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Stability analysis and simulation of dynamic behavior of virtual synchronous generator in microgrid system using small signal model

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Abstract:

The penetration of renewable power production units in electrical networks through power electronic converters due to their low rotating inertia, leads to increased frequency fluctuations and reduced power system stability. The synchronization of the power converters with the main network is of great importance, so that it must be maintained even during disturbances. Virtual synchronous machines are among the efficient methods to comply with the scarcity of inertia in the power network. In this paper, the aim is to investigate the stability and simulate the dynamic behavior of connecting a virtual synchronous generator (VSG) to an infinite bus employing a small-signal representative. The characteristics of the VSG are compared with the droop method for controlling active and reactive powers. An evaluation between these two different control strategies has been carried out using simulation results in the MATLAB environment. Also, the attributes of the synchronous machines due to changes in the point of damping and inertia parameters are shown. For the accuracy of the simulation results, the small signal model of the studied system has also been implemented in MATLAB/Simulink. Integrating the VSG in the microgrid, in addition to reducing frequency and voltage deviations, also improves stability.

Keywords: Droop control; Microgrid system; Small signal stability; Virtual inertia; Virtual synchronous machine

1. Introduction

The rapid expansion of energy consumption and the ongoing crisis in energy production, coupled with environmental challenges, have significantly increased the adoption of distributed generation systems powered by renewable power sources like photovoltaic systems and wind turbines [1, 2]. This shift has fundamentally altered the structure of energy generation and network dynamics, presenting novel challenges for the operation and stability of energy grids [3, 4]. The integration of these renewable power production units has accelerated the shift from centralized to distributed power generation models [5, 6].

Voltage source converters (VSCs), commonly referred to as inverters, serve as critical interfaces between energy storage systems, distributed generators, and loads [7, 8]. The increasing reliance on power electronic converters for grid connection has substantially modified the dynamic characteristics and operating modes of modern power systems [9, 10]. These converters enable the better connection of renewable power sources to the energy system, delivering electricity with minimal inertia [11, 12]. However, the absence of mechanical rotating components and their inherent regulation capacity can adversely affect system stability by reducing inertia. Additionally, sudden load variations and short-circuit incidents can lead to frequency fluctuations, posing risks to system security and equipment integrity [13, 14].

Microgrids offer a practical solution to address the discontinuous character of renewable power production units. These localized distribution systems facilitate the integration of spread generation units, enhancing power availability in remote areas while improving flexibility and system reliability. Microgrids operate in two primary modes: grid-tied and islanded (independent). However, the integration of renewable energy production units into microgrids often results in diminished system inertia, adversely impacting frequency stability and voltage regulation [15, 16]. The structure of a future power system according to Fig. 1 is formed by the association of renewable energy production units, and loads using power electronic devices [17, 18].

Background and motivation

Low inertia in energy grids introduces two primary challenges: (a) increased frequency deviations during disturbances due to insufficient kinetic energy, which can harm generators and consumers, and (b) rapid frequency changes that may activate protection systems, causing generator shutdowns. Consequently, inertia is a crucial factor for stabilizing microgrid frequency under load fluctuations [19, 20].

Droop control, a decentralized strategy for managing microgrid converters, is a widely used method. Virtual synchronous generator technology provides an alternative approach by simulating the dynamic behavior of synchronous generators [21, 22]. Unlike droop control, VSG incorporates inertia, offering enhanced system stability during disturbances. By mimicking the rotational characteristics of synchronous machines, VSGs improve active and reactive power regulation, which are critical for distributed generation units. The common droop control equations for microgrids are expressed as follows [23, 24]:

$$\begin{cases} \omega = \omega_n - m_p(P - P_0) \\ U = U_n - n_q(Q - Q_0) \end{cases} \quad (1)$$

where ω is the angular frequency with set point ω_n and U indicates the voltage magnitude with set point U_n. The droop slopes of reactive energy and active energy are denoted by m_p, and n_q, respectively. The selection of droop constants requires considering the balance between voltage accuracy and load sharing performance. Selecting higher droop slopes improves load sharing but results in higher voltage droop in the microgrid. During power system disturbances, traditional droop control in the inverter has problems such as rapid frequency change and large oscillations, which lead to deterioration of power quality [25, 26].

To balance the insufficiency of inertia and damping in the energy grid and also to improve stability of the energy network, the virtual synchronous machine technique is applied [27, 28]. Virtual synchronous generators are similar to a generating unit with a power electronic converter, which has the same dynamic behavior and characteristics as synchronous generators. Virtual synchronous generators are an inverter-based control method, which is applied in a distributed generation unit, and has a behavior like a synchronous machine to support the stability of the energy network [29, 30]. Energy storage in conventional synchronous generators is mechanical, but in virtual synchronous generators, energy is stored electrically using an inverter. In a real synchronous machine, the point of inertia and damping ratio are fixed, but the virtual inertia of VSG is flexible [31, 32]. Also, the control with the oscillation equation allows the dynamic characteristics of the virtual machine to be tuned considering to the grid needs. By providing virtual inertia, the virtual synchronous machine can regulate the reactive and active energies to integrate the distributed units [33, 34].

The droop characteristics are the main feature of power control in the virtual synchronous machine and droop reg-

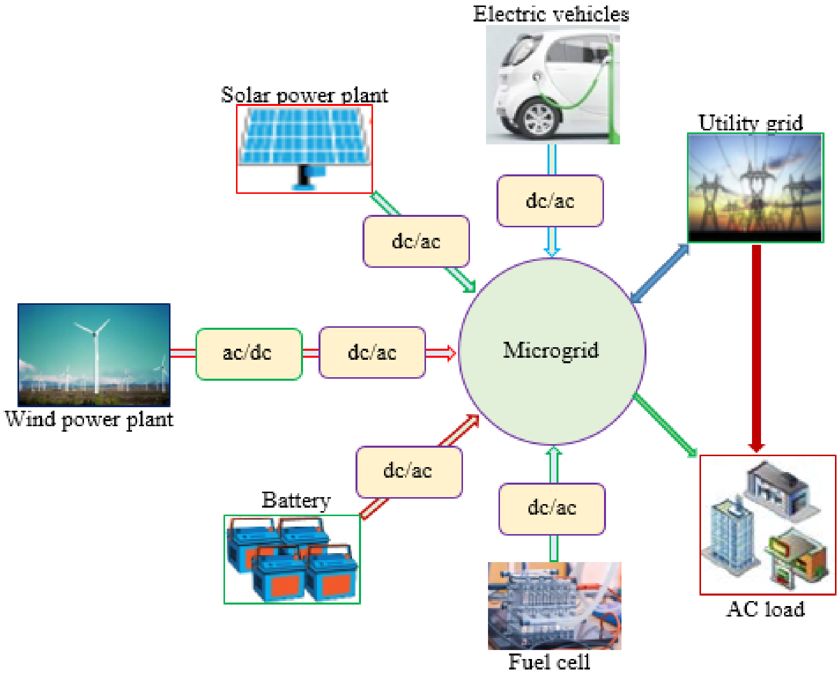

Figure 1. Integration of renewable power sources, and loads through power electronic devices in the energy system structure.

ulation methods, and the only difference between them is the existence of inertia in the virtual synchronous generator technique [35, 36]. The leading distinction between droop management and VSG lies in the provision of inertia and damping capabilities. While droop control relies on predefined slopes to balance load sharing and voltage regulation, it lacks the dynamic support provided by VSGs [37, 38]. Table 1 summarizes the key distinctions between the two methods [39, 40].

Literature Surveys

Extensive research has explored the application of VSGs to enhance system performance [41, 42]. These studies demonstrate transient stability [43], improved bang-bang control [44], frequency response [45], and power quality improvements in microgrid systems [46]. For instance, VSGs have been employed to mitigate energy and frequency fluctuations in AC microgrids [51], adaptive optimal frequency regulation for ac microgrids [52], enhance frequency stability in islanded systems [53], transient angle suppression and voltage [54] and improve overall grid stability.

Comparative analyses of current-controlled and voltage-controlled VSG models in [55] reveal that voltage-controlled VSGs are more stable and suitable for grid-connected renewable energy systems. Furthermore, integrating VSGs with advanced power storage technologies, such as superconducting magnetic power storage, has shown promise in compensating for resource depletion and maintaining voltage stability.

A VSG combined with superconducting magnetic power storage is proposed in [56] to reimburse for the depletion of traditional resources and sustain the voltage stability and the frequency stability. The active power of SMES, that has a more instantaneous reaction compared to other power storage units, is determined based on the damping ratio and virtual inertia with a PI controller and the reactive energy is determined based on the voltage regulation.

An improved damping and angular frequency deviation feed forward based VSG control method is suggested in [57] to address the oscillation and steady-state error issues with the active output energy of grid-tied power inverters regulated by VSGs. A small-signal closed loop model of actual power is used to study the impact of damping and inertia on the transient and steady state implementation of VSG. The system's dynamic performance has been enhanced, according to the simulation results, by the precision of active power regulation.

An adaptive regulation method with joint damping is proposed to solve the problem of frequency oscillations when multiple VSGs operate in parallel in [58]. The suggested procedure enhances the frequency dynamics with respect to the change ratio of the frequency. Also, the Lyapunov method is used to prove the stability, and the simulation outcomes demonstrate the efficient operation of the method.

A systematic analysis method with a small signal model is presented to evaluate the stability of multi-VSG synchronization in [59]], in which the characteristics of the power system are considered. The results show the stability enhancement using the above method in a power system with six VSGs.

The optimization method for the virtual inductor in VSG is investigated in [60], which aims to increase the power isolation capacity of the inverter. The power stability analysis with different control parameters is carried out using the dynamic coupling model. The power coupling degree function is used to optimize the virtual inductor parameters.

Table 2 lists a number of review studies on the application of synchronous generators.

Innovation and contributions

As power electronics-based generation units are integrated into energy grids, the scarcity of inertia and inadequate damping reduce the system's ability to keep stability during fluctuations [61]. In order to solve this problem, droop control and virtual synchronous machine regulation methods can be utilized in voltage source inverters. In this study, by presenting a small signal structure, the above two methods are compared in terms of response speed to load and parameter changes. The simulation results show the angular velocity changes and active power changes of the inverter output for input step changes. The simulation results of the active power output step response are compared in terms of overshoot, peak time, and rise time. The simulation results show that the low pass filter method has less overshoot than the other methods. Also, the rise time and peak time in the active power loop method are longer than other methods.

This study investigates VSGs' dynamic behavior and stability using a small signal model. Key contributions include:

- Examining the influence of virtual damping or inertia on system dynamics.
- Analyzing the small signal model of VSGs based on transfer functions.
- Comparing VSG performance with traditional droop control methods under step changes.
- Evaluating various control techniques for VSGs regarding response speed and stability.

Table 1. Comparison of the characteristics of the two regulation techniques.

Regulation Method / Comparison Quantity	Output oscillation	Rate of frequency change	Inertia support	Response speed	Current sharing effect
Virtual Synchronous Generator	Yes	Low	Yes	Fast	General
Droop Control	Yes	High	No	Slow	General

Table 2. Review of a number of review studies on the application of virtual synchronous generators.

Reference	Subject	Study Highlights
[47]	Topology and control techniques	Virtual inertia-based power inverters are conceived to provide inertial reaction similar to that of a synchronous machine, and to regulate the frequency of the energy system. This study reviews the structure of a virtual synchronous generator and examines various topologies for virtual inertia. The drawbacks of a virtual synchronous machine contain the scarcity of overcurrent security. Reactive and active energy management along with voltage and frequency control are described. The parameters for selecting a virtual inertia-based inverter topology depend on the use of a current/voltage source and on the exact simulation equation of the synchronous generator behavior.
[48]	Low frequency oscillations	Based on the oscillation equations considered for the virtual synchronous generator, low-frequency oscillations should be considered. The strategies for reducing low-frequency oscillations in the virtual synchronous generator are distinguishable from those in energy plans with conventional synchronous machines. This paper reviews these strategies. The various causes of low-frequency oscillations associated with the virtual synchronous machine and the control approaches for reducing them are classified, and their advantages and disadvantages are compared.
[49]	Virtual frequency and inertia tuning	One of the solutions for expanding the use of renewable power production plants in the electrical grid is the use of virtual synchronous generators. This paper reviews active power control and inertia compensation methods. One of the appropriate solutions to compensate for the inertia deficiency of the entire energy system and also enrich the energy stability of the grid is the use of electronic interfaces to disable simultaneous generation and the widespread penetration of power production plants.
[50]	Synchronverter model and stability	Synchronverter is one of the simulation techniques used to compensate for inertia because of the penetration of renewable power production plants in the energy grid. In this study, a review of synchronverter technology is suggested. The impact of coefficient deviation on transient operation is also discussed and stability assessment techniques are mentioned.

The remnant of this study is categorized as follows: The active power and reactive power relations of the VSG linked to the infinite bus are expressed and based on the linearization of these relations, the small signal model is determined in section 2. Also, the simple structure of the VSG is shown in this part. In section 3, the small signal representative of the droop management strategy and VSG management are mentioned. In section 4, the simulation outcomes and comparison of the two regulation schemes are delivered. Ultimately, in section 5, the conclusions are drawn. The overall workflow of the present study is shown in Fig. 2.

2. Virtual synchronous generator connected to infinite bus

Conventional synchronous generators have almost constant inertia and damping coefficient values and are not flexible in response to disturbances and changes. The virtual synchronous generator can have a similar performance to the electromechanical transient features of traditional synchronous machines, and increase the damping and inertia of the network [62, 63]. The general structure of the virtual synchronous machines as illustrated in Fig. 3 consists of a distributed generation unit, power storage system, power electronic device, transmission network and filter circuit [64, 65]. In this model, the regulation bandwidth of the internal current and the internal voltage regulation is usually much larger than that of the external power regulation, and therefore the effect of the internal regulation transient reaction on the external regulation can be ignored. VSG

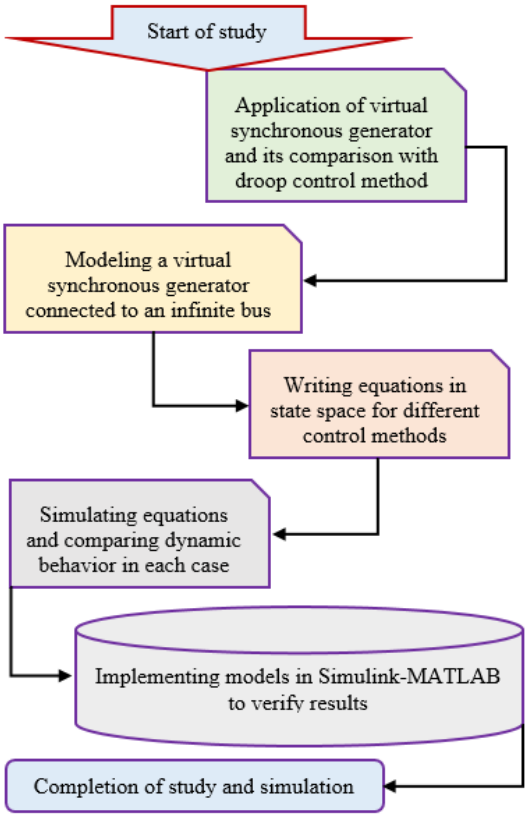

Figure 2. Workflow structure of present study.

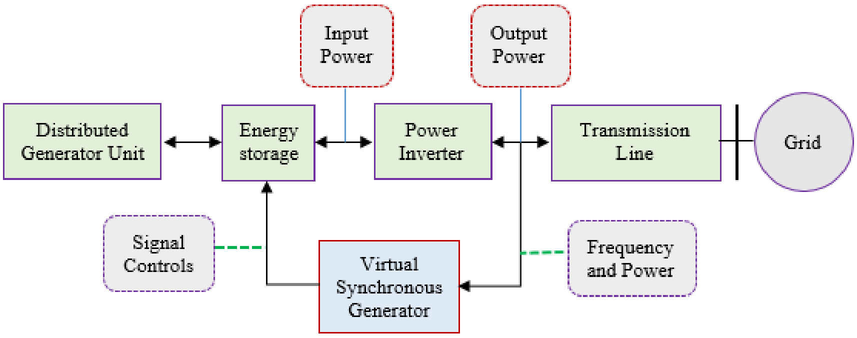

Figure 3. Virtual synchronous machine topology with regulation structure.

control offers a method to enhance the energy stability of renewable power generation units connected to the grid by simulating the external behavior of synchronous machines, relying on damping and inertia coefficient [66, 67].

A simple model of connecting a virtual synchronous machine connected to large power system depicted as an infinite bus through a transmission line with impedance $R_L + jX_L$ is shown in Fig. 4. In a microgrid, the power electronic converter (inverter) performs as a voltage source. The VSG output voltage and the energy grid voltage are E_V and U_B, respectively, and their phases are zero and δ, respectively [68, 69]. Ignoring the resistance between the VSG output source and the infinite bus and considering only the total reactance $X_T = X_V + X_L$, considering the equivalent topology of the grid, the power shared with the energy network is equal to:

$$\begin{cases} P_E = \frac{U_B E_V}{X_T} \sin\delta \\ Q_E = \frac{U_B E_V}{X_T} \cos\delta - \frac{U_B^2}{X_T} \end{cases} \tag{2}$$

where δ is the phase difference among the VSG output grid and the voltage source. By regulating the inverter output voltage, the reactive energy delivered to the load can be regulated, so the reference voltage can be calculated using the controller from the reactive output power. The small signal model is determined by linearizing the power equations:

$$\begin{cases} \Delta P_E = K_{pd}\Delta\delta + K_{pe}\Delta E \\ \Delta Q_E = K_{qd}\Delta\delta + K_{qe}\Delta E \end{cases} \tag{3}$$

where

$$\begin{cases} K_{pd} = \frac{U_B E_V}{X_T} \cos\delta \\ K_{pe} = \frac{U_B}{X_T} \sin\delta \end{cases} \tag{4}$$

$$\begin{cases} K_{qd} = -(\frac{U_B E_V}{X_T} \sin\delta) \\ K_{qe} = \frac{U_B}{X_T} \cos\delta \end{cases} \tag{5}$$

Therefore, the small signal representative of the VSG linked to the infinite grid bus will be a multi input multi output representative considering the reactive energy and active energy regulation equations with two inputs including the reference actual energy and the reference reactive energy and two outputs including the reactive energy changes and the active energy changes as shown in Fig. 5.

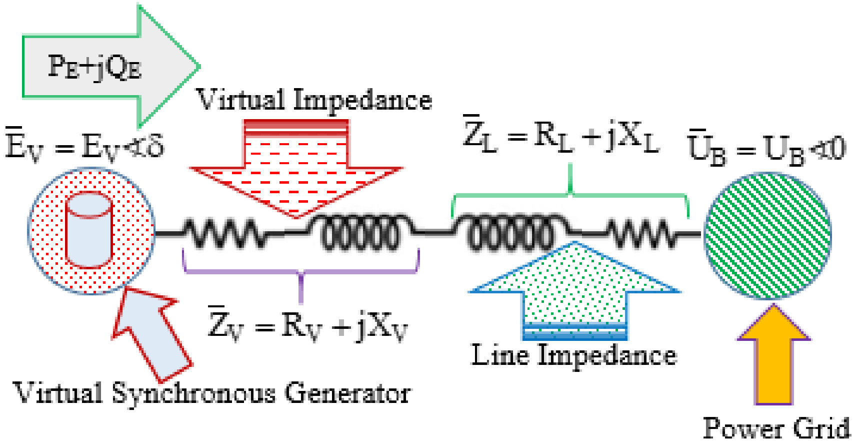

Figure 4. Electrical model of the virtual synchronous machine connection network to the grid.

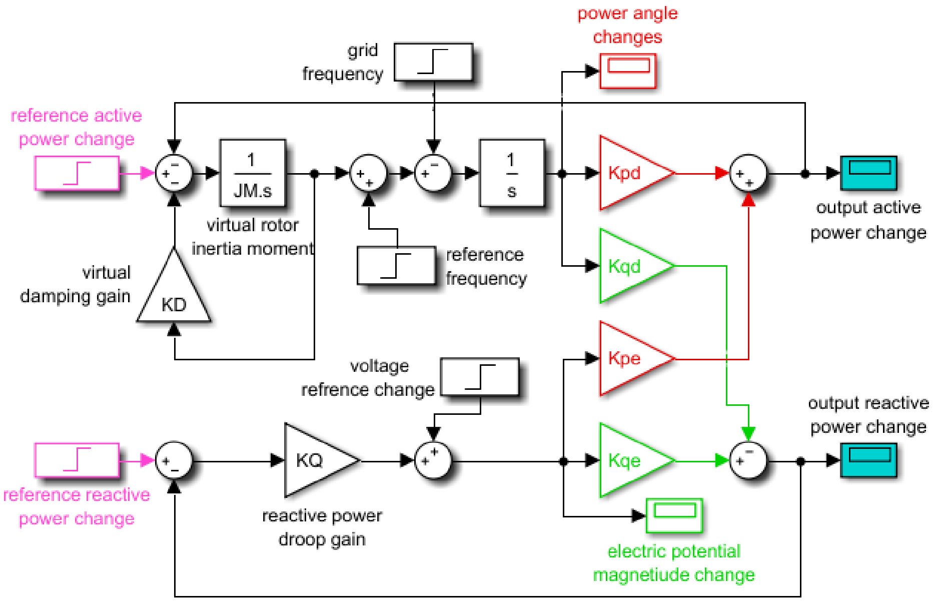

Figure 5. Small signal representative of virtual synchronous machine considering power regulation equations.

3. Small signal reperesentation of virtual synchronous machine control

The virtual synchronous generator considering the rotational inertia oscillation equation has a simple structure and only simulates the mechanical parts of a traditional synchronous generator. In this case, the design parameters will only include the inertia constant and the damping coefficient, and only by using these parameters, the damping effect and the synchronization power effect are provided [70]. The virtual oscillation equation of VSG is expressed according to the oscillation relationship of the synchronous machine as follows [71]:

$$\begin{cases} J_V\frac{d(\omega_V-\omega_g)}{dt} = \frac{P_{\text{in}}}{\omega_b} - \frac{P_{\text{out}}}{\omega_b} - K_D(\omega_V-\omega_g) \\ \frac{d\theta_m}{dt} = \omega_V \\ \frac{d\delta}{dt} = \omega_V - \omega_b \end{cases} \tag{6}$$

where K_D is the virtual damping parameters, ω_g is the system angular frequency at the common connection point (grid voltage rotational speed), ω_b is the base angular frequency, and ω_V is the output virtual rotor angular frequency (angular frequency). Also, J_V is the virtual rotational inertia moment, δ is the power angle and θ_m is the virtual mechanical phase. The input mechanical power (reference active power) and the output electrical power (electrical output energy) are denoted by Pin and Pout, respectively [72, 73]. The oscillation equation mimics the inertia of a generator and can therefore be added to the traditional droop regulation to sweeten its temporary performance.

The active power loop equivalent circuit based on the linearization of the oscillation equation is shown in Fig. 6 [74, 75]. By choosing two state variables, the VSG control

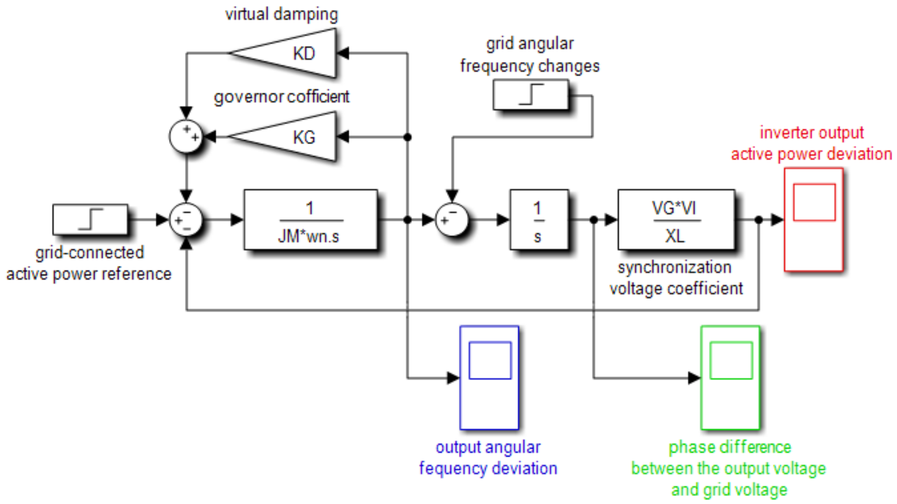

Figure 6. Equivalent circuit of active energy loop of virtual synchronous generator.

relationships in the state space are expressed as:

$$\frac{d}{dt}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{K_S}{J_V\,\omega_b} & -\frac{K_G+K_D}{J_V\,\omega_b} \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{J_V\,\omega_b} \end{bmatrix}[\Delta P_{\text{in}}] \tag{7}$$

where K_S is the voltage synchronizing factor and K_G is the governor constant. The real angular speed of the constant and the damping factor are equal to:

$$\begin{cases} \omega_n = \sqrt{\frac{K_S}{J_V\,\omega_b}} \\ \eta = \frac{K_G+K_D}{2\sqrt{J_V\,\omega_b}} \end{cases} \tag{8}$$

Therefore, the major aspects affecting the VSG reaction are the real angular frequency of the constant and the damping factor. With the increase of the virtual inertia, the speed change rate will be lower and the frequency dynamics will be longer. Also, virtual inertia only affects the dynamic process, and will not influence the steady state frequency reaction [76].

To sweeten the temporary damping of the network as shown in Fig. 7, a control approach considering angular frequency feed-forward balance in the small signal representative is employed, where K_d is the feedforward compensation coefficient and T_f is the time constant of the filter [77]. By choosing three state variables, the equations of the control method using a low-pass filter will be expressed as follows:

$$\frac{d}{dt}\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{K_S}{J_V\,\omega_b} & -\frac{K_D}{J_V\,\omega_b} & 0 \\ \frac{K_S K_d}{J_V\,\omega_b} & -\frac{K_S K_d}{J_V\,\omega_b} & \frac{1}{T_f} \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{J_V\,\omega_b} \\ \frac{K_d}{J_V\,\omega_b} \end{bmatrix}[\Delta P_{\text{in}}] \tag{9}$$

To increase the comparable damping proportion in order to diminish overshoot and sweeten the transient reaction of the plant in Fig. 8, a derivative controller with a compensation coefficient K_m is added. The transfer function of the PID controller with three gain coefficients for K_{PC}, K_{IC}, and K_{DC} for the proportional, integrator, and derivative components, respectively, is considered as follows:

$$\mathrm{G}_{\mathrm{PID}} = K_{PC} + \frac{K_{IC}}{S} + K_{DC}S \tag{10}$$

If the output of the integrator controller is considered to be the state variable x_3, the equations in the state space

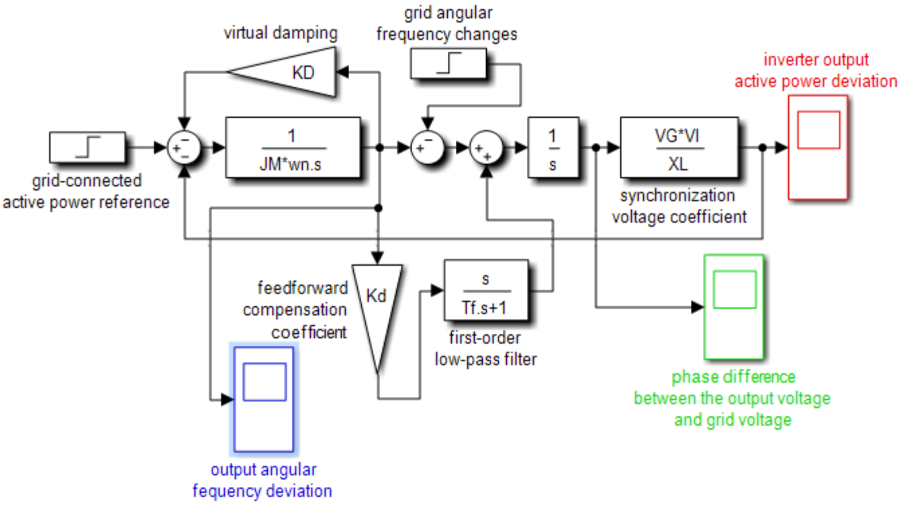

Figure 7. Small signal representation of virtual synchronous machine regulation using low pass filter.

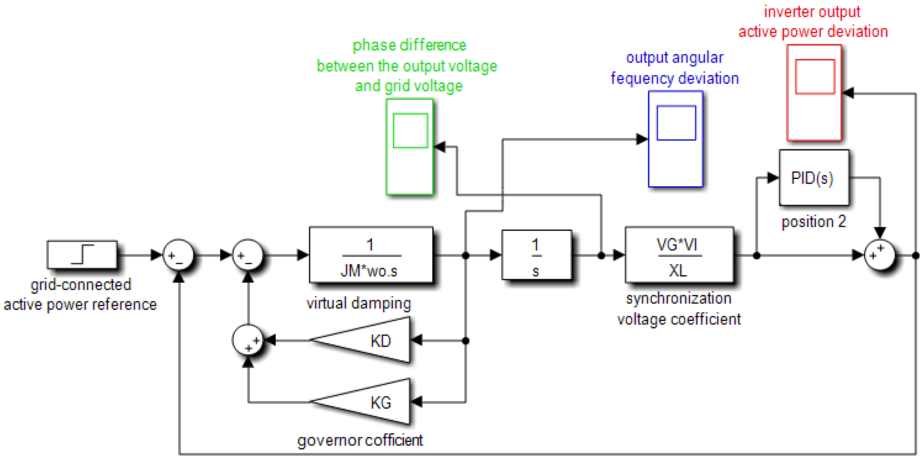

Figure 8. Small signal representation of synchronous machine control with inertia droop control.

for the inertial loop control method can be expressed as follows:

$$\frac{d}{dt}\begin{bmatrix}X_1\\X_2\\X_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ -\frac{(1+K_{PC})K_S}{J_V\,\omega_b} & -\frac{K_D+K_G-K_{DC}K_S}{J_V\,\omega_b} & -1\\ K_{IC}K_S & 0 & 0\end{bmatrix}\begin{bmatrix}X_1\\X_2\\X_3\end{bmatrix} + \begin{bmatrix}0\\ -\frac{1}{J_V\,\omega_b}\\ 0\end{bmatrix}[\Delta P_{\text{in}}] \tag{11}$$

4. Analysis of simulation results

The stability problems of microgrids during disturbances depend on the nature of the disturbance. The intermittent nature of renewable power production units has led to the importance of stability issues, especially in microgrid systems, because these sources reduce the available grid inertia. Virtual synchronous generator technology is a practical method to compensate for the lack of rotational inertia in renewable energy-based energy systems to maintain the speed while reducing the equivalent system inertia [78, 79]. The inverter in VSG is controlled to imitate the features of conventional VSG. In this section, the variations of the electric power and the angular speed of the virtual rotor are shown for step changes in load for drop control and virtual synchronous generator.

The changes in the active energy output for step changes in the input are depicted in Fig. 9. It is evident that in the inertia loss control method with the derivative controller, the overshoot is the lowest. In the active energy regulation method, the overshoot is the highest. In all four methods, the final amount of active output energy is the same.

The angular frequency changes of the inverter output for input step changes for the four studied methods are explained in Fig. 10. Fig. 11 shows the phase difference between the output voltage and the grid voltage for different control modes. It is evident that the angular frequency changes in the steady state tend to zero. In inertia loss control with the derivative controller, the response overshoot also has the lowest value.

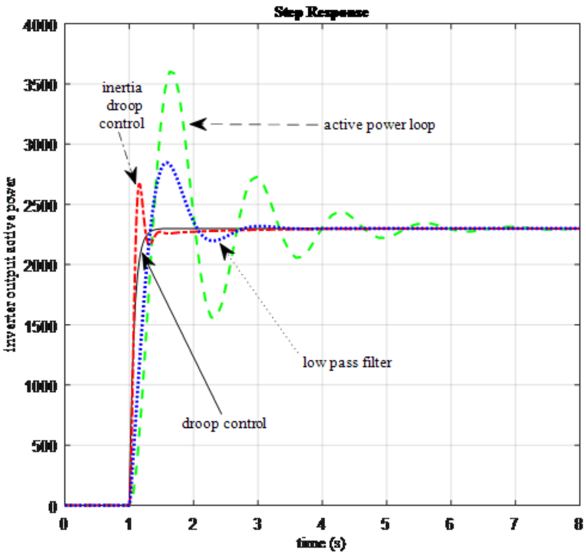

Figure 9. Comparison of the response of active energy output changes to input step changes.

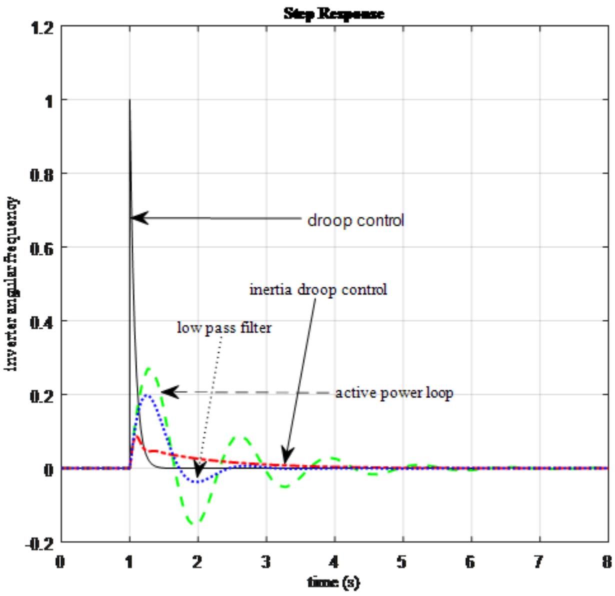

Figure 10. Comparison of inverter angular frequency response to input step changes.

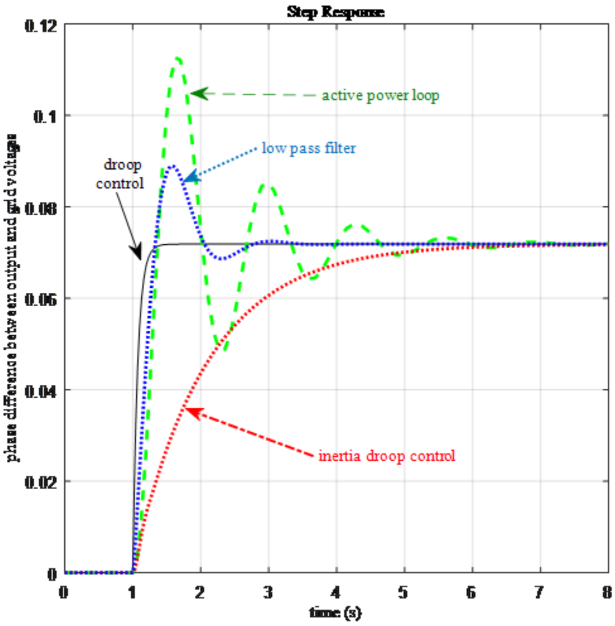

Figure 11. Comparison of inverter angular frequency response to input step changes.

Comparison of response characteristics of active energy output changes to input step changes for different methods including peak time, overshoot and rise time is given in Table 3.

Fig. 12 shows the comparison of the response of active energy output changes to the inertia constant changes. As can be seen, by decreasing the inertia constant, the amount of overshoot and response fluctuations will be reduced.

Table 3. Comparison of response characteristics of active energy output changes.

Method	Peak time (sec)	Overshoot (%)	Rise time (sec)
Active power loop	1.6276	56.69	1.4145
Low pass filter	1.1472	16.08	1.1107
Inertia droop control	1.5848	23.77	1.0472

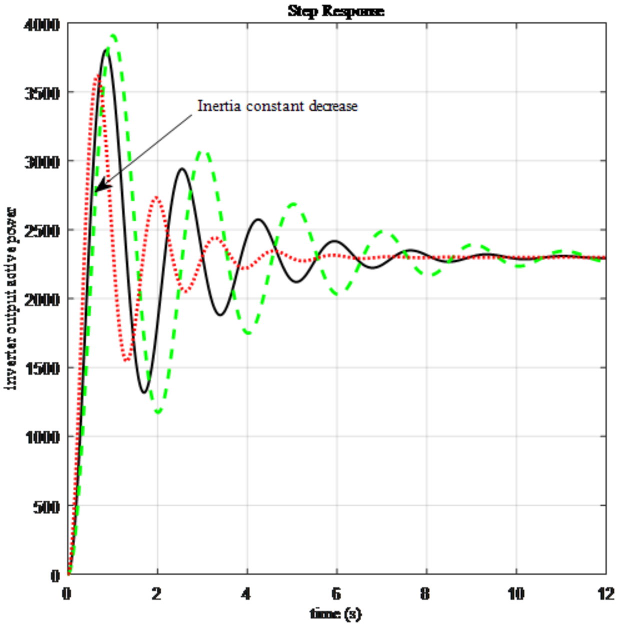

Figure 12. Comparison of the response of active energy output changes to inertia constant changes.

5. Conclusion

The increasing penetration of distributed generators and renewable power production units leads to a gradual reduction in inertia and damping of the energy grid, which will disrupt the performance and stability of the energy grid. One of the techniques used to overcome the reduction of inertia in renewable power production units considering energy converters is the use of virtual synchronous machines. This approach is among the most straightforward methods to implement virtual inertia, and has several advantages, and plays a critical role in the production of renewable power production units based on power electronics. In this work, the behavior of the virtual synchronous machine in the energy system is studied and simulated. Three different regulation approaches are analogized with the droop regulation strategy in terms of response and settling time. In the droop control strategy, only the initial frequency regulation and the aspects of the partial excitation control of synchronous machines are simulated. Also, in this method, the characteristics of the rotor motion of synchronous generators are not simulated, and it is not capable of providing virtual inertia. Simulation results show that the virtual synchronous machine control has better frequency support than droop regulation. Because of the introduction of virtual inertia through virtual synchronous generator technology, the grid inertia increases. To improve the response of this method, a derivative compensator and a low-pass filter are used. The active energy response speed of the VSG procedure is very slow compared to the droop method and there is a large droop. Simulation results show that in the active energy output step response, the overshoot value in the three methods of active power loop, low pass filter, and inertia droop control is 56.69%, 16.08%, and 23.77%, respectively. Also, the rise time and peak time in the active power loop method are longer than the other two methods, and the low pass filter method has a lower value than the other two methods.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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