularly pointing to the integration of multiple virtual inertial units at the system level.
© 2017 Elsevier Inc. All rights reserved.
Keywords: Microgrids; Virtual inertia; Stability analysis; Virtual synchronous generator; Coordination; Power sharing

1. Introduction

Because of rising concerns about the long-term sufficiency of nonrenewable energy sources such as oil, coal, and natural gas, as well as their environmental footprints, the penetration of RESs in power systems have rapidly expanded and is becoming a must. For example, in Japan, up to 64 GW of solar capacity is expected to be added to the grid by 2030 [1].

In order to assist the appropriate transfer of electrical energy from RESs to the power system, a converter-interface unit is often required to integrate the RESs-based generating units into the power system. Because of the lack of rotating mass as a source of inertia, such power-electronics interfaces lack inertia. As a result, the increasing use of inverter-based generating units may have a negative impact on system dynamic behavior, with the total inertia in a power system dominated by inverter-based renewable generating units being significantly lower than in a traditional power system dominated by classic synchronous generators.

http://dx.doi.org/10.1016/j.ijepes.2023.000000

Nomenclature

RES	Renewable Energy Source
VSG	Virtual Synchronous Generator
VISMA	Virtual Synchronous Machine
SG	Synchronous Generator
DG	Distributed Generator
MGCC	Microgrid Central Controller
PLL	Phase Locked Loop
PI	Proportional Integral
PID	Proportional Integral Derivative
RoCoF	Rate of Change of Frequency
LFO	Low-Frequency Oscillation
ESS	Energy Storage System
SoC	State of Charge
PWM	Pulse Width Modulation
EV	Electric Vehicles
VSC	Voltage Source Converter
CoI	Center of Inertia
PV	Photovoltaic
BES	Battery Energy Storage
DFIG	Doubly-Fed Induction Generator
MAS	Multi-Agent System
MPC	Model Predictive Control
PSO	Particle Swarm Optimization
LVRT	Low Voltage Ride Through
HVRT	High Voltage Ride Through
SVD	Singular Value Decomposition
VOC	Virtual Oscillator Control
IBG	Inertial-Based Generator

Consequently, while the rapid rise in the application of inverter-based RESs generation units is great for the environment and implies good utilization of available resources, it is detrimental to power system stability, particularly frequency stability [1–6], because frequency stability is closely related to the amount of inertia in the system.

Fig. 1 depicts an example of the connection between inertia and frequency. With decreased system inertia, the frequency nadir exposed to a frequency event is clearly demonstrated to be lower. Furthermore, in addition to the direct impact on overall system inertia, increasing the penetration of RES-based generation units may have negative consequences such as excess electricity supply in the system, power fluctuations due to the variable nature of RESs, and deterioration of frequency regulation [7].

To address some of the aforementioned issues, frequency control methods in power systems have been proposed over the past years. These methods can be mainly categorized into three levels of primary, secondary and tertiary control. Each of the mentioned levels can be implemented in one of the centralized, decentralized and distributed forms. The above techniques are effective for achieving frequency stability in power systems, but their operation in networks with low inertia faces problems, and for the same reason, a technique called virtual inertia has been introduced in recent years to respond more quickly to frequency deviations. The comparison and connection of these different levels in time scale and according to their communications system is shown in Fig. 2. The focus of this article is on virtual inertia, which might possibly provide inertia support to the power system in order to allow it for a high penetration of RESs. In general, virtual inertia control is the concept of replicating inertia in the power system using an inverter and/or an ESS with suitable control. This concept is often referred to as a synchronverter [8], VISMA [9], or virtual synchronous generator [10]. The aforementioned systems all have the same purpose of virtually adding extra inertia by employing an inverter and an ESS and being backed by a suitable virtual inertia control mechanism. By employing the aforementioned approaches, the reservoir of kinetic energy in the rotating mass of a classical synchronous generator might be replicated on the inverter-based unit, allowing the inverter-based generation to imitate virtual inertia.

Because of their ability to offer extra inertia support in the low inertia power system, virtual inertia control units would be a core part of the future power systems dominated by RESs. The creation of the idea of virtual inertia is critical for ensuring the smooth functioning of the power system with a high penetration of RESs-based generating units [11]. A glance at the development of the virtual inertia topic in the past years shows that its implementation preliminary methods emerged during 2008-2011. In continuation and considering the need to develop these methods, the use of time-varying values, in order to have effective parameters, was raised for the first time in 2015 [12]. Numerous papers using different techniques have addressed this topic and expanded it until 2019. Later and especially from 2019 onwards, the studies on virtual inertia have focused on the application of optimization techniques and various algorithms to improve the results. Furthermore, the adoption of several virtual inertial units is a topic that has been raised since 2020. Some of the reasons for the tendency towards this topic in recent years are the distribution of RESs with different structures and energy density and high-power quality and the issue of their optimal location in networks. Therefore, new studies deal with the issue of coordination between RESs and use optimization methods to increase their response speed. In addition to the above topics, other topics such as siting of virtual inertial units, the type of energy source used to provide power, and the type of operating system were among the trends that have been addressed over the years, along with the main topics above. By examining the research conducted in recent years on the subject of virtual inertial control, as seen in Fig. 3, the most trends are on the subjects, VSG, RES, and wind turbines. Despite these trends in the topic of virtual inertia in recent years, there is a need to provide a comprehensive review that examines multi-VSG methods in detail, how they communicate to each other, and the types of methods used to coordinate between them. For better perception see Fig. 4.

In addition, in recent years, interesting review researches have been conducted on the topic of virtual inertia [13,14]. Ref [13] examines the challenges, proposes solutions and emphasizes the necessity of new models and methods in power system sustainability by changing the type of energy sources towards RES. Also, Ref [14] provides a comprehensive overview of the necessity of inertial estimation, covering fundamental aspects such as oscillation equation, definition of inertial constant, correlation between RoCoF and inertial constant and etc. In addition, various types of virtual inertial algorithms are reviewed with a detailed examination of their advantages and limitations. Building upon prior research, this review study meticulously examines methods aimed at enhancing virtual inertial control, exploring their characteristics concerning the number of resources used, adaptivity of parameters, utilization of optimization methods, coordination among multiple resources, and the type of communication network.

Considering the importance of this concept application, a comprehensive review on virtual inertia strategies is presented in this paper. Section 1 deals with introductory part while concept of the virtual inertia is discussed in Section 2. In Section 3, various strategies for emulating the virtual inertia are discussed and Section 4 presents different stability analysis techniques and gives a comprehensive overview of the methods presented in recent years in the subject of virtual inertia and compares them from different aspects. In section 5, the challenges and future directions in the field of virtual inertia have been raised, and at the end, in section 6, research gaps are introduced and guidelines for continuing studies in this area are provided.

2. Virtual Inertia Concept

Although the related content has already been discussed in the literature [9]-[10], due to the importance of this section and in order for the reader not to jump to the related texts and equations in other references, virtual inertial concept has been summarized in this section. Grid-forming control methods provide a solution, offering the ability to raise virtual inertia, enhance frequency stability, and synchronize with the main grid without the need for a phase-locked loop. Despite mimicking synchronous generators' behavior, grid-forming converters differ fundamentally, posing challenges related to small-signal stability models, current limitations, and dynamic responses. The advantage of network-forming converters can be seen in the possibility of setting parameters such as inertia and damping constants. The technical challenges of power-electronic-dominated systems, limited penetration levels, and the need for grid-forming solutions are discussed. While estimates suggest a 100% IBG penetration level is theoretically feasible, a comprehensive study on stability challenges, especially focusing on grid-forming solutions, remains a gap in the literature [15,16].

The concept of the virtual inertia was developed to regulate an inverter, which lacks inertia, to mimic the inertia characteristic of an SG. This was accomplished by implementing the swing equation of an SG into the inverter of the inverter-based RESs generation units. The needed inertia power output from the virtual inertia control system is determined by the inverter control for virtual inertia emulation using simulation of the usual SG swing equation, as follows:

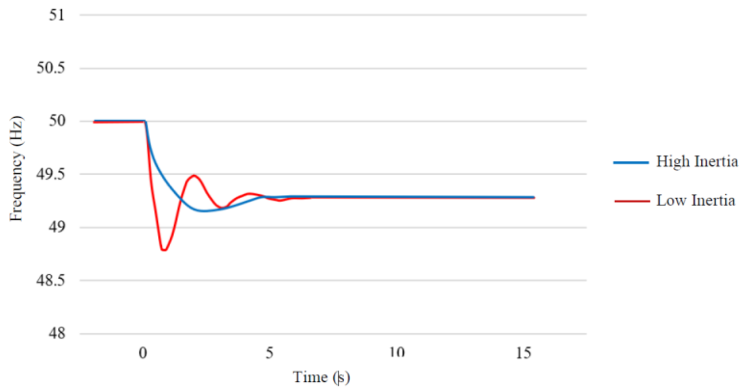

Fig. 1. An illustration of the correlation between inertia and frequency in a power system with high or low inertia

$$\bar{P}_m - \bar{P}_e = \bar{P}_a = \frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = \frac{2H}{\omega_0}\frac{d\Delta\omega_r}{dt} \tag{1}$$

where, $\bar{P}_m$ stands for mechanical power input provided by the SG [p.u.], $\bar{P}_e$ for electrical power output demanded by the load [p.u.], $\bar{P}_a$ for acceleration power [p.u.], H for inertia constant [MW.s/MVA], ω_0 for the rated angular velocity of the rotor [rad/s], ω_r for the actual angular velocity of the rotor [rad/s], and δ for rotor angle [rad].

The quantity $d^2\delta / dt^2$ in (1) denotes the change in system frequency or the angular rotor velocity of an SG. It also correlates the active power and angular rotor velocity of an SG with the system frequency. The system frequency can change based on the balance between the mechanical power input $\bar{P}_m$ and the electrical power output $\bar{P}_e$, according to the swing equation. The acceleration power $\bar{P}_a$ is positive when ($\bar{P}_m - \bar{P}_e$) is positive and system frequency will rise in this condition, and vice versa. A speed controlling mechanism in the SG units is used to control the generation-load balance at a steady-state operating point in order to maintain the system frequency.

Equation (1) changes when the damping element is included:

$$\bar{P}_m - \bar{P}_e = \frac{2H}{\omega_0}\frac{d\Delta\omega_r}{dt} + K_D\frac{\Delta\omega_r}{\omega_0} \tag{2}$$

where, K_D stands for the damping factor. This equation may alternatively be expressed as the following in frequency (Hz):

$$\bar{P}_m - \bar{P}_e = \frac{2H}{f_0}\frac{d\Delta f}{dt} + K_D\frac{\Delta f}{f_0} \tag{3}$$

where, f is the frequency of power system and f_0 is its rated frequency in Hz. The RoCoF of the power system is commonly referred to as $d\Delta f \,/\, dt$.

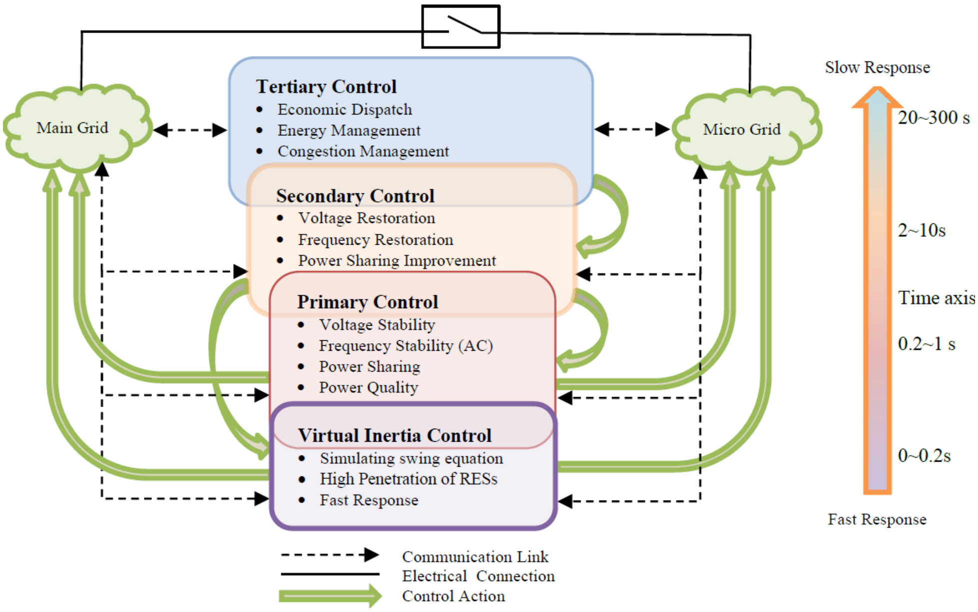

Fig. 2. Comparison of different levels of hierarchical control in time scale and according to their communications

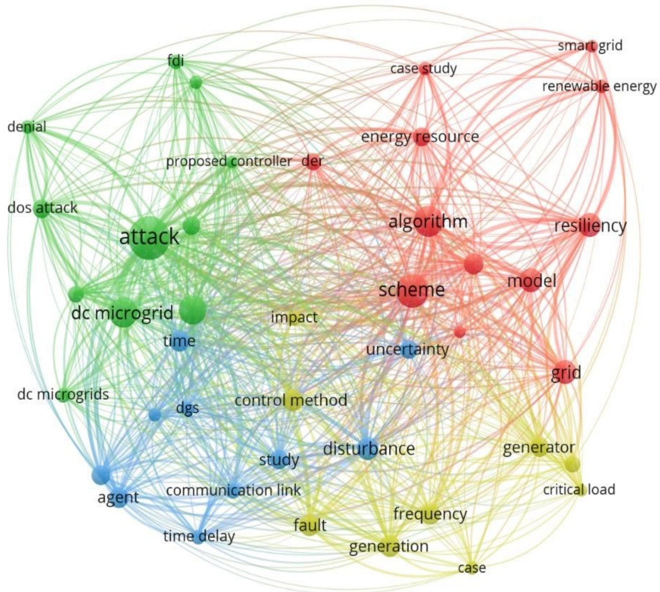

Fig. 3. Trends and thematic communications with the concept of virtual inertia in recent years

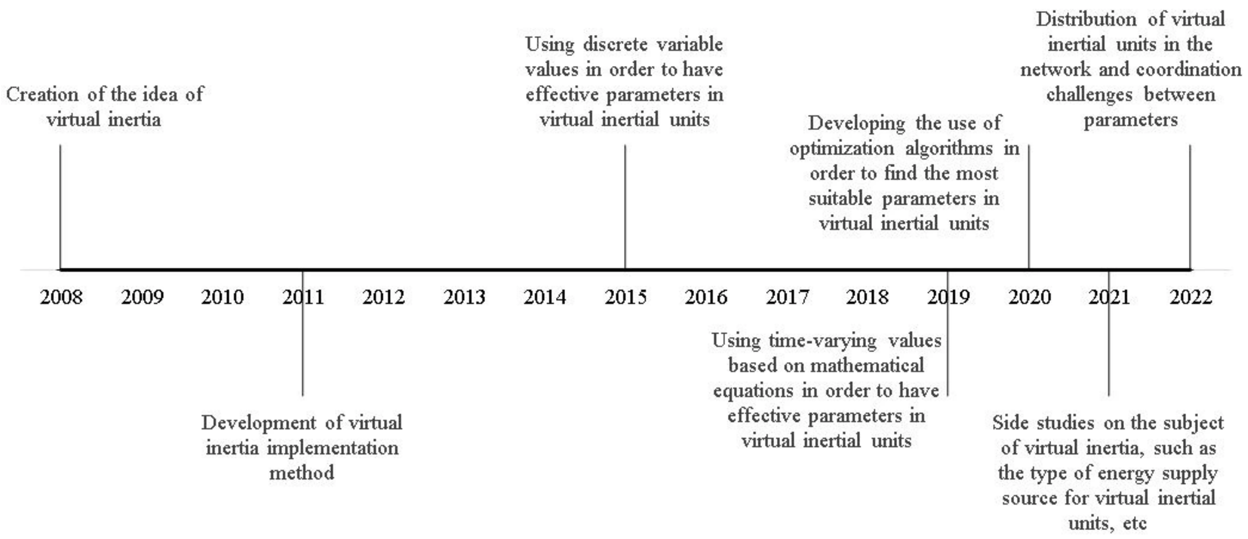

Fig. 4. The development of virtual inertia control

In this review, some virtual inertia modelling strategy are discussed such as strategy based on droop control which takes advantage of the inherent droop capabilities in SGs for power-sharing in steady-state conditions; strategy based on synchronous generator model in which synchronverters, which have a voltage-source-based design, can be used as the components of the network. They are particularly well-suited for transferring inertia from distributed generators that are not connected to the primary power grid; strategy based on virtual oscillator control (VOC) which offers a reliable method for achieving network synchronization in a communication-limited setting. This technology guarantees consistent network synchronization while controlling voltage and frequency by utilizing proportional load sharing capabilities. Finally, a comparison of the strategies is discussed. [17]

When an approximate replication is sufficient, simpler methods such as Ise Lab's strategy are often used. On the other hand, if the objective is to solely provide the dynamic frequency response without accurately modeling the behavior of SGs, the VSG technique is more suitable. The research presented centered on the investigation of advanced virtual inertial systems. Specifically, it examined the usage of numerous virtual inertial units and their optimization approaches. These techniques provide enhancements in RES units that contribute to the inertial response, while simultaneously limiting any deterioration in the lifespan of the ESS.

3. VIRTUAL INERTIA STRATEGIES

A review of the literature on recent advancements in the synthesis and control of virtual inertia will be given in this part. In future power systems, the amount of inverter-based producing units and the resulting reduction in overall system inertia may have a significant impact on how smoothly and steadily the power system operates. The implications of a large fraction of inverter-based generating units and low inertia on stability and operation are explored in a number of papers, including [18–21].

One potential strategy to lessen the consequences of low system inertia and improve the stability of low inertia power systems, particularly the frequency stability, is to simulate greater inertia into the power system without using actual rotating mass. The many strategies that can simulate virtual inertia are listed in [9]-[10]. These strategies were all created using a common fundamental idea. The amount of detail in how they are implemented, however, varies. A few important strategies will briefly be described and the differences between the strategies will be emphasized, to provide an overview of the various strategies for virtual inertia simulation.

Three broad categories might be used to classify the virtual inertia modeling strategy [17]:

- Strategy based on droop control
- Strategy based on synchronous generator model
- Strategy based on swing equation
- Strategy based on frequency-power response

- Strategy based on Virtual Oscillator Control (VOC)
- Strategy based on Matching Control

3.1. Strategy based on droop control

The implementation of droop control for the integration of parallel inverters in active power networks follows a straightforward approach. This strategy exploits the steady-state power-sharing droop capabilities inherent in SGs [22,23] In predominantly inductive networks, droop control relies intricately on steady-state relationships including active power and angular frequency, as well as reactive power and voltage difference. However, challenges may appear in highly robust networks, which require controllers specifically built to accommodate alternative behaviors. A central aspect of droop control involves simulating the frequency regulation characteristics of the governor control. This simulation establishes a negative feedback correlation between the real power and the frequency, which potentially involves measuring inertia [24] Equation (4) illustrates the droop equation:

$$\omega = \omega_s - K_p \left(P - P_s \right) \quad (4)$$

$$\frac{d\theta}{dt} = \omega \quad (5)$$

where, ω represents the instantaneous angular frequency, ω_s is the angular frequency reference, P denotes the power output of the converter, P_s is the reference power, K_p is the droop coefficient, and θ represents the power angle. The relationship between the angular frequency and the power angle, which is presented in equation (5), allows the reduction of the active power according to the angular frequency ω or the power angle θ slow. In certain scenarios, angle drop is preferred due to limitations in frequency tuning in networks that experience frequent load changes [25]. The relation of angle drop is expressed in equation (6):

$$\theta = \theta_{set} - K_p \left(P - P_{set} \right) \quad (6)$$

where, θ_{set} represents the power angle set value. The introduction of voltage drop is necessary to ensure the sharing of reactive power in the voltage magnitude loop. This mechanism establishes a negative feedback relationship between reactive power and voltage value, as expressed in equation (7):

$$V = V_{set} - K_q \left(Q - Q_{set} \right) \quad (7)$$

where V represents the instantaneous voltage, V_{set} is the voltage reference, Q represents the instantaneous reactive power and Q_{set} is the reference reactive power. Fig. 5 shows a simple implementation of the droop controller that emphasizes the active power control loop and the reactive power control loop. The droop controller is compatible with virtual synchronous machine control in steady-state systems [26] and uses low-pass filters in power loops to simulate inertia [27]. An exploration of the relationship between angle drop, virtual impedance, and frequency drop is described in [28], highlighting the effectiveness of angle drop as a virtual inductance method. The combination of virtual inductance and frequency drop increases the oscillatory damping in a proportional derivative manner.

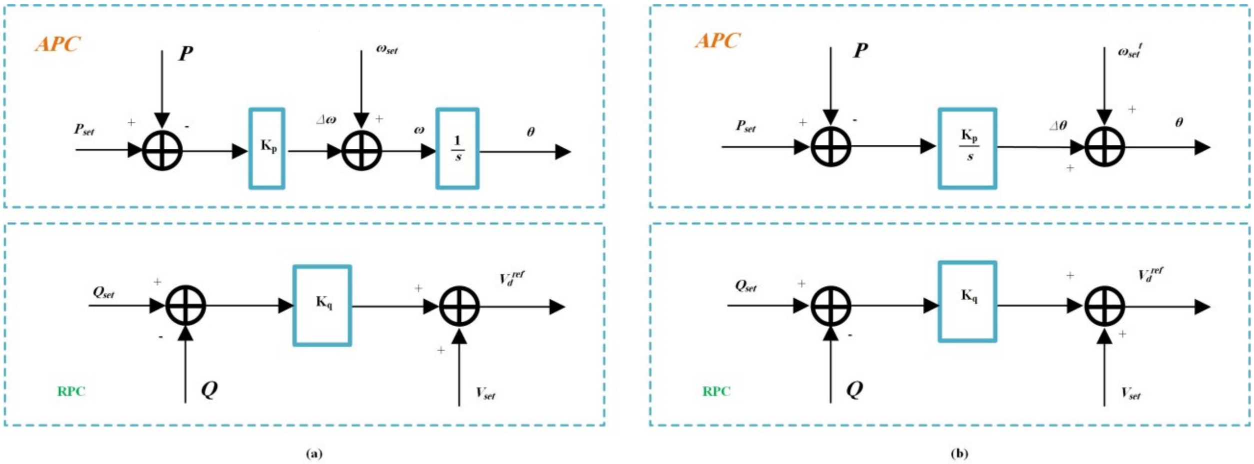

Fig. 5. a) Droop control. (b) Power synchronization control (PSC)

3.2. Strategy based on synchronous generator model (Synchronverter)

From the perspective of the grid, synchronverters run inverter-based DGs as SGs that represent the same dynamics [8]. This is predicated on the idea that such an approach enables the power system's conventional operation to be maintained without significant modifications to the operational structure. In [29], a thorough development of the strategy has been provided. The power output from the inverter is controlled via a frequency drooping mechanism, much as how the SG controls its power output [30]. To describe the dynamics of the SG, the fundamental equations below are used:

$$T_e = M_f i_f \langle i , sin\theta \rangle \tag{8}$$

$$e = \theta M_f i_f \; sin\,\theta \tag{9}$$

$$Q = -\theta M_f i_f \langle i , cos\,\theta \rangle \tag{10}$$

where, Q is the reactive power produced, e is the no-load voltage produced, T_e is the synchronverter's electromagnetic torque, M_f is the mutual inductance between the field coil and the stator coil size, i_f is the field excitation current, and θ is the angle between the rotor axis and one of the phases of the stator winding. In (8) and (10), $\langle \,.\, , \,.\, \rangle$ stands for the standard inner product of two vectors in three-dimensional space. A three-phase stator's vectors i , sin θ, and cos θ are defined, as follows:

$$i=\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} , \; sin\theta=\begin{bmatrix} sin\theta \\ sin\left(\theta\text{-}\dfrac{2\pi}{3}\right) \\ sin\left(\theta\text{-}\dfrac{4\pi}{3}\right) \end{bmatrix} , \; cos\theta = \begin{bmatrix} cos\theta \\ cos\left(\theta\text{-}\dfrac{2\pi}{3}\right) \\ cos\left(\theta\text{-}\dfrac{4\pi}{3}\right) \end{bmatrix} \tag{11}$$

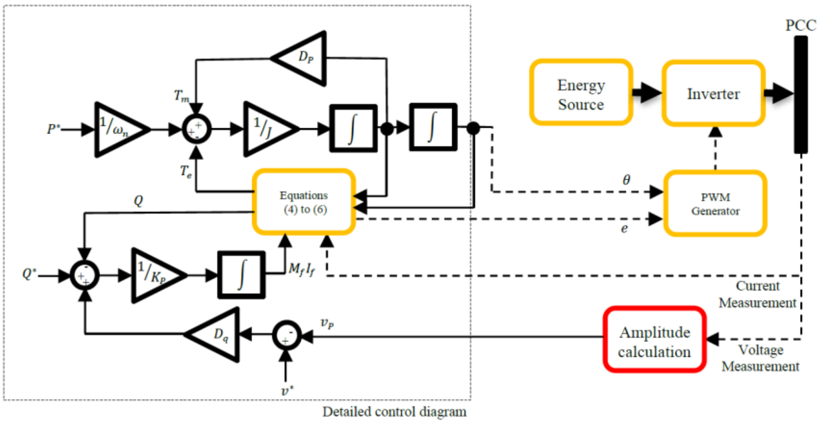

Fig. 6. Synchronverter topology

First, equations (8)-(10) are separated and then solved in each control cycle of a digital controller .In this way, the gate signals are generated for the DG unit under consideration. The synchronverter's fundamental schematic is shown in Fig. 6. The control part of the synchronverter is represented by the dashed box and details are shown in Fig. 6. Grid voltage and inverter output current are the feedback signals utilized by the controller to solve the differential equations. Additionally, the required damping factor D_p and moment of inertia J can be adjusted. According to [31], the choice of these factors is essential in terms of the stability of the system. As seen in Fig. 6, the voltage and frequency looping create the mechanic torque, T_m and $M_f I_f$, as control inputs. The reference active power $\bar{P}$ is utilized to construct T_m in the frequency loop based also on nominal angular frequency of the grid, which is ω_n . Thus, this loop produces the virtual angular frequency of the synchronverter, which is employed for PWM and integrated to determine the phase command θ . Similarly, the difference observed between the amplitude of the grid voltage v and reference voltage $\bar{v}$ in the voltage loop is increased by a voltage drop constant D_q . This increases the gap between the reference reactive power $\bar{Q}$ and the calculated reactive power Q using (10). Then, the obtained signal is sent through an integrator with a gain of $1/k_v$ in order to produce. The $M_f I_f$ controller outputs, e and θ , are used to produce PWM.

Basic equations of a synchronverter strategy generate an amplified PLL or sinusoid-locked loop, which is innately able to maintain synchronization with the terminal voltage [32]. In [33], the synchronverter was also constructed in single phase versions. Although their use in networks with low inertia is unstable, PLLs are required to synchronize the primary form of the synchronizer to the network [34]. In [35], self-synchronized synchronverters has been proposed as a solution to this problem. The synchronverter architecture [36], which assists in acquiring inertial reaction from the load side of the power system, has also influenced the operation of rectifiers as synchronous motors. Furthermore, due to their voltage-source-based architecture, synchronverters may be utilized as the units forming the network and they are ideal for repeating inertia from DGs that are not connected to the main grid. Given how frequently derivative terms contribute noise into systems, the fact that the frequency derivative is not needed for execution is a great advantage. Even when the synchronverter can replicate an SG's exact dynamics, the complexities of the differential equations involved might induce numerical instability. Furthermore, because a voltage-source technique lacks inherent safety against powerful grid transients, it may necessitate the deployment of additional protective devices in order to perform properly.

3.3. Strategy based on swing equation (Ise Lab's Strategy)

The strategy developed by Ise Lab to implement virtual inertia is similar to the approach described earlier, but instead of applying a fully model of the SG, the strategy solves the power-frequency swing equation in each cycle to simulate the inertia. [37]. The strategy schematic design, shown in Fig. 7, displays the operational principle. The controller determines the grid frequency ω_g and the inverter active power output P_{out} after measuring the inverter output current i and the connection point voltage v . These two parameters, along with P_{in} , the prime mover input power, are inputs to the principal control algorithm block. [12]. Every control cycle of the control algorithm involves solving the swing equation denoted by (8), which produces the phase command θ for the PWM generator. A SG's usual swing equation is:

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D_p\left(\omega_m - \omega_g\right) \tag{12}$$

$$\Delta\omega = \omega_m - \omega_g \tag{13}$$

where, ω_m, ω_g, J, D_p, P_{in} and P_{out} are the virtual angular frequency, grid/reference angular frequency, moment of inertia, damping factor, input power (equivalent to prime mover input power in an SG), and output power of the inverter, respectively. The input power P_{in} is estimated using a governor model based on frequency fluctuations from the reference frequency ω^*, as shown in Fig. 7. To simulate the governor, a first-order lag element with gain K and a time constant T_d is employed in this technique. For the DG unit, P_0 stands for continuous power reference. The governor model's delay causes larger RoCoF and hence higher frequency nadirs. The Q-V droop technique is a method that may be used to create the voltage reference e, as stated in [38].

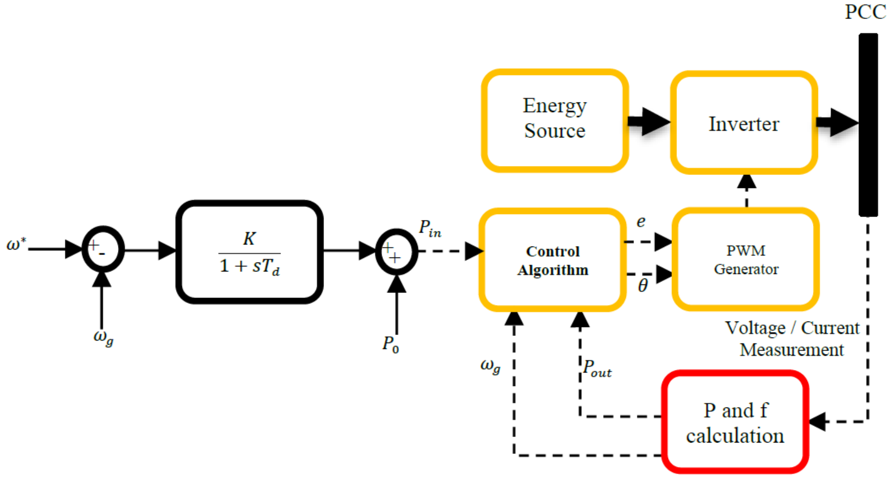

Fig. 7. Ise Lab's topology

The control technique may be implemented without the need of a frequency derivative, much like a synchronverter. This is very advantageous, since frequency derivatives are known as noise adding source into the system, making it challenging to manage. Additionally, DG units may be employed with this strategy to function as grid-forming units. However, there are still issues with numerical instability, which when combined with incorrect parameter tuning for J and D_p, can cause oscillatory system behavior [12].

3.4. Strategy based on frequency-power response (Virtual Synchronous Generator)

VSGs are designed with the primary goal of simulating an SG's inertial response properties in a system with high penetration of DGs, to react to frequency variations [24]. In other words, the VSG is a dispatchable current source that adjusts its output depending on variations in frequency of system. Given that it does not include all the complex equations necessary for an SG, this is one of the easiest methods for implementing virtual inertia in DG systems. But it is known that instability may occur when using many DG units as current sources [39].

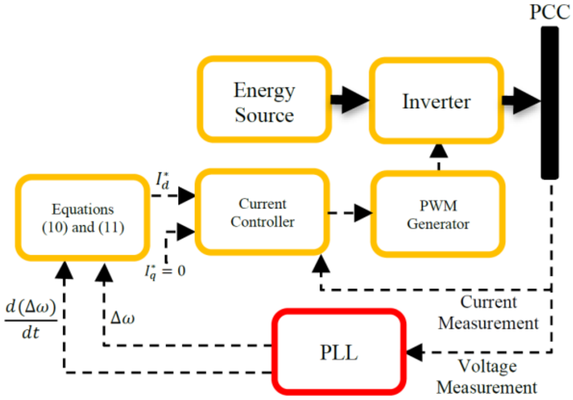

Fig. 8. Topology based on frequency-power response (VSG)

Equation (14) is used to manage the VSG converter output power:

$$P_{VSG} = K_D \varDelta\omega + K_I \frac{d\varDelta\omega}{dt} \tag{14}$$

where, the angular frequency change and its related rate-of-change are represented by $\varDelta\omega$ and $d\varDelta\omega / dt$, respectively. The damping and the inertial constant are denoted by the letters K_D and K_I, respectively. Similar to frequency droop, the damping constant aids in bringing the frequency back to its steady-state value and lessens the frequency nadir. By offering quick dynamic frequency response based on the frequency derivative, the inertial constant stops the RoCoF. This functionality is particularly crucial in an isolated grid where a high initial RoCoF might trigger unneeded protective relays. Fig. 8 presents an illustration of the VSG strategy . The change in system frequency and RoCoF are measured using a PLL [40,41]. The active power reference for the inverter is then calculated using (14). On the basis of this reference power, the current references are then produced for the current controller. However, the strategy depicted here assumes a direct-quadrature (d-q) based current control strategy. D-axis current reference for d-q control may be computed as [42]:

$$I_d^* = \frac{2}{3}\left(\frac{V_d P_{VSG} - V_q Q}{V_d^2 + V_q^2}\right) \tag{15}$$

where, V_d and V_q are the measured grid voltage d-axis and q-axis components, respectively. Assuming that just the active power is being regulated, the reactive power Q and the q-axis current reference I_q are both set to zero. The gate signals needed to operate the inverter are produced by the current controller using the grid current feedback. As a result, the inverter operates as a voltage source inverter with current control [43].

According to [44], the VSG architecture has extensively been used to simulate virtual inertia from wind power systems. This strategy fundamental flaw is its inability to be used in island modes, where the unit of virtual inertia must function as a unit that forms a grid. Additionally, the system simulates inertia during frequency fluctuations but not during changes in input power [45]. For this type of technology, precise frequency derivative measurement by PLLs might be difficult [46,47]. Particularly for weak grids, the performance of PLLs might deteriorate and compete with one another [48]. With frequency changes, harmonic distortions and voltage sags/swells, PLL systems are known to exhibit instability and steady-state errors, particularly in weak grids [34]. It has been demonstrated in [49] that the instability issues are exacerbated when the inner-current control loop of the inverter is implemented using a PI controller. As a result, for a VSG to be implemented successfully, a strong and complex PLL is needed [50]. The derivative sentence required to calculate the RoCoF constructs the VSG vulnerable to noise, which might result in unstable operation, which is another drawback of the VSG technique.

3.5. Strategy based on Virtual Oscillator Control (VOC)

Using the synchronization capabilities of a network including weakly coupled nonlinear oscillators, the VOC model provides a robust approach to network synchronization in a communication-constrained environment. This technique ensures stable network synchronization while regulating voltage and frequency through proportional load sharing capabilities [51].

VOC, distinct in its non-simulator nature, does not rely on phase measurement or computation of quantities in a predefined synchronous mode [52]. Instead, it achieves real-time system synchronization stability and avoids the need for direct network communication. Despite different loads in a network, VOC minimizes frequency deviations, ensures system stability and voltage maintenance with steady-state droop capability, as demonstrated in [53].

The basic VOC model, shown in Fig. 9, is built on a dead zone oscillator, which has a parallel tank that determines the resonant frequency and tunes the system frequency. (v_c) represents a voltage-dependent source with its maximum slope, σ, associated with the damping resistance. The constant v is a voltage scaling factor corresponding to the RMS value of the network, and φ and k_i ensure safe voltage supply to the load. κ is related to the power rating of grid-forming converter compared to other inverters in the network. Global synchronization relies on the filter impedance, z_f, the effective impedance of the parallel branch RLC in the oscillator, and the scale factors k_v and k_i.

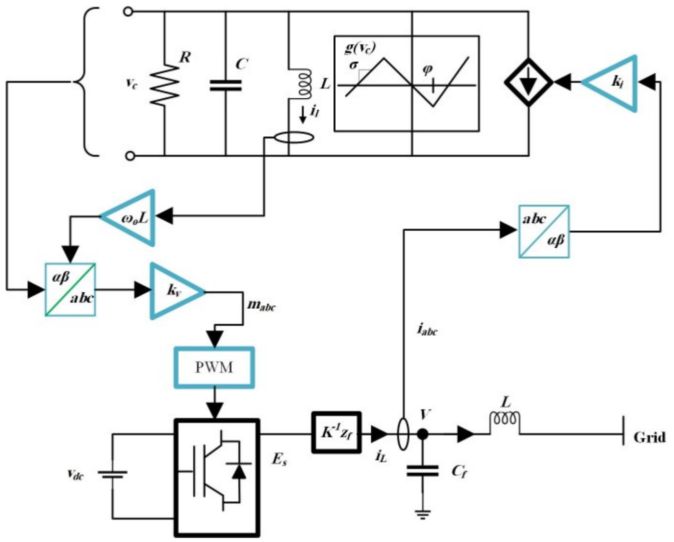

Fig. 9. Basic diagram of the VOC

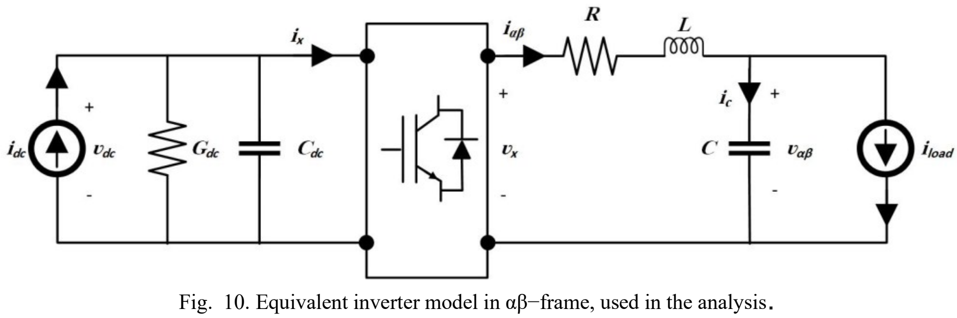

Fig. 10. Equivalent inverter model in αβ−frame, used in the analysis.

3.6. Strategy based on Matching Control

Contrary to traditional power synchronizing controllers, control matching introduces a unique perspective, challenging the conventional assumption of a clear separation between the DC and AC sides of a DC-to-AC power converter [54]. This innovative method centers around measuring the DC voltage at the inverter's DC bus, acting as an indicator for frequency equilibrium on the AC side. The dynamic link established between the control of AC frequency and the fluctuations in the DC voltage marks a departure from conventional approaches [55]. The DC bus voltage, serving as a reservoir of energy in the inverter, provides real-time insights into power transfer dynamics, offering an effective avenue for controlling active power transfer. The concept of matching control strategically leverages the inherent similarities shared by power converters and synchronous machines [56].

To explore the interconnected dynamics within the 3-phase model of a converter, depicted as a linear AC and DC circuit coupled with a nonlinear modulation block representing a 6-switch 2-level inverter (refer to Fig. 10), and a single pole pair , non-salient rotor synchronous generator externally excited, both systems are aligned in the αβ−frame [57]. The resulting converter model is articulated through the modulation signal $m_{\alpha\beta} \in [-1,1]$, linking it to the 3-phase currents $i_x = 0.5\, m_{\alpha\beta}{}^T i_{\alpha\beta}$ and voltages $v_x = 0.5\, m_{\alpha\beta} v_{dc}$.

Within the closed-loop system presented in Fig. 10, the inverter model takes on a new expression:

$$C_{dc}\dot{v}_{dc} = -G_{dc}v_{dc} + i_{dc} - \frac{1}{2} i_{\alpha\beta}{}^T m_{\alpha\beta} C\dot{v}_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta} L\dot{i}_{\alpha\beta} = -Ri_{\alpha\beta} - v_{\alpha\beta} + \frac{1}{2} v_{dc} m_{\alpha\beta} \tag{16}$$

The generator model, as detailed in [101], assumes a distinct form:

$$M\dot{\omega} = -D\omega + \tau_m + i_{\alpha\beta}{}^T L_m i_f \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} C\dot{v}_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta} L_s \left(\dot{i}_{\alpha\beta}\right) = -Ri_{\alpha\beta} - v_{\alpha\beta} + \omega L_m i_f \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \dot{\theta} = \omega \tag{17}$$

where M is the rotor inertia, D is the damping coefficient, τ_m is the mechanical torque, L_m is the mutual inductance of the machine, i_f is rotor current, θ is the electrical angle, C is the capacitance at the output, $i_{\alpha\beta}$ and $v_{\alpha\beta}$ are the output inductance current and output voltage expressed in the αβ−frame, i_{load} is the load current, L_s is the stator inductance, R is the stator resistance, and ω is the angular frequency.

The alignment of the two sets of models in Equations (16) and (17) involves identifying commonalities in these equations. Introducing the modulation $m_{\alpha\beta} = \mu[-\sin\theta \quad \cos\theta]^T$, where $\mu \in [0,1]$ is the amplitude gain constant, and defining angular frequency $\dot{\theta} = \eta v_{dc}$, resembling the rotor angle, with $\dot{\theta} = \omega_0 / v_{dc}^{ref}$, transforms the converter model into:

$$\frac{C_{dc}}{\eta^2}\omega_c = -\frac{G_{dc}}{\eta^2}\omega_c + \frac{1}{\eta} i_{dc} - \frac{1}{\eta} i_x \tag{18}$$

$$Cv^*_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta} \tag{19}$$

$$Li_{\alpha\beta} = -Ri_{\alpha\beta} - v_{\alpha\beta} + \frac{1}{2\eta}\omega_c m_{\alpha\beta} \tag{20}$$

Delving into Equation (19) i_{dc} in the converter now corresponds to the mechanical torque of the machine, dictating the active power set point, while the voltage v_{dc} controls the primary energy source.

Fig. 11 serves as a visual representation of the controller implementing matching control, where v is the amplitude of the AC side voltage, v_{dc}^{ref} is the voltage reference, G_{dc} is the DC-side conductance, and k_{dc} is the compensator gain. The incorporation of power loss in the calculation of i_{dc} compensates for the losses in the converter, ensuring accurate tracking of power set points. This controller model forms an inner loop, with additional outer loops catering to desired performance, such as inertia, voltage, and frequency regulation through modulation of η , i_{dc} and μ . The integration of a droop controller can further regulate the relationship between the DC voltage v_{dc} and the frequency ω_c .

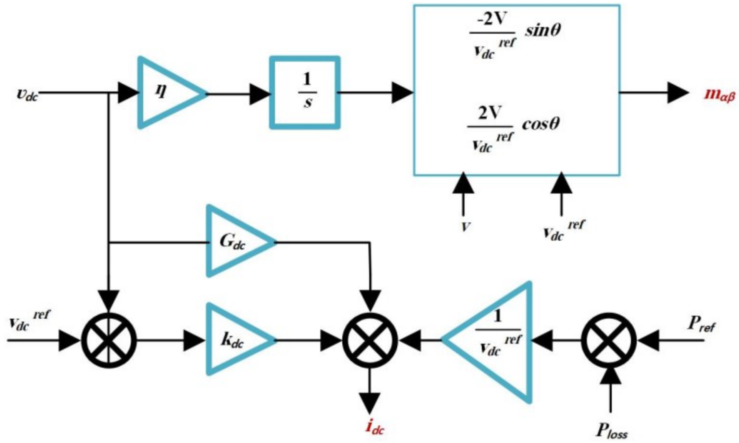

Fig. 11. The basic controller implementing matching control

The allure of matching control lies in its adept utilization of the interaction between the AC and DC sides of the converter, obviating the necessity for measurement delays present in feedback loops of alternative control approaches. A study in [58] delves into the concept of the electronic synchronous machine, emphasizing the intrinsic relationship between the DC bus voltage and the angular frequency of the AC side, resulting in a synchronization of machine dynamics and power flow within the converter.

3.7. Comparison of strategies

The characteristics of the discussed strategies can be seen in Table 1. Considering the features and weaknesses mentioned for each of the strategies , many new studies, due to the simplicity of the VSG strategy , follow the issue of the virtual inertia with this title and fix the weaknesses of this method with techniques like the presence of a strong PLL. However, in some cases, it can be seen that despite the term VSG being mentioned in the title, the equations presented in the article are related to the strategy of Ise Lab.

Table 1. Characteristics of strategies presented to implement the concept of virtual inertia

Strategies	Main Features	Weak Points
Strategy based on synchronous generator model (Synchronverter)	✓ Accurate simulation of SG dynamics ✓ No need for frequency derivative ✓ PLL is only used for synchronization	❖ The possibility of numerical instability ❖ Typically, implementation as a voltage source, without overcurrent protection
Strategy based on swing equation (Ise Lab's Strategy)	✓ Simpler model compared to Synchronverter ✓ No need for frequency derivative ✓ PLL is only used for synchronization	❖ The possibility of power and frequency Oscillations ❖ Typically, implementation as a voltage source, without overcurrent protection
Strategy based on frequency-power response (VSG)	✓ Very simple implementation ✓ Typically, implementation as a voltage source, with inherent overcurrent protection	❖ The possibility of instability due to PLL ❖ Need for frequency derivative ❖ System susceptible to noise

4. Stability Analysis and Coordinated Control Methods of Virtual Inertia Units

The primary objective of a virtual inertia control system is to increase power system stability through power electronics technology used in RES. Depending on the type of the disturbance and for effective analysis, many types of power system stability have been classified and discussed. For a power system equipped with virtual inertial controllers, small signal stability and transient stability are typically two types of stabilities that are taken into account and discussed in this section. Also, the general classification of methods can be seen in Fig. 12. The capacity of a power system to maintain steady state voltage in the presence of little disturbances, such as minor adjustments in system load, is referred to as small signal stability [59]. The features of the load, continuous control and discrete control at a particular moment all generally have an impact on small signal stability [60,61]. The small signal stability of VSG-based power systems in grid-connected and islanded modes is another area of active study. In [62], models of small-signal sequence impedance of voltage-controlled and current-controlled VSGs -have been developed and the sequence impedance properties of these two types of VSGs have been compared and studied. A linearized small-signal model has been created for the stability study of the parallel VSGs system with the suggested self-adaptable reactive power voltage controller and the parametric sweep results of line impedance have been evaluated in [63,64]. The full small-signal modeling of the VSG control system and an improved VSG controller without a PLL have been proposed in [65]. A detailed linearized small-signal model of the VSG in isolated operation has been created, with electrical and control components that examine the dynamic properties of the improved VSG control system. To ascertain if a system will be stable following a disturbance, transient stability analysis is the study of the system in reaction to these changes. Transient stability analysis is typically more difficult to linearize than small-signal stability analysis [38,66]. Therefore, it is crucial to guarantee that the system returns to a new, stable condition after a disturbance [67].

Lyapunov function approach, center of inertia technique and equal area criteria are three primary techniques for transient stability analysis of VSG-based power systems [68–71]. In [68], the direct Lyapunov approach has been used to examine transient angle stability of a VSG. The inverter internal voltage has been handled as a parameter rather than a state variable in the suggested technique. Additionally, an improved control technique has been used to increase the transient angle stability by changing the reference power, coupled with research on the impact of various factors on transient angle stability. Similar to this, in [52], [55] and [56], a number of writers investigate the transient stability of the VSG using the Lyapunov approach along with certain modified and enhanced control techniques to improve power system performance. In [53] and [54], the governor block has been modified to improve transient stability after the center of inertia approach has been utilized to examine the transient stability of the VSG. The reason that we have briefly explained the stability analysis methods is to investigate the techniques mentioned in this section from the viewpoint of stability analysis as well.

Nowadays, the integration of RESs is decentralized and distributed, generating more energy with higher power quality for local communities [72]. Along with the development of ESSs, this technology has gotten better toward high energy density [73]. It is believed that not only the value of VSG power but also its locating can impact the system efficiency [74,75]. Consequently, the VSG systems may be underpowered compared to the overall system. Therefore, it is expected that the use of VSG will be distributed throughout the system. Imitation of inertial power using multiple VSG units is required to ensure stable and secure operation. Compared with a single large-capacity VSG, the concept of several VSGs with less sizes means that each VSG can independently operate based on its individual/auxiliary control droops and mimics inertia and damping in response to disturbances to support other VSGs.

With the increasing number of VSGs along with different types of control strategies, coordination of several

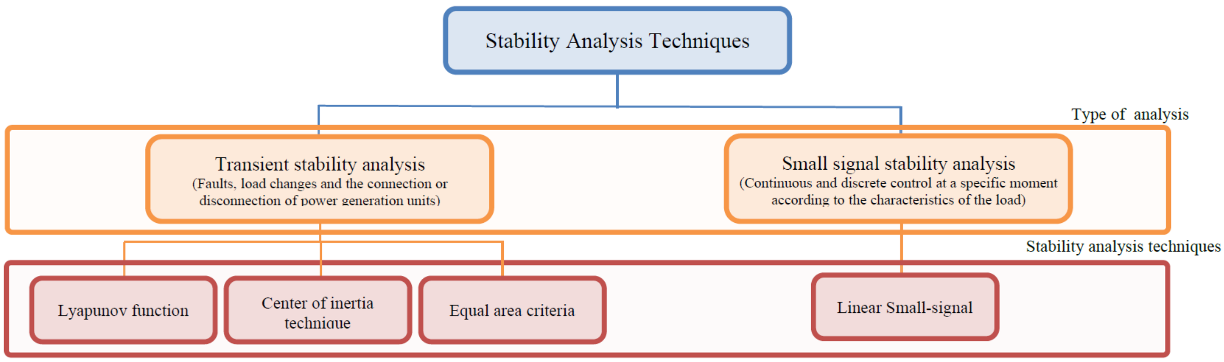

Fig. 12. General classification of stability analysis methods

VSGs in the network is a big problem. VSG coordination requires to communicate with controllers and share the inertia load in the network. It is also observed that different load areas have different frequency deviations. A load imbalance in one area affects the inertial frequency in another area. A study has demonstrated that the placement of virtual inertial services in the system plays a key role in the inertial response [76]. Thus, the strategic coordination of multiple VSGs in a power system helps to improve the lack of inertia for the whole system. In this section, several methods of improving virtual inertia that have used a single unit to implement this concept, are first studied. Then, the studies that use several virtual inertial units in centralized, decentralized and distributed control structures, are discussed.

4.1. Single VSG-based Methods

In this section, the methods that are trying to increase the stability by using techniques such as optimization methods or using adaptive values for control parameters are reviewed. These methods use only one VSG, and this application has greatly been addressed in the literature [77–83]. In [84], a power control method has been suggested to regulate frequency in photovoltaic farms in a hybrid power system considering a type of coordination among PV units. In this study, frequency stability analysis has been presented as an economic model and fuzzy rules have been used to adjust the parameters. A control strategy based on the VSG control has been presented in [85] in a network with coordinated hybrid ESSs, which flexibly adjusts the control parameters according to the state of charge of the ESSs. The approach provided in [86] in the field of DC microgrid coordinates fuel cells and virtual inertia units. In this research, a primary control layer with the support of virtual inertia and secondary and tertiary controllers has been implemented as a MAS. Also, parameters have been adjusted using adaptive droop control based on time-varying droop coefficients.

The authors in [87] has proposed a method to improve system frequency by using virtual inertia units by taking into account the limitations of frequency protective relays. Similarly, a method to improve rotor angle stability in interconnected power systems has been presented in [88], which in addition to improving the previous method, attempts to optimize the parameters. The authors in [89] propose a fuzzy adaptive virtual inertia control strategy for ESSs considering SoC constraints. The strategy aims to extend the lifespan of energy storage units by avoiding deep over-charging and over-discharging. By dynamically adjusting the virtual inertia and damping while satisfying SoC constraints, the proposed strategy effectively stabilizes grid frequency and mitigates power fluctuations. The integration of SoC constraints with virtual inertia and damping adjustments improves system stability and reduces fluctuations. The solution suggested in [90], which incorporates the concept of virtual inertia, has improved the voltage profile in a DC microgrid and evaluated the stability in islanded and grid-connected operating modes. The authors in [91] has presented a multi-objective optimization problem to determine the optimal values of the virtual inertia control system in order to enhance frequency stability in an islanded microgrid. Nonetheless, the details of the optimization method have not clearly been stated. Moreover, the method in [92] has analyzed wind turbines that operate together with capacitive energy storage devices and has attempted to adjust their frequency using the virtual inertia concept. In this study, a PID droop controller, whose parameters are optimized using Imperialist Competition Algorithm, have been used to adjust the control parameters. In [93], a derivative controller has been introduced to increase the dynamic stability of a microgrid. The controller operates based on virtual inertia and utilizes PV units and ESSs. A modified VSG control has been introduced in [94] to stabilize a VSG-based microgrid that operates in the islanding mode. This paper also has focused on integrating the VSG with a traditional synchronous generator and has claimed that this may lead to catastrophic events, including significant frequency variations in the microgrid. EVs have also been used as another solution to frequency control [95]. The method proposed in [95] has been based on VSG, whose control parameters are adjusted according to the droop characteristic of an EV and helps advance frequency stability in microgrids.

In [96], a VSG controller has been discussed, in which controller parameters are adaptively set and tuned so that LFO modes are substantially improved and adverse effects of the presence of the VSG on DC voltage stability are significantly reduced concerning VSC-based multi-terminal DC systems operation. This reference has also carried out various studies, including state-space, modal, eigenvalue, and singular value decomposition analyses. Nevertheless, the relationships between VSGs of different types and excitation strategies of power variation have not been discussed. The authors in [97] have investigated the same subject under varying irradiance and temperature in grid-connected PV-based power systems. This study has used the synchronverter as a virtual inertial model and has presented overloading fault, sudden load change, LVRT and HVRT analysis. In [98], an adaptive virtual inertia control strategy has been introduced to control distributed battery energy storage in a DC microgrid. The presented method has EV batteries as spinning reserve energy storage sources in the grid and a source for virtual inertial units. Also, fuzzy logic algorithm based on battery SoC and bus voltage fluctuations has been used to adaptively tune virtual inertia and droop parameters.

In [99], an adaptive method has been presented for frequency control in wind power systems, in which concepts of virtual inertia have been used. In this study, a dynamic equation based on fuzzy logic has been used to adjust the parameters, and a wide range of wind speed has been considered from the perspective of wind turbine stability and frequency security. In [100], the authors have introduced a method with the support of EVs to implement virtual inertia in multi-area microgrids. The method updates the parameters in the control method by regulating the integral controllers gains for plug-in EVs charging/discharging using Harris hawk's optimization-based Balloon Effect. The authors in [101] have provided a mathematical relationship to determine the values of virtual inertia parameters. This relationship shows the values of the parameters in two cases: frequency deviation from the nominal value and reference power deviation from a default value. The fuzzy method has been used in other references to improve virtual inertia control [102], which has been implemented by increasing the output power of the governor during the transient by adding a correction term. Among the optimization algorithms that have been introduced to improve virtual inertial control in microgrids, one can mention the reinforcement learning approach [103]. More precisely, optimal control with online training of the Heuristic Dynamic Programming has been the method implemented in this study. Also, in [104], a virtual primary and secondary control method has been presented, which adjusts the virtual inertia control parameter values coordinated with digital over/under frequency protection. In this study, the parameters have been adjusted in real time by the PI controller which has optimally been designed using the PSO algorithm. The Newton-based eigenvalue optimization algorithm is also a method that has been proposed in another study [105] for the purpose of optimizing control parameters. In this method, coordinated control parameter of a DFIG has been set in wind farms with virtual inertial control. The authors of [106] have also used the robust control method in order to improve the frequency stability in the microgrid and has considered the frequency measurement noise in the study. Also, in [107] authors introduce an extended VSG control method for suppressing FOs in low-inertia MGs. The severity of FOs in MGs, particularly those caused by converter interfaced generators, can lead to instability and frequency oscillations. The proposed control method utilizes virtual forced components to attenuate the dynamic effects of FOs and improve MG stability. The main contributions of the paper include the analysis of FO impacts, the development of the extended VSG method for FO suppression, the elimination of power measurements, and the improved performance compared to other control techniques. The proposed control approach can be applied in both stand-alone and interconnected MGs and provides a reliable solution for FO suppression without the need for additional measurement techniques. A summary of the properties the studied references is listed in Table 2Table .

Table 2. Summary of Single VSG Methods

Ref	Features	Adaptivity / Intelligence	Stability analysis
[84]	• Inertial response from PV system • Hybrid power system • Study on various non-linearities such as Generation Rate Constraint, Governor Dead Band, and delay in Area Control Error signal • Economic analysis	Using fuzzy rules to adjust parameters	Sensitivity analysis
[85]	• Considering the charge state of the energy storage unit • Providing a flexible virtual inertia control strategy • Considering hybrid energy storages (supercapacitor and lithium battery)	Calculation of virtual inertia parameter according to SoC and frequency changes	-
[86]	• A primary control layer with virtual inertia support	Adaptive droop control based on time-varying droop	-

Ref	Features	Adaptivity / Intelligence	Stability analysis
	• MAS control in the secondary and tertiary control layers • Coordinated management in Fuel cell-based DC microgrids • Local energy management strategy • Suppress the bus voltage disturbance • Tertiary control regular is applied for the battery SoC converge uniformly in finite time • Secondary voltage control loop is used for the bus voltage smooth control at the moment of MGs interconnection	coefficient	
[87]	• Taking the frequency protection scheme of the system into account • Dynamic change of the virtual inertia constant • Small and large disturbances	-	-
[88]	• Rotor angle stability • Transient virtual energy • Improve the first swing stability of the rotor angle in the interconnected power grid • regulating the variable inertias of wind turbines	Using fuzzy logic algorithm	Transient stability analysis
[89]	• fuzzy adaptive virtual inertia control strategy • considering SoC constraints • dynamically adjusting the virtual inertia and damping	Using fuzzy logic algorithm	-
[90]	• DC bus voltage control unit of a DC microgrid • Reduce the steady state error • Small-signal model	-	Equal area criterion
[91]	• Multi-objective optimization problem • Using ultracapacitor used for emulating inertia are determined • Inertia constant is tuned together with frequency droop coefficient of DERs and load frequency controllers' parameters	Pareto optimal solutions	Small-signal analysis
[92]	• Capacitive energy storage system • Study on isolated microgrids • Study on tidal power plants • Considering model nonlinearity factors like generation rate constraint and governor dead band	Fixed and PID droop controllers Imperialist Competitive Algorithm	-
[93]	• Derivative control method • Virtual inertia support from both ESS and solar PV	-	-
[94]	• Study on stability of isolated microgrids • Integrating the VSG with a traditional synchronous generator	-	Equal area criterion Lyapunov's direct method
[95]	• Power adjustment to change charging power • Primary and secondary frequency regulation • Study on plug-in EVs • Using charging/discharging device	According to the droop characteristic of an EV	-
[96]	• State-space analysis • Modal analysis assessment	Parameter alternating VSG	The influence of VSG parameters on the system dynamics is investigated by

Ref	Features	Adaptivity / Intelligence	Stability analysis
	• Eigenvalue analysis assessment • Lack of analysis on interactions between different VSGs and power oscillation excitation mechanisms • LFO modes and the impact on dc voltage stability		SVD
[97]	• Study on varying irradiance and temperature • Grid-connected PV-based power systems • Using synchronverter • Overloading fault and sudden load change analysis • LVRT and HVRT analysis	-	Pole-zero map stability analysis
[98]	• Using battery as sources • Distributed inertia control method for DC microgrid • Virtual battery algorithm • Using dual extended Kalman filter algorithm	Using fuzzy logic algorithm based on battery state and bus voltage fluctuations for Adaptive virtual inertia and droop parameters	Small-signal analysis
[99]	• Study on wind power systems • Study on kinetic energy and DC-link capacitor • Wide range of wind speeds on the perspectives of wind turbine stability and frequency security	Tuning the inertia gains with fuzzy logic-based dynamic equation	Small-signal analysis
[100]	• Study on EVs • Study on multi-area microgrids	On-line setting the integral controllers' gains for plug-in EVs charging/discharging using Harris hawk's optimization-based Balloon Effect	-
[101]	• Study on frequency deviation from the nominal • Study on reference power deviation from a default value	Tuning the inertia gains with mathematical relationship	-
[18]	• Using fuzzy logic Theory for improving • Study on multi-area wind power systems • Takes into consideration the energy level of energy storage (SoC) • PSO is employed so that flywheel ESS tracks any random reference signal	Using Fuzzy logic-based PSO to adjust VSG parameters	-
[102]	• Using fuzzy logic theory • Online measurement	Adding a correction term to the output power of the governor that changes the inertia of the system during the transients	Transient stability analysis
[103]	• Using reinforcement learning method • Adjust the controller setting based on the system parameters	Optimal control with Online training of the Heuristic Dynamic Programming	-
[104]	• Virtual primary and secondary control • Determining virtual inertial control parameter values coordinated with digital over/under frequency protection • Preservation the dynamic security of renewable power systems • Power system stability and resiliency • Considering uncertainties of RESs and load	Adjustment the parameters with the PI controller, which is optimally designed by using PSO algorithm	-
[105]	• Optimization of control parameters	Newton-based eigenvalue	Small-signal stability

Ref	Features	Adaptivity / Intelligence	Stability analysis
	• Study on DFIG • Coordinated control parameter setting of wind farms with virtual inertia control • Providing guidance for adjusting wind farm control parameters	optimization algorithm	analysis Sensitivity analysis
[106]	• Coefficient diagram method • Considering frequency measurement noise	Using robust control method	-
[107]	• extended VSG control method for suppressing FOs in low-inertia MGs • elimination of power measurements • can be applied in both stand-alone and interconnected MGs	-	Small-signal stability analysis

4.2. Multiple VSG-based Methods

As was observed so far, the aforementioned methods in the previous section all employ a single virtual inertia unit. In this section, the methods are studied that use multiple VSGs from points of view such as the coordination between the units, the adaptability of the parameters and the type of communication system. The authors of [108] have used the PSO algorithm to adjust the parameters and maintain the voltage angle deviation in several VSG units aiming at improving the transient stability of the power system. Authors in [109] have attempted to focus on coordination control of multiple VSGs in an uncontrolled microgrid. The method presented in this paper deals with power sharing, but it has examined this issue only with the damping parameter, and no discussion has been made regarding inertia. The method presented in [110] could coordinate the damping values in multiple VSGs using the Prony method. In this study, a two-area system with a linearized state-space model has been used to analyze the presented method. In another study [111], a fluctuation attenuation method has been proposed that can be implemented in systems with multiple VSGs. In this study, using the small-signal state-space model, coordination between the droop characteristics of virtual inertial units has been realized using a central controller. Also, one of the other features of the proposed method is to get rid of the ill effect caused by PLL. Similarly, the authors in [92] and [93] have presented a method for power oscillation suppression that uses coordination between virtual inertial units with the help of a distributed controller. The study conducted in [112] has used a mathematical relation based on adjacent VSGs information to adjust the parameters. Authors in [114] present an adjustable, communication-free virtual inertia control method that enables the suppression of power oscillations in continuous-time VSGs. In this approach, the frequency of the transmission line current serves as common information in the continuous structure. When the frequency of DGs deviates from the transmission line current frequency, a larger inertia is added to impede the deviations. Conversely, when the DGs' frequencies approach the transmission line current frequency, a smaller inertia is employed to accelerate system convergence. The proposed control strategy facilitates the rapid frequency alignment of all DGs with the transmission line current frequency, effectively suppressing power oscillations. Furthermore, the proposed method is designed solely based on local DGs' information, eliminating the need for communication and ensuring a reliable system. Also in [115], a derivative-free distributed method for frequency regulation in islanded uninterruptible power AC micro-grid has been discussed, which uses EVs for virtual inertial sources. In this study, each VSG can select the optimal communication direction based on the real-time system state, and the parameters are updated using a consensus-based cooperative adaptive virtual inertia method. Ref [116] introduces an improved power control strategy for VSGs by considering the dynamic characteristics of ESS. The analysis reveals the importance of ESS in VSG control and highlights the time-varying characteristics of SoC as key factors. A Radial Basis Function neural network is employed to learn and process the nonlinear relationship between SoC and battery current. The proposed strategy optimizes the dynamic response of VSGs during transients, resulting in improved system performance.

On the other hand, the authors in [117] have presented an approach that considers the EV charging system and leads to low-frequency oscillations. The main problem of the presented method is that it only has considered the damping factor. The authors in [118] have determined the power correction term for each VSG by comparing the local frequency with the CoI frequency. This method requires communication networks with high bandwidth communication channels, which results in poor reliability. In [119] the small-signal analysis has been conducted on a network with multiple VSGs, and the superiority of using several virtual inertial units instead of a single unit with their total capacity has been demonstrated. Designers have investigated this subject in interconnected power systems by modeling tie-line control and by time-domain and eigenvalue analysis under a wide range of control parameter variations [120]. Also, the method presented in [121] has tested plug-and-play EV integration in an interconnected power system using a hierarchical structure for virtual inertial units. In this study, objective of primary control is to rapidly and accurately track the control references, and the secondary control strategy is based on model predictive control and finds optimal reference signals for all primary controllers for tracking. In [122] a study have presented on active power sharing in islanded microgrids using a PI controller whose parameters are optimized using a centralized MPC. The authors of [101] have also studied the load frequency control with the day-ahead prediction method. In this study, wind turbine clusters, photovoltaic array EVs considered as a source. It has also been used PI controller at the secondary level with the feature of self-adaptive frequency regulation.

In [123], a decentralized VSG control scheme for hybrid AC-DC microgrids has been used to operate the entire microgrid as a synchronous generator with a battery acting as the governing role, a supercapacitor acting as the rotor mass of the synchronous generator, and connecting the interlinking power electronic converters of DC-bus sources and loads to the AC bus. In [124], a new decentralized control strategy has been proposed for fault-free and communication-free frequency regulation in an islanded microgrid containing several VSGs. The entire process can be completed with only locally measured signals by each VSG and through local frequency feedback instead of relying on the MGCC and information interaction between adjacent VSGs. The proposed control strategy enables multiple VSGs to collectively achieve frequency restoration, thus avoiding the overload problem of frequency regulation of single VSG. The effect of VSG control parameters on the control system has also been analyzed by root locus. In [19], the voltage of the DC bus has been used to adaptively regulate droop characteristics of VSGs in an islanded DC microgrid. In this study, PV/BES-VSGs have been used in order to implement the method, and the battery charging/discharging power limits has been assessed. In this way, power sharing among PV/BES-VSG units has been allocated according to the maximum output power of PVs and the limit of charging/discharging power of BESs. To reduce active/reactive power damping of parallel VISMAs in microgrids, the virtual stator reactance regulator has been used based on inversed voltage droop control feature (V-Q droop control) [125].

In [126], a distributed method for using virtual inertial units has been presented. The aim of this paper is to improve the transient control performance of independent microgrids and has reduced the problems of implementing of distributed load algorithms. The goals are achieved by increasing the inertia of PV systems to mimic traditional SGs. To simulate inertia, the overall output must be flexibly regulated based on the frequency of network. To minimize the impact on energy efficiency, the first option is to suitably select ESS components, called the DC-link capacitor in PV systems. Also, the authors of [127] have enhanced stability in weak grids by using modified distributed virtual inertia method and discharging the preserved energy of dc-side capacitors. The presented methods have exploited distributed virtual inertial resources while neglecting the coordination between them. In this study, the compensator has been designed so as it can eliminate the negative effect of DVI regulator on system stability. On the other hand, the authors in [128] have introduced a method similar to the previous methods, in which the coordination between virtual inertial units has also been discussed.

The inertia interaction between VSGs has been analyzed in [129] by studying the frequency of parallel VSGs; yet, the authors did not address the equivalent inertia. Moreover, in [130], the necessary conditions have been discussed when trying to reach more desirable transient active power sharing using state space model. The study has highlighted that this can be realized by using the same values of parameters of the VSGs. In [131], a method using decentralized VSGs has been proposed for accurate sharing of reactive power using AC bus voltage estimation. This study has used fuzzy logic theory based on increasing the virtual stator reactance to improve the results. The authors of [132] have presented a method to mitigate load variations but did not study unstable conditions of the power system. In this study, active power oscillations caused by weak damping and large inertia and the virtual reactance assessment by adding a virtual damping element for enhancing the stability of power system have been investigated. In [133], stabilizing reactive power at the nominal value has been investigated by compensating voltage variations. A small-signal analysis has also been carried out to enhance the reliability of the method. To address the faulty operation of parallel VSGs, the pre-synchronization control module has been used by analyzing the stable operation of the VSGs. Active and reactive power expressions have been added to the active-frequency droop in [134], to enhance the accuracy of active power sharing between the loads. This helps guarantee steady-state operation and enhance dynamic features so that the impact of the line impedance between VSGs on active frequency droop has been decreased. Besides this, the operation of VSGs in a parallel arrangement has acceptably been improved. In [135], the neglecting of transient power sharing as a shortcoming of the previous literature has been mentioned and a method has been proposed for adjusting the inertia and damping parameters in different VSGs. The method improves the frequency behavior of the network in both stable and transient states. The authors have also mentioned the relationship between the inertia value and the nominal generation capacity as the reason for the imbalance in power sharing, and it has been pointed out that determining the inertia values in VSGs can be used as a solution to solve this problem.

As discussed above, recent methods have been oriented towards the issue of coordination in these resources, taking into account some limitations. A summary of the characteristics of the references studied above are listed in Table 3, and in the next section, a conclusion and guidance for further studies in this field will be provided.

Table 3. Summary of Multiple VSG Methods

Ref	Feature(s)	Communication	Coordination	Adaptivity / Intelligence	Stability Analysis
[108]	• Transient stability assessment • Voltage angle deviation assessment • maintaining the VADs of generators within a specific limit	Without communication	-	Tuning the parameters of the VSG using PSO algorithm	CoI assessment
[109]	• Unequal droop or damping coefficient of multiple VSGs • Different power ratings assessment • Considering damping factor only • P−ω control during the dynamic state	Without communication	Between droop characteristics	-	Eigenvalue analysis
[110]	• Considering damping factor only • two-area system with a linearized state-space model	Without communication	Between droop characteristics	Using Prony method	Modal analysis
[111]	• Providing a fluctuation attenuation method • Study on small-signal state-space model of VSG • getting rid of the ill effect introduced through PLL • Study on power-sharing among the multi-VSG system	Centralized	Between droop characteristics	-	Eigenvalue analysis
[112]	• Study on power oscillation suppression • distributed adaptive virtual inertia control method	Communication with adjacent VSGs	Average frequency of its neighbors	As a formula based on adjacent VSGs information	Lyapunov function
[113]	• Study on power oscillation suppression • distributed cooperation control	Distributed consensus algorithm to estimate CoI-frequency	CoI frequency	-	-
[114]	• adjustable virtual inertia control method • communication-free virtual inertia	Without communication	-	As a formula based on local information	Small-signal analysis

Ref	Feature(s)	Communication	Coordination	Adaptivity / Intelligence	Stability Analysis
	control method				
[115]	• Study on islanded microgrids • Considering EVs • Providing a derivative-free method which avoid derivation noise	Local VSG can sense the state of neighboring VSGs	Each VSG can select the optimal communication direction based on the real-time system state	Consensus-based cooperative adaptive virtual inertia as a formula	Lyapunov function
[116]	• Considering the dynamic characteristics of ESS • Time-varying characteristics of SoC • Radial Basis Function neural network	Without communication	-	Neural network	Small-signal analysis
[70]	• State-space analysis • CoI assessment	Centralized	-	Using PID controller for improving	-
[117]	• considers the EV charging system • only considers the damping factor	Centralized	-	-	-
[118]	• set the power correction term for each VSG	Centralized	-	Comparing the local frequency with the CoI frequency	-
[119]	• conducts the small-signal analysis on a network with multiple virtual synchronous machines • the superiority of using several virtual inertial units instead of a single unit with their total capacity is demonstrated	Centralized	-	A study	-
[120]	• Study on interconnected power systems • Modeling of Tie Line Control	Centralized	-	A study	Clearly analyzed by the time-domain and eigenvalue analysis under a wide range of control parameter variations
[121]	• Study on interconnected power systems • Hierarchical control scheme • objective of primary control is to track the control references rapidly and accurately • secondary control strategy is based on model predictive control and find the optimal reference signals for all the primary controllers to track	Centralized	Regulating the equivalent output powers with model predictive control to cooperate DGs	MPC	Sensitivity analysis
[122]	• Study on active power sharing • Islanded microgrids	Centralized	MPC	PI controller	-
[136]	• Study on load frequency control • wind turbine, photovoltaic array, and EV clusters	Centralized	Self-adaptive secondary frequency	PI controller	-

Ref	Feature(s)	Communication	Coordination	Adaptivity / Intelligence	Stability Analysis
	• Day-ahead prediction method		regulation		
[123]	• hybrid AC-DC microgrids • battery acting as the governing role • supercapacitor acting as the rotor mass	Decentralized	-	PI controller	-
[124]	• islanded microgrid • Study on non-error frequency control	Decentralized	proportional link achieves accurate proportional power sharing among VSGs	PI controller	Root locus analysis
[125]	• State-space analysis • Study on active and reactive power sharing • Microgrids	Decentralized	-	Adjusting the virtual stator reactance based on inversed voltage droop control feature (V-Q droop control)	Eigenvalue analysis
[126]	• Islanded microgrids • Study on multiple photovoltaic systems • Increase the inertia of PV system through inertia emulation • Charging/discharging of the DC-link capacitor	Distributed	-	-	-
[127]	• State-space model • Discharging the preserved energy of dc-side capacitors • The compensator is designed so as eliminates the negative effect of DVI regulator on system stability.	Distributed	-	-	Eigenvalue analysis
[128]	• Power and frequency oscillation in microgrid • Small-signal modeling of multiple VSGs in parallel	Distributed	multiple VSGs cooperative control strategy	optimizes the output control of each VSG	Lyapunov stability theory
[129]	• Not considering the equivalent inertia • Both grid-connected and islanded modes • Transfer function model of paralleled inverters • Inertia interaction among different inverters is analyzed in detail	Distributed	-	-	-
[130]	• Islanded microgrids • State-space analysis assessment • state-space models	Distributed	-	-	sensitivity of the closed-loop poles and study the step responses analytically and experimentally
[131]	• Not considering multiple virtual inertia units	Decentralized	-	Use fuzzy logic theory for improving	-

Ref	Feature(s)	Communication	Coordination	Adaptivity / Intelligence	Stability Analysis
	• Microgrids • oscillation damping • AC bus voltage estimation for accurate reactive power sharing			based on increasing the virtual stator reactance	
[132]	• Study on power oscillation suppression • Not considering multiple virtual inertia units • Voltages is not constant during the operation • Study on active power oscillation caused by weak damping and large inertia • instantaneous active power sharing	Decentralized	-	Virtual reactance assessment by adding a virtual damping element for enhancing	Fundamental analysis
[133]	• Not considering multiple virtual inertia units • power decoupling method • reactive power • designing the pre-synchronization control module to solve the problem of circulation in parallel operation of VSGs • Wind-PV-Super Capacitor microgrid	Decentralized	-	Based on adaptive voltage compensation	Small-signal analysis
[134]	• Study on reactive power sharing • Not considering multiple virtual inertia units • Suppressing current circulation	Distributed	-	By adding virtual negative impedance	-
[135]	• Not considering multiple virtual inertia units • Microgrids • damping coefficient • parallel operation • steady state and the system transients	Distributed	-	-	-

5. Challenges and Future Directions

This comprehensive review investigates the evolving landscape of virtual inertia systems in the context of increasing RES penetration in current power systems. The study explores various strategies for implementing virtual inertia, emphasizing their suitability based on factors such as complexity and the precise simulation of SGs dynamics. Notably, the synchronverter and Ise lab's strategy are discussed, each offering distinct advantages depending on simulation requirements.

5.1. Strategies for Virtual Inertia Implementation

This paper discusses the different strategies used for virtual inertia, highlighting their intended use for delivering dynamic frequency responses through powerful electronic converters. Specific strategies, like the synchronverter, are discussed for replicating the exact dynamics of SGs, while more basic strategies, such as Ise lab's strategy, are employed when an approximate replication is sufficient. The VSG technique is also mentioned for cases where the goal is to offer dynamic frequency response without simulating the precise behavior of SGs.

5.2. Advanced Virtual Inertia Systems

The research explores advanced virtual inertia systems, particularly focusing on the utilization of multiple virtual inertial units and their optimization methods. These methods aim to enhance the contribution of RES units to inertial response while safeguarding the lifespan of energy storage systems. Significant progress is noted in terms of overall dynamics and stability. The challenges identified include the need for coordination methods between inertia values and virtual damping, optimized coordination control procedures to handle uncertainties, and improving communication links between units.

5.3. Challenges in VSG Integration

The integration of numerous VSGs in power systems poses technical challenges. The article emphasizes the necessity of developing a centralized control method [137,138] to enhance various VSG control aspects, including grid connection, voltage and frequency control, and power circulation control.

5.4. VSG Control Algorithms

To balance supply and demand effectively on modern power grids, the exploration of more flexible VSG control algorithms is recommended. The VSG frequency regulation is discussed, highlighting the need for active practical algorithms and control methods, along with further investigations to coordinate kinetic energy discharge time and dimensions with traditional SG properties.

5.5. Efficient VSG Modeling

Efficient modeling of VSGs is crucial, and the article suggests a deeper study of the mathematical derivation of equivalence between the VSG concept and the SG. The aim is to achieve an effective and robust control system by improving existing models, focusing on the preferable parts.

5.6. VSG Energy Storage Systems

The integration of energy storage systems with VSG-based photovoltaic systems is discussed. The combination of batteries and ultra-capacitors [139] is suggested to address high-frequency effects and provide a more economical solution. However, the article proposes the development of a new and economical ESS with characteristics combining conventional batteries, ultra-capacitors, and compact sizes, aiming to overcome economic challenges associated with current technology.

6. Conclusion

This study reviewed the research on virtual inertia systems in the context of a high-RES penetration in the current power system. For the implementation of virtual inertia, many strategies were identified. It has been shown that all strategies are basically intended to deliver dynamic frequency response using power electronic converters. Based on the required strategy (current source or voltage source implementation) and desired complexity level in simulating the precise behavior of SGs, the best strategy may be chosen. For instance, strategies like the synchronverter are frequently employed to replicate the exact dynamics of SGs. If an approximate replication is adequate, more basic strategies like Ise lab's strategy are frequently utilized. In contrast, when the goal only offers the dynamic frequency response without simulating the precise behavior of SGs, the VSG technique is more appropriate. In the presented research, the investigation of advanced virtual inertial systems was followed, which focused on the use of multiple virtual inertial units and their optimization methods. These methods enable improvements in RES units contributing to the inertial response while preventing the worsening of the ESS lifespan. Additionally, tremendous progress was made in terms of overall dynamics and stability. Also, in complementing the research review presented earlier, certain difficulties and potential research gaps were highlighted. These include but are not limited to providing coordination methods between inertia values and virtual damping in virtual inertial units in order to share transient power and frequency stability during disturbances, optimized coordination control and adjustment procedure to handle uncertainties, and resource limitations, as well as improving the communication links among units and increase the reliability of the method.

References

[1] Cabrera-Tobar A, Bullich-Massagué E, Aragüés-Peñalba M, Gomis-Bellmunt O. Review of advanced grid requirements for the integration of large scale photovoltaic power plants in the transmission system. Renewable and Sustainable Energy Reviews 2016;62:971–87. https://doi.org/10.1016/j.rser.2016.05.044.

[2] Rezaei N, Kalantar M. Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework. Energy Conversion and Management 2015;92:287–301. https://doi.org/10.1016/j.enconman.2014.12.049.

[3] Fernández-Guillamón A, Gómez-Lázaro E, Muljadi E, Molina-García Á. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. Renewable and Sustainable Energy Reviews 2019;115:109369. https://doi.org/10.1016/j.rser.2019.109369.

[4] da Silva GS, de Oliveira EJ, de Oliveira LW, de Paula AN, Ferreira JS, Honório LM. Load frequency control and tie-line damping via virtual synchronous generator. International Journal of Electrical Power and Energy Systems 2021;132:107108. https://doi.org/10.1016/j.ijepes.2021.107108.

[5] Othman MH, Mokhlis H, Mubin M, Talpur S, Aziz NFA, Dradi M, et al. Progress in control and coordination of energy storage system-based VSG: A review. IET Renewable Power Generation 2020;14:177–87. https://doi.org/10.1049/iet-rpg.2019.0274.

[6] Mallemaci V, Mandrile F, Rubino S, Mazza A, Carpaneto E, Bojoi R. A comprehensive comparison of Virtual Synchronous Generators with focus on virtual inertia and frequency regulation. Electric Power Systems Research 2021;201:107516. https://doi.org/10.1016/j.epsr.2021.107516.

[7] Bevrani H, Ise T, Miura Y. Virtual synchronous generators: A survey and new perspectives. International Journal of Electrical Power and Energy Systems 2014;54:244–54. https://doi.org/10.1016/j.ijepes.2013.07.009.

[8] Zhong QC, Weiss G. Synchronverters: Inverters that mimic synchronous generators. IEEE Transactions on Industrial Electronics 2011;58:1259–67. https://doi.org/10.1109/TIE.2010.2048839.

[9] Beck HP, Hesse R. Virtual synchronous machine. 2007 9th International Conference on Electrical Power Quality and Utilisation, EPQU, IEEE; 2007, p. 1–6. https://doi.org/10.1109/EPQU.2007.4424220.

[10] Driesen J, Visscher K. Virtual synchronous generators. IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES, IEEE; 2008, p. 1–3. https://doi.org/10.1109/PES.2008.4596800.

[11] Kerdphol T, Rahman FS, Watanabe M, Mitani Y. Virtual Inertia Synthesis and Control. 2021.

[12] Alipoor J, Miura Y, Ise T. Power system stabilization using virtual synchronous generator with alternating moment of inertia. IEEE Journal of Emerging and Selected Topics in Power Electronics 2015;3:451–8. https://doi.org/10.1109/JESTPE.2014.2362530.

[13] Milano F, Dorfler F, Hug G, Hill DJ, Verbič G. Foundations and challenges of low-inertia systems (Invited Paper). 20th Power Systems Computation Conference, PSCC 2018, IEEE; 2018, p. 1–25. https://doi.org/10.23919/PSCC.2018.8450880.

[14] Prabhakar K, Jain SK, Padhy PK. Inertia estimation in modern power system: A comprehensive review. Electric Power Systems Research 2022;211:108222. https://doi.org/10.1016/j.epsr.2022.108222.

[15] Mohammed N, Alhelou HH, Bahrani B. Grid-Forming Power Inverters: Control and Applications. CRC Press; 2023.

[16] Shakerighadi B, Johansson N, Eriksson R, Mitra P, Bolzoni A, Clark A, et al. An overview of stability challenges for power-electronic-dominated power systems: The grid-forming approach. IET Generation, Transmission and Distribution 2023;17:284–306. https://doi.org/10.1049/gtd2.12430.

[17] Tamrakar U, Shrestha D, Maharjan M, Bhattarai BP, Hansen TM, Tonkoski R. Virtual inertia: Current trends and future directions. Applied Sciences (Switzerland) 2017;7:654. https://doi.org/10.3390/app7070654.

[18] Osbouei BA, Taylor GA, Bronckart O, Maricq J, Bradley M. Impact of inertia distribution on power system stability and operation. 2019 IEEE Milan PowerTech, PowerTech 2019 2019;47:7290–7. https://doi.org/10.1109/PTC.2019.8810689.

[19] Tielens P, Van Hertem D. The relevance of inertia in power systems. Renewable and Sustainable Energy Reviews 2016;55:999–1009. https://doi.org/10.1016/j.rser.2015.11.016.

[20] Wang Y, Silva V, Lopez-Botet-zulueta M. Impact of high penetration of variable renewable generation on frequency dynamics in the continental Europe interconnected system. IET Renewable Power Generation 2016;10:10–6. https://doi.org/10.1049/iet-rpg.2015.0141.

[21] Ulbig A, Borsche TS, Andersson G. Impact of low rotational inertia on power system stability and operation. IFAC Proceedings Volumes (IFAC-PapersOnline), vol. 19, 2014, p. 7290–7. https://doi.org/10.3182/20140824-6-za-1003.02615.

[22] Zhang H, Xiang W, Lin W, Wen J. Grid Forming Converters in Renewable Energy Sources Dominated Power Grid: Control Strategy, Stability, Application, and Challenges. Journal of Modern Power Systems and Clean Energy 2021;9:1239–56. https://doi.org/10.35833/MPCE.2021.000257.

[23] Abdel-Rahim O, Funato H, Junnosuke H. Droop method based on model predictive control for DC microgrid. 19th International Conference on Electrical Machines and Systems, ICEMS 2016, IEEE; 2017, p. 1–6.

[24] Rosso R, Wang X, Liserre M, Lu X, Engelken S. Grid-forming converters: Control approaches, grid-synchronization, and future trends—A review. IEEE Open Journal of Industry Applications 2021;2:93–109.

[25] Majumder R, Ledwich G, Ghosh A, Chakrabarti S, Zare F. Droop control of converter-interfaced microsources in rural distributed generation. IEEE Transactions on Power Delivery 2010;25:2768–78. https://doi.org/10.1109/TPWRD.2010.2042974.

[26] D'Arco S, Suul JA. Virtual synchronous machines - Classification of implementations and analysis of equivalence to droop controllers for microgrids. 2013 IEEE Grenoble Conference PowerTech, POWERTECH 2013, IEEE; 2013, p. 1–7. https://doi.org/10.1109/PTC.2013.6652456.

[27] D'Arco S, Suul JA. Equivalence of virtual synchronous machines and frequency-droops for converter-based Microgrids. IEEE Transactions on Smart Grid 2014;5:394–5. https://doi.org/10.1109/TSG.2013.2288000.

[28] Sun Y, Hou X, Yang J, Han H, Su M, Guerrero JM. New Perspectives on Droop Control in AC Microgrid. IEEE Transactions on Industrial Electronics 2017;64:5741–5. https://doi.org/10.1109/TIE.2017.2677328.

[29] Zhong QC. Virtual Synchronous Machines: A unified interface for grid integration. IEEE Power Electronics Magazine 2016;3:18–27. https://doi.org/10.1109/MPEL.2016.2614906.

[30] Kundur P. Power System Stability And Control by Prabha Kundur.pdf. 1994.

[31] Kryonidis GC, Malamaki KND, Mauricio JM, Demoulias CS. A new perspective on the synchronverter model. International Journal of Electrical Power and Energy Systems 2022;140. https://doi.org/10.1016/j.ijepes.2022.108072.

[32] Zhong QC, Hornik T. Control of Power Inverters in Renewable Energy and Smart Grid Integration. Wiley Online Library; 2012. https://doi.org/10.1002/9781118481806.

[33] Shao T, Zheng TQ, Li H, Zhang X. Parameter design and hot seamless transfer of single-phase synchronverter. Electric Power Systems Research 2018;160:63–70. https://doi.org/10.1016/j.epsr.2018.02.006.

[34] Wang S, Hu J, Yuan X. Virtual Synchronous Control for Grid-Connected DFIG-Based Wind Turbines. IEEE Journal of Emerging and Selected Topics in Power Electronics 2015;3:932–44. https://doi.org/10.1109/JESTPE.2015.2418200.

[35] Zhong QC, Nguyen PL, Ma Z, Sheng W. Self-synchronized synchronverters: Inverters without a dedicated synchronization unit. IEEE Transactions on Power Electronics 2014;29:617–30. https://doi.org/10.1109/TPEL.2013.2258684.

[36] Ma Z, Zhong QC, Yan JD. Synchronverter-based control strategies for three-phase PWM rectifiers. Proceedings of the 2012 7th IEEE Conference on Industrial Electronics and Applications, ICIEA 2012, IEEE; 2012, p. 225–30. https://doi.org/10.1109/ICIEA.2012.6360727.

[37] Sakimoto K, Miura Y, Ise T. Stabilization of a power system including inverter-type distributed generators by a virtual synchronous generator. Electrical Engineering in Japan (English translation of Denki Gakkai Ronbunshi), vol. 187, IEEE; 2014, p. 7–17. https://doi.org/10.1002/eej.22426.

[38] Hirase Y, Abe K, Sugimoto K, Sakimoto K, Bevrani H, Ise T. A novel control approach for virtual synchronous generators to suppress frequency and voltage fluctuations in microgrids. Applied Energy 2018;210:699–710. https://doi.org/10.1016/j.apenergy.2017.06.058.

[39] Wen B, Boroyevich D, Burgos R, Mattavelli P, Shen Z. Small-Signal Stability Analysis of Three-Phase AC Systems in the Presence of Constant Power Loads Based on Measured d-q Frame Impedances. IEEE Transactions on Power Electronics 2015;30:5952–63. https://doi.org/10.1109/TPEL.2014.2378731.

[40] Van Wesenbeeck MPN, De Haan SWH, Varela P, Visscher K. Grid tied converter with virtual kinetic storage. 2009 IEEE Bucharest PowerTech: Innovative Ideas Toward the Electrical Grid of the Future, IEEE; 2009, p. 1–7. https://doi.org/10.1109/PTC.2009.5282048.

[41] Tan B, Zhao J, Netto M, Krishnan V, Terzija V, Zhang Y. Power system inertia estimation: Review of methods and the impacts of converter-interfaced generations. International Journal of Electrical Power and Energy Systems 2022;134. https://doi.org/10.1016/j.ijepes.2021.107362.

[42] Shrestha D, Tamrakar U, Ni Z, Tonkoski R. Experimental verification of virtual inertia in diesel generator based microgrids. Proceedings of the IEEE International Conference on Industrial Technology, IEEE; 2017, p. 95–100. https://doi.org/10.1109/ICIT.2017.7913065.

[43] Tamrakar U, Tonkoski R, Zhen N, Hansen TM, Tamrakar I. Current control techniques for applications in virtual synchronous machines. 2016 IEEE 6th International Conference on Power Systems, ICPS 2016, IEEE; 2016, p. 1–6. https://doi.org/10.1109/ICPES.2016.7584166.

[44] Yan R, Saha TK, Modi N, Masood N Al, Mosadeghy M. The combined effects of high penetration of wind and PV on power system frequency response. Applied Energy 2015;145:320–30. https://doi.org/10.1016/j.apenergy.2015.02.044.

[45] Zhang W, Cantarellas AM, Rocabert J, Luna A, Rodriguez P. Synchronous Power Controller with Flexible Droop Characteristics for Renewable Power Generation Systems. IEEE Transactions on Sustainable Energy 2016;7:1572–82. https://doi.org/10.1109/TSTE.2016.2565059.

[46] Blaabjerg F, Teodorescu R, Liserre M, Timbus A V. Overview of control and grid synchronization for distributed power generation systems. IEEE Transactions on Industrial Electronics 2006;53:1398–409. https://doi.org/10.1109/TIE.2006.881997.

[47] Colak I, Kabalci E, Bayindir R. Review of multilevel voltage source inverter topologies and control schemes. Energy Conversion and Management 2011;52:1114–28. https://doi.org/10.1016/j.enconman.2010.09.006.

[48] Ashabani M, Freijedo FD, Golestan S, Guerrero JM. Inducverters: PLL-Less Converters With Auto-Synchronization and Emulated Inertia Capability. IEEE Transactions on Smart Grid 2016;7:1660–74. https://doi.org/10.1109/TSG.2015.2468600.

[49] Samavati E, Mohammadi HR. An improved method for harmonic mitigation and stability improvement of the grid-connected inverters under local load variation and weak grid condition. International Journal of Electrical Power and Energy Systems 2020;123. https://doi.org/10.1016/j.ijepes.2020.106310.

[50] Svensson J. Synchronisation methods for grid-connected voltage source converters. IEE Proceedings: Generation, Transmission and Distribution 2001;148:229–35. https://doi.org/10.1049/ip-gtd:20010101.

[51] Tôrres LAB, Hespanha JP, Moehlis J. Synchronization of Identical Oscillators Coupled Through a Symmetric Network With Dynamics: A Constructive Approach With Applications to Parallel Operation of Inverters. IEEE Transactions on Automatic Control 2015;60:3226–41. https://doi.org/10.1109/TAC.2015.2418400.

[52] Aghdam SA, Agamy M. Virtual oscillator-based methods for grid-forming inverter control: A review. IET Renewable Power Generation 2022;16:835–55.

[53] Sinha M, Dörfler F, Johnson BB, Dhople S V. Virtual Oscillator Control subsumes droop control. Proceedings of the American Control Conference, vol. 2015- July, IEEE; 2015, p. 2353–8. https://doi.org/10.1109/ACC.2015.7171084.

[54] Arghir C, Jouini T, Dörfler F. Grid-forming control for power converters based on matching of synchronous machines. Automatica 2018;95:273–82. https://doi.org/10.1016/j.automatica.2018.05.037.

[55] Sinha M, Dorfler F, Johnson BB, Dhople S V. Uncovering droop control laws embedded within the nonlinear dynamics of van der pol oscillators. IEEE Transactions on Control of Network Systems 2017;4:347–58. https://doi.org/10.1109/TCNS.2015.2503558.

[56] Curi S, Gros D, Dorfler F. Control of low-inertia power grids: A model reduction approach. 2017 IEEE 56th Annual Conference on Decision and Control, CDC 2017, vol. 2018- January, IEEE; 2018, p. 5708–13. https://doi.org/10.1109/CDC.2017.8264521.

[57] Remon D, Cantarellas AM, Rakhshani E, Candela I, Rodriguez P. An active power synchronization control loop for grid-connected converters. IEEE Power and Energy Society General Meeting, vol. 2014- October, IEEE; 2014, p. 1–5. https://doi.org/10.1109/PESGM.2014.6939250.

[58] Mahamedi B, Fletcher JE. The Equivalent Models of Grid-Forming Inverters in the Sequence Domain for the Steady-State Analysis of Power Systems. IEEE Transactions on Power Systems 2020;35:2876–87. https://doi.org/10.1109/TPWRS.2020.2968114.

[59] Makarov Y V., Dong ZY, Hill D. A General Method for Small Signal Stability. IEEE Power Engineering Review 1997;17:62.

[60] Serban I, Ion CP. Microgrid control based on a grid-forming inverter operating as virtual synchronous generator with enhanced dynamic response capability. International Journal of Electrical Power and Energy Systems 2017;89:94–105. https://doi.org/10.1016/j.ijepes.2017.01.009.

[61] Remon D, Cantarellas AM, Mauricio JM, Rodriguez P. Power system stability analysis under increasing penetration of photovoltaic power plants with synchronous power controllers. IET Renewable Power Generation 2017;11:733–41. https://doi.org/10.1049/iet-rpg.2016.0904.

[62] Wu W, Chen Y, Zhou L, Luo A, Zhou X, He Z, et al. Sequence Impedance Modeling and Stability Comparative Analysis of Voltage-Controlled VSGs and Current-Controlled VSGs. IEEE Transactions on Industrial Electronics 2019;66:6460–72. https://doi.org/10.1109/TIE.2018.2873523.

[63] Zhang B, Li D, Wang Y, Yan X. Self-adaptable reactive power-voltage controller for virtual synchronous generators. The Journal of

Engineering 2019;2019:2969–73. https://doi.org/10.1049/joe.2018.8452.

[64] D'Arco S, Suul JA, Fosso OB. Small-signal modeling and parametric sensitivity of a virtual synchronous machine in islanded operation. International Journal of Electrical Power and Energy Systems 2015;72:3–15. https://doi.org/10.1016/j.ijepes.2015.02.005.

[65] Zhang B, Zhang X, Song Z, Yan X. Enhanced control and parameter analysis for virtual synchronous generators without PLL. The Journal of Engineering 2019;2019:3082–7. https://doi.org/10.1049/joe.2018.8453.

[66] Zhu S, Liu K, Qin L. Transient Stability Analysis of Virtual Synchronous Generator. Dianli Xitong Zidonghua/Automation of Electric Power Systems 2018;42:51–8. https://doi.org/10.7500/AEPS20171115017.

[67] Liu J, Yang D, Yao W, Fang R, Zhao H, Wang B. PV-based virtual synchronous generator with variable inertia to enhance power system transient stability utilizing the energy storage system. Protection and Control of Modern Power Systems 2017;2. https://doi.org/10.1186/s41601-017-0070-0.

[68] Shuai Z, Shen C, Liu X, Li Z, John Shen Z. Transient angle stability of virtual synchronous generators using lyapunov's direct method. IEEE Transactions on Smart Grid 2019;10:4648–61. https://doi.org/10.1109/TSG.2018.2866122.

[69] Li M, Huang W, Tai N, Yu M. Lyapunov-based large signal stability assessment for VSG controlled inverter-interfaced distributed generators. Energies 2018;11. https://doi.org/10.3390/en11092273.

[70] Choopani M, Hosseinain SH, Vahidi B. A novel comprehensive method to enhance stability of multi-VSG grids. International Journal of Electrical Power and Energy Systems 2019;104:502–14. https://doi.org/10.1016/j.ijepes.2018.07.027.

[71] Cheema KM, Mehmood K. Improved virtual synchronous generator control to analyse and enhance the transient stability of microgrid. IET Renewable Power Generation 2020;14:495–505. https://doi.org/10.1049/iet-rpg.2019.0855.

[72] Lo CH, Ansari N. Decentralized controls and communications for autonomous distribution networks in smart grid. IEEE Transactions on Smart Grid 2013;4:66–77. https://doi.org/10.1109/TSG.2012.2228282.

[73] Yaqoot M, Diwan P, Kandpal TC. Review of barriers to the dissemination of decentralized renewable energy systems. Renewable and Sustainable Energy Reviews 2016;58:477–90. https://doi.org/10.1016/j.rser.2015.12.224.

[74] Golpira H, Atarodi A, Amini S, Messina AR, Francois B, Bevrani H. Optimal Energy Storage System-Based Virtual Inertia Placement: A Frequency Stability Point of View. IEEE Transactions on Power Systems 2020;35:4824–35. https://doi.org/10.1109/TPWRS.2020.3000324.

[75] Poolla BK, Bolognani S, Dorfler F. Optimal Placement of Virtual Inertia in Power Grids. IEEE Transactions on Automatic Control 2017;62:6209–20. https://doi.org/10.1109/tac.2017.2703302.

[76] Rakhshani E, Remon D, Mir Cantarellas A, Rodriguez P. Analysis of derivative control based virtual inertia in multi-area high-voltage direct current interconnected power systems. IET Generation, Transmission and Distribution 2016;10:1458–69. https://doi.org/10.1049/iet-gtd.2015.1110.

[77] Khayat Y, Naderi M, Bevrani H, Blaabjerg F. Virtual inertia emulating in power electronic–based power systems. Control of Power Electronic Converters and Systems, 2021, p. 541–60. https://doi.org/10.1016/b978-0-12-819432-4.00019-6.

[78] Mandal R, Chatterjee K. Virtual inertia emulation and RoCoF control of a microgrid with high renewable power penetration. Electric Power Systems Research 2021;194. https://doi.org/10.1016/j.epsr.2021.107093.

[79] Encarnação LF, Carletti D, de Angeli Souza S, de Barros O, Broedel DC, Rodrigues PT. Virtual Inertia for Power Converter Control. Advances in Renewable Energies and Power Technologies, vol. 2, 2018, p. 377–411. https://doi.org/10.1016/B978-0-12-813185-5.00010-3.

[80] Heydari R, Savaghebi M, Blaabjerg F. Virtual inertia operation of renewables. Control of Power Electronic Converters and Systems: Volume 3, 2021, p. 523–40. https://doi.org/10.1016/B978-0-12-819432-4.00011-1.

[81] Hirase Y, Ohara Y, Bevrani H. Virtual synchronous generator based frequency control in interconnected microgrids. Energy Reports 2020;6:97–103. https://doi.org/10.1016/j.egyr.2020.10.044.

[82] Zhong C, Li H, Zhou Y, Lv Y, Chen J, Li Y. Virtual synchronous generator of PV generation without energy storage for frequency support in autonomous microgrid. International Journal of Electrical Power and Energy Systems 2022;134. https://doi.org/10.1016/j.ijepes.2021.107343.

[83] Bevrani H, Raisch J. On Virtual inertia Application in Power Grid Frequency Control. Energy Procedia, vol. 141, 2017, p. 681–8. https://doi.org/10.1016/j.egypro.2017.11.093.

[84] Rajan R, Fernandez FM. Power control strategy of photovoltaic plants for frequency regulation in a hybrid power system. International Journal of Electrical Power and Energy Systems 2019;110:171–83. https://doi.org/10.1016/j.ijepes.2019.03.009.

[85] Yu J, Meng J, Wang K, Liu H, Liu D. Research on the control strategy of hybrid energy storage cooperative operation based on VSG control. Proceedings - 2021 International Conference on Power System Technology: Carbon Neutrality and New Type of Power System, POWERCON 2021, 2021, p. 1189–95. https://doi.org/10.1109/POWERCON53785.2021.9697612.

[86] Han Y, Pu Y, Li Q, Fu W, Chen W, You Z, et al. Coordinated power control with virtual inertia for fuel cell-based DC microgrids cluster. International Journal of Hydrogen Energy 2019;44:25207–20. https://doi.org/10.1016/j.ijhydene.2019.06.128.

[87] Rahman FS, Kerdphol T, Watanabe M, Mitani Y. Optimization of virtual inertia considering system frequency protection scheme. Electric Power Systems Research 2019;170:294–302. https://doi.org/10.1016/j.epsr.2019.01.025.

[88] Zhang X, Zhu Z, Fu Y, Li L. Optimized virtual inertia of wind turbine for rotor angle stability in interconnected power systems. Electric Power Systems Research 2020;180. https://doi.org/10.1016/j.epsr.2019.106157.

[89] Zhang X, Li D, Yang Z, Tian L, Meng J, Liu Y, et al. Fuzzy adaptive virtual inertia control of energy storage systems considering SOC constraints. Energy Reports 2023;9:2431–9. https://doi.org/10.1016/j.egyr.2023.01.078.

[90] Samanta S, Mishra JP, Roy BK. Implementation of a virtual inertia control for inertia enhancement of a DC microgrid under both grid connected and isolated operation. Computers and Electrical Engineering 2019;76:283–98. https://doi.org/10.1016/j.compeleceng.2019.04.006.

[91] Hajiakbari Fini M, Hamedani Golshan ME. Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables. Electric Power Systems Research 2018;154:13–22. https://doi.org/10.1016/j.epsr.2017.08.007.

[92] Singh K, Zaheeruddin. Enhancement of frequency regulation in tidal turbine power plant using virtual inertia from capacitive energy storage system. Journal of Energy Storage 2021;35:102332. https://doi.org/10.1016/j.est.2021.102332.

[93] Saxena P, Singh N, Pandey AK. Enhancing the dynamic performance of microgrid using derivative controlled solar and energy storage based virtual inertia system. Journal of Energy Storage 2020;31. https://doi.org/10.1016/j.est.2020.101613.

[94] Mehmood Cheema K, Sarmad Mahmood R, Faizan Tahir M, Mehmood K, Yaqoob Javed M, Rehman Tariq A. Modified control of Virtual Synchronous Generator for Microgrid Stability Improvement. Proceedings of 18th International Bhurban Conference on Applied Sciences and Technologies, IBCAST 2021, 2021, p. 673–7. https://doi.org/10.1109/IBCAST51254.2021.9393174.

[95] Li P, Hu W, Xu X, Huang Q, Liu Z, Chen Z. A frequency control strategy of electric vehicles in microgrid using virtual synchronous generator control. Energy 2019;189. https://doi.org/10.1016/j.energy.2019.116389.

[96] Wang W, Jiang L, Cao Y, Li Y. A Parameter Alternating VSG Controller of VSC-MTDC Systems for Low Frequency Oscillation Damping. IEEE Transactions on Power Systems 2020;35:4609–21. https://doi.org/10.1109/TPWRS.2020.2997859.

[97] Yap KY, Lim JMY, Sarimuthu CR. A novel adaptive virtual inertia control strategy under varying irradiance and temperature in grid-connected solar power system. International Journal of Electrical Power and Energy Systems 2021;132. https://doi.org/10.1016/j.ijepes.2021.107180.

[98] Xing W, Wang H, Lu L, Han X, Sun K, Ouyang M. An adaptive virtual inertia control strategy for distributed battery energy storage system in microgrids. Energy 2021;233:121155. https://doi.org/10.1016/j.energy.2021.121155.

[99] Pradhan C, Bhende CN, Samanta AK. Adaptive virtual inertia-based frequency regulation in wind power systems. Renewable Energy 2018;115:558–74. https://doi.org/10.1016/j.renene.2017.08.065.

[100] Abubakr H, Mohamed TH, Hussein MM, Guerrero JM, Agundis-Tinajero G. Adaptive frequency regulation strategy in multi-area microgrids including renewable energy and electric vehicles supported by virtual inertia. International Journal of Electrical Power and Energy Systems 2021;129. https://doi.org/10.1016/j.ijepes.2021.106814.

[101] Li M, Huang W, Tai N, Yang L, Duan D, Ma Z. A Dual-Adaptivity Inertia Control Strategy for Virtual Synchronous Generator. IEEE Transactions on Power Systems 2020;35:594–604. https://doi.org/10.1109/TPWRS.2019.2935325.

[102] Karimi A, Khayat Y, Naderi M, Dragičević T, Mirzaei R, Blaabjerg F, et al. Inertia Response Improvement in AC Microgrids: A Fuzzy-Based Virtual Synchronous Generator Control. IEEE Transactions on Power Electronics 2020;35:4321–31. https://doi.org/10.1109/TPEL.2019.2937397.

[103] Saadatmand S, Shamsi P, Ferdowsi M. Adaptive critic design-based reinforcement learning approach in controlling virtual inertia-based grid-connected inverters. International Journal of Electrical Power and Energy Systems 2021;127. https://doi.org/10.1016/j.ijepes.2020.106657.

[104] Magdy G, Shabib G, Elbaset AA, Mitani Y. Renewable power systems dynamic security using a new coordination of frequency control strategy based on virtual synchronous generator and digital frequency protection. International Journal of Electrical Power and Energy Systems 2019;109:351–68. https://doi.org/10.1016/j.ijepes.2019.02.007.

[105] Liu J, Yang Z, Yu J, Huang J, Li W. Coordinated control parameter setting of DFIG wind farms with virtual inertia control. International Journal of Electrical Power and Energy Systems 2020;122:106167. https://doi.org/10.1016/j.ijepes.2020.106167.

[106] Ali H, Magdy G, Xu D. A new optimal robust controller for frequency stability of interconnected hybrid microgrids considering non-inertia sources and uncertainties. International Journal of Electrical Power and Energy Systems 2021;128:106651. https://doi.org/10.1016/j.ijepes.2020.106651.

[107] Kerdphol T, Ngamroo I, Surinkaew T. Forced oscillation suppression using extended virtual synchronous generator in a low-Inertia microgrid. International Journal of Electrical Power and Energy Systems 2023;151:109126. https://doi.org/10.1016/j.ijepes.2023.109126.

[108] Alipoor J, Miura Y, Ise T. Stability assessment and optimization methods for microgrid with multiple VSG units. IEEE Transactions on Smart Grid 2018;9:1462–71. https://doi.org/10.1109/TSG.2016.2592508.

[109] Yan X, Rasool A, Abbas F, Rasool H, Guo H. Analysis and optimization of the coordinated multi-VSG sources. Electronics (Switzerland) 2019;8:28. https://doi.org/10.3390/electronics8010028.

[110] Zhao M, Yin H, Xue Y, Zhang X-P, Lan Y. Coordinated Damping Control Design for Power System With Multiple Virtual Synchronous Generators Based on Prony Method. IEEE Open Access Journal of Power and Energy 2021;8:316–28. https://doi.org/10.1109/oajpe.2021.3104755.

[111] Sun Z, Zhu F, Cao X. Study on a Frequency Fluctuation Attenuation Method for the Parallel Multi-VSG System. Frontiers in Energy Research 2021;9. https://doi.org/10.3389/fenrg.2021.693878.

[112] Fu S, Sun Y, Liu Z, Hou X, Han H, Su M. Power oscillation suppression in multi-VSG grid with adaptive virtual inertia. International Journal of Electrical Power and Energy Systems 2022;135. https://doi.org/10.1016/j.ijepes.2021.107472.

[113] Luo Z, Han H, Chen S, Wu Z, Shi M, Zhang K. Power oscillation suppression method based on distributed cooperative control of multi-VSG grids. Proceedings of the Energy Conversion Congress and Exposition - Asia, ECCE Asia 2021, 2021, p. 1875–8. https://doi.org/10.1109/ECCE-Asia49820.2021.9479167.

[114] Li L, Sun Y, Liu Y, Tian P, Shen S. A communication-free adaptive virtual inertia control of cascaded-type VSGs for power oscillation suppression. International Journal of Electrical Power and Energy Systems 2023;149:109034. https://doi.org/10.1016/j.ijepes.2023.109034.

[115] Dai Y, Zhang L, Chen Q, Zhou K, Hua T. Multi-VSG-based frequency regulation for uninterruptible power AC micro-grid with distributed electric vehicles. International Journal of Electrical Power and Energy Systems 2022;137:107785. https://doi.org/10.1016/j.ijepes.2021.107785.

[116] Fang J, Zhao J, Mao L, Qu K, Gao Z. An improved virtual synchronous generator power control strategy considering time-varying characteristics of SOC. International Journal of Electrical Power and Energy Systems 2023;144:108454. https://doi.org/10.1016/j.ijepes.2022.108454.

[117] Bhowmik P, Satpathy PR, Thanikanti SB, Jana N. A novel virtual inertia emulation technique for the single phase electric vehicle charging topology. Computers and Electrical Engineering 2022;101:108114. https://doi.org/10.1016/j.compeleceng.2022.108114.

[118] Choopani M, Hosseinian SH, Vahidi B. New Transient Stability and LVRT Improvement of Multi-VSG Grids Using the Frequency of the Center of Inertia. IEEE Transactions on Power Systems 2020;35:527–38. https://doi.org/10.1109/TPWRS.2019.2928319.

[119] Kerdphol T, Rahman FS, Watanabe M, Mitani Y, Hongesombut K, Phunpeng V, et al. Small-signal analysis of multiple virtual synchronous machines to enhance frequency stability of grid-connected high renewables. IET Generation, Transmission and Distribution 2021;15:1273–89. https://doi.org/10.1049/gtd2.12101.

[120] Skinder KS, Kerdphol T, Mitani Y, Turschner Di. Frequency Stability Assessment of Multiple Virtual Synchronous Generators for Interconnected Power System. IEEE Transactions on Industry Applications 2022;58:91–101. https://doi.org/10.1109/TIA.2021.3121219.

[121] Hu W, Lv Y, Shen Y, Dou X, Yang F. Inertia-enhanced method for active distribution network based on hierarchical control structure. International Journal of Electrical Power and Energy Systems 2022;142:108365. https://doi.org/10.1016/j.ijepes.2022.108365.

[122] Zheng X, Antoine M, Li HY. Multi-VSG inverter oower sharing MPC-VSG Control for islanded microgrid 2021:589–94. https://doi.org/10.1049/icp.2021.2335.

[123] Bandla KC, Gururaj M V., Padhy NP. Decentralized and Coordinated Virtual Synchronous Generator control for Hybrid AC-DC Microgrids. 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy, PESGRE 2020, IEEE; 2020, p. 1–6. https://doi.org/10.1109/PESGRE45664.2020.9070695.

[124] Yang Y, Yang P, Lin W, Li Z, Lu G. A decentralized control for Non-error frequency regulation in an islanded microgrid containing multiple VSGs. International Journal of Electrical Power and Energy Systems 2021;133:107337. https://doi.org/10.1016/j.ijepes.2021.107337.

[125] Liu J, Miura Y, Bevrani H, Ise T. Enhanced Virtual Synchronous Generator Control for Parallel Inverters in Microgrids. IEEE Transactions on Smart Grid 2017;8:2268–77. https://doi.org/10.1109/TSG.2016.2521405.

[126] Im WS, Wang C, Liu W, Liu L, Kim JM. Distributed virtual inertia based control of multiple photovoltaic systems in autonomous microgrid. IEEE/CAA Journal of Automatica Sinica 2017;4:512–9. https://doi.org/10.1109/JAS.2016.7510031.

[127] Saeedian M, Pournazarian B, Eskandari B, Shahparasti M, Pouresmaeil E. Enhancing Frequency Stability of Weak Grids with

Modified Distributed Virtual Inertia Method. 2020 IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2020, IEEE; 2020, p. 187–92. https://doi.org/10.1109/PEDG48541.2020.9244475.

[128] Bao F, Guo J, Wang W, Wang B. Cooperative Control Strategy of Multiple VSGs in Microgrid Based on Adjacent Information. IEEE Access 2021;9:125603–15. https://doi.org/10.1109/ACCESS.2021.3110848.

[129] Wang Z, Zhuo F, Yi H, Wu J, Wang F, Zeng Z. Analysis of dynamic frequency performance among voltage-controlled inverters considering virtual inertia interaction in microgrid. IEEE Transactions on Industry Applications 2019;55:4135–44. https://doi.org/10.1109/TIA.2019.2910784.

[130] Liu J, Miura Y, Bevrani H, Ise T. A Unified Modeling Method of Virtual Synchronous Generator for Multi-Operation-Mode Analyses. IEEE Journal of Emerging and Selected Topics in Power Electronics 2021;9:2394–409. https://doi.org/10.1109/JESTPE.2020.2970025.

[131] Lalitha MP, Anupama S, Faizal KSM. Fuzzy logic controller for parallel inverters in microgrids using virtual synchronous generator control. 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing, ICECDS 2017, IEEE; 2018, p. 2690–6. https://doi.org/10.1109/ICECDS.2017.8389943.

[132] Shuai Z, Huang W, Shen ZJ, Luo A, Tian Z. Active Power Oscillation and Suppression Techniques between Two Parallel Synchronverters during Load Fluctuations. IEEE Transactions on Power Electronics 2020;35:4127–42. https://doi.org/10.1109/TPEL.2019.2933628.

[133] Yu Y, Hu X. Improved control of parallel virtual synchronous generator based on adaptive voltage compensation. International Journal of Dynamics and Control 2022;10:890–901. https://doi.org/10.1007/s40435-021-00843-y.

[134] Liu G, Jing Y, Wang W, Blaajerg F. An Improved Reactive Power Control Strategy for the Parallel Inverter System Based on VSG. 2019 22nd International Conference on Electrical Machines and Systems, ICEMS 2019, 2019. https://doi.org/10.1109/ICEMS.2019.8922222.

[135] Mohamed SYA, Yan X, Abdo AMA. Parallel Operation of Virtual Synchronous Generators in a Microgrid. Proceedings of: 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering, ICCCEEE 2020, IEEE; 2021, p. 1–6. https://doi.org/10.1109/ICCCEEE49695.2021.9429663.

[136] Zhang Q, Li Y, Ding Z, Xie W, Li C. Self-Adaptive Secondary Frequency Regulation Strategy of Micro-Grid with Multiple Virtual Synchronous Generators. IEEE Transactions on Industry Applications 2020;56:6007–18. https://doi.org/10.1109/TIA.2020.2975144.

[137] Al-Tameemi M, Miura Y, Liu J, Bevrani H, Ise T. A novel control scheme for multi-terminal low-frequency AC electrical energy transmission systems using modular multilevel matrix converters and virtual synchronous generator concept. Energies 2020;13. https://doi.org/10.3390/en13030747.

[138] Basir Khan MR, Jidin R, Pasupuleti J. Multi-agent based distributed control architecture for microgrid energy management and optimization. Energy Conversion and Management 2016;112:288–307. https://doi.org/10.1016/j.enconman.2016.01.011.

[139] Dou CX, Liu B. Multi-agent based hierarchical hybrid control for smart microgrid. IEEE Transactions on Smart Grid 2013;4:771–8. https://doi.org/10.1109/TSG.2012.2230197.