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Research article

Analysis and simulation of small signal stability of parallel connection of virtual synchronous generators in a microgrid system

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Abstract

The penetration of renewable energy sources into electrical networks using power electronic converters, due to their low inertia, causes electrical networks to respond negatively to load changes and the periodic nature of generation, which leads to increased frequency fluctuations and reduced power system stability. Synchronization of the inverter with the main grid is of great importance in inverter-based units, so that even in times of disruption or changes this synchronization with the grid must be maintained. Virtual synchronous generator (VSG) technology is used to simulate the characteristics of a synchronous generator to create damping and virtual inertia in a renewable energy-based power system in order to reduce frequency fluctuations and improve stability. Small-signal stability analysis using a small-signal model of parallel connection of two virtual synchronous generators is presented in this paper. For modeling, the second-order model of the virtual synchronous generator was used. The results of the dynamic behavior simulation are reviewed and analyzed by calculating the modes of the system matrix. Also, the participation coefficients are calculated to show the relationship between the system modes and state variables.

Keywords: Small signal stability, System matrix modes, System microgrid, Parallel connection, Virtual synchronous generator.

1- Introduction

With the expansion of energy consumption in the world and in order to reduce environmental problems, the penetration of distributed generation systems based on renewable energy sources, such as fuel cells and photovoltaics, in power systems has been continuously increasing [1, 2]. The rapid development of renewable energies in the power generation structure has led to significant changes in the frequency response characteristics of the grid, which is accompanied by new challenges in the stable operation and control of the power system [3, 4]. The power system has transformed from centralized generation to distributed generation by connecting new energy sources to the power grid [5, 6]. The voltage source converter (inverter) is the communication device between the new power generation and the microgrid. Microgrids are local distribution systems, which are an important form of connecting distributed generation units to the grid. The microgrid can operate in two operating modes: grid-connected and grid-independent [7, 8]. A number of parallel distributed generation units are required to maintain microgrid voltage stability and appropriate load sharing in an islanded microgrid, but in grid-connected mode, control of interface inverters is used for efficient power exchange with the grid [9, 10].

With the increase in energy units, the use of power electronic converters has increased significantly in order to connect them to inject high-quality power into the main grid. Therefore, the trend of transforming the grid into power systems influenced by power electronic converters is expanding, which will cause changes in the operating mode and dynamic characteristics and stability of the power system [11, 12]. Inertia instability is one of the main problems in this type of systems, because power electronic converters are not able to provide the required inertia and damping to the grid. In addition to having a random nature of the output, renewable energy sources are also unpredictable, and on a large scale they reduce the inertia of the system, and will have an adverse effect on stability [13, 14]. The power generated on the primary side of distributed generation units can be adjusted using inverters, but they are not able to provide the inertia and damping required by the power grid. Inertia plays a major role in shaping the network frequency response during the first seconds of transients due to small or large disturbances in the power system [15, 16].

Problem Statement

The increasing penetration of distributed units has gradually caused the power grid to become a dominant converter system, which may result in the power system having less damping if control strategies are not properly designed. By reducing the mechanical inertia of the power grid, problems related to frequency reduction and its changes due to various disturbances in the power system will arise. Inertia plays an important role in stabilizing the frequency of the microgrid system during load imbalance or load fluctuation [17,18].

So far, various virtual inertia control strategies applicable to microgrids have been proposed to increase microgrid inertia [19, 20]. So far, various virtual inertia control strategies applicable to microgrids have been proposed to increase microgrid inertia [21, 22]. To compensate for the lack of inertia and damping in the power system, the VSG technique, which has electromechanical transient characteristics, such as a conventional synchronous generator with a switching pattern of distributed generation inverters, is used [23, 24].

Having a fast response has led to the VSG method being widely used to improve the system inertia. The tunability of the moment of inertia in the VSG compared to the synchronous generator has made the VSG superior to improve the transient stability in the power system. The development of the VSG is an economic solution for the use of renewable energy sources. By providing virtual inertia, the VSG can control the active and reactive powers for the integration of distributed units such as photovoltaic generation systems. Having significant advantages, VSGs have played an important role in power systems, especially in microgrids and distribution networks. The VSG oscillation equation parameters can be controlled in real time, unlike a synchronous machine, and the virtual machine response will be faster in tracking the steady-state frequency [25, 26]. The disadvantages of VSG include the presence of many parameters to adjust, which complicates its operation process [27, 28]. In addition, unlike synchronous generators, power converters cannot absorb or deliver any kinetic energy, and additional energy storage systems are required. Given that in a network with low inertia, even a small disturbance will cause the system to experience oscillations, a larger inertia is effective in the decay rate and system oscillations and stability. However, choosing too large inertia will reduce the phase margin, which will worsen the stability of the entire system, so the inertia value should be selected by considering the phase margin [29, 30].

Literature Review

Disturbance in load demand or change of setpoint during parallel operation of multiple VSGs can lead to oscillations in frequency and active power. So far, various studies have been presented on the application of VSGs to improve system performance, such as improving the performance of independent gas generators and improving stability [31], maintaining and increasing the transient stability of the microgrid system [32], designing a dual droop control strategy based on artificial neural networks in microgrids [33], adjusting the frequency of photovoltaic energy storage microgrid systems [34], and suppressing microgrid voltage harmonics [35]. Various studies have also been presented on the simultaneous operation of multiple VSGs to supply common loads [36, 37]. Different moments of inertia in VSGs cause differences in the rate of frequency change. When the virtual inertia is low, the response of the VSG will be faster than when the virtual inertia is high. The improvement of the dynamic performance of VSGs in steady and transient states based on different adaptive mechanisms of inertia and damping has been investigated in [38]. It has been shown by power sharing error analysis that for proportional load sharing between multiple VSGs, the inertia coefficients and damping coefficients must match. The dynamics of parallel inverters with VSGs have been investigated in [39], where the change of regulation points and load disturbance are considered, and the equivalent inertia and damping characteristics are studied. The simulation results show the influence of parameters on the dynamics of VSGs in a parallel system. In the presence of a load disturbance or change of VSG setpoint, the inertia and damping characteristics of VSGs are independent of other VSG parameters, and only the parameters of VSGs themselves are affected. An adaptive control strategy with a mutual damping term to reduce frequency and active power fluctuations in parallel connection of VSGs to improve frequency dynamics is presented in [40]. A mutual damping term is used to reduce power fluctuations in the system when operating with multiple VSGs. The Lyapunov method is used to prove the stability of the system, and simulation results in the Simulink environment of MATLAB software demonstrate the effectiveness of the method. A VSG for a three-phase parallel-connected split-source converter (SSC) for local voltage regulation and active power sharing in an islanded AC microgrid is presented in [41]. In order to have fast dynamic performance with stability and increase current limitation, a model predictive control method is used. Also, the use of the virtual inertia method reduces the frequency change rate due to sudden load changes. The relationship between oscillation and the distribution of inertial-decay parameters of parallel VSGs using a simple frequency response model is proposed in [42]. The parameter tuning problem is considered with a transfer function, and a learning-based dynamic inertial-decay control strategy is presented. The proposed method uses dynamically changing VSG parameters to suppress oscillations. Also, review studies have been presented by various researchers on the application of VSG so far [43, 44]. The intermittent nature of renewable energy sources creates problems for the stability of microgrids, as mentioned in [45]. The provision of virtual inertia by VSG helps to improve stability, and for this reason, different models and control algorithms of VSG technology have been reviewed. The use of virtual synchronous machine technology makes renewable energy generators such as solar and wind energy and flexible loads effective in regulating the voltage and frequency of the grid. The mathematical model and control strategies of virtual synchronous machine technology are reviewed in [46]. In addition, issues related to the sustainability of the technology are evaluated.

Innovation and Structure

In a power system with low inertia, there is a possibility of sudden frequency changes, which leads to problems for power system stability. Although the VSG simulates the characteristics of a conventional synchronous generator well, there is a possibility of creating problems related to low-frequency oscillations in the power system during load changes. In addition to load sharing, VSGs have the ability to inject virtual inertia into the microgrid when needed. The performance of parallel generators varies based on the different virtual moments of inertia they have. The aim of this paper is to analyze and simulate the dynamic behavior of connecting two VSGs to supply a common load. The main points to be discussed in this article can be summarized as follows:

- Investigation of the characteristics of the virtual synchronous generator due to changes in the moment of inertia and damping coefficient
- Small-signal model of parallel connection of two virtual synchronous generators

The rest of the article is organized as follows: In the section 2, the structure of the virtual synchronous generator is presented by examining the effect of the moment of inertia and damping coefficient on its characteristics. In the section 3, the small-signal model of two virtual synchronous generators is shown by linearizing the power equations. In the section 4, the results of its simulation and analysis are presented. Finally, in the section 5, the conclusions are stated.

2- VSG Structure

The main circuit topology and control structure of the virtual synchronous generator are shown in Fig. 1. As can be seen, the DC power supply, three-phase inverter bridge, LCL filter, line impedance, local load, common junction point and control loop are the main parts that constitute the topology and control structure of the VSG [47,48]. The control loop includes the power detection module, the VSG module, the virtual impedance module and the pulse width modulation module [49, 50].

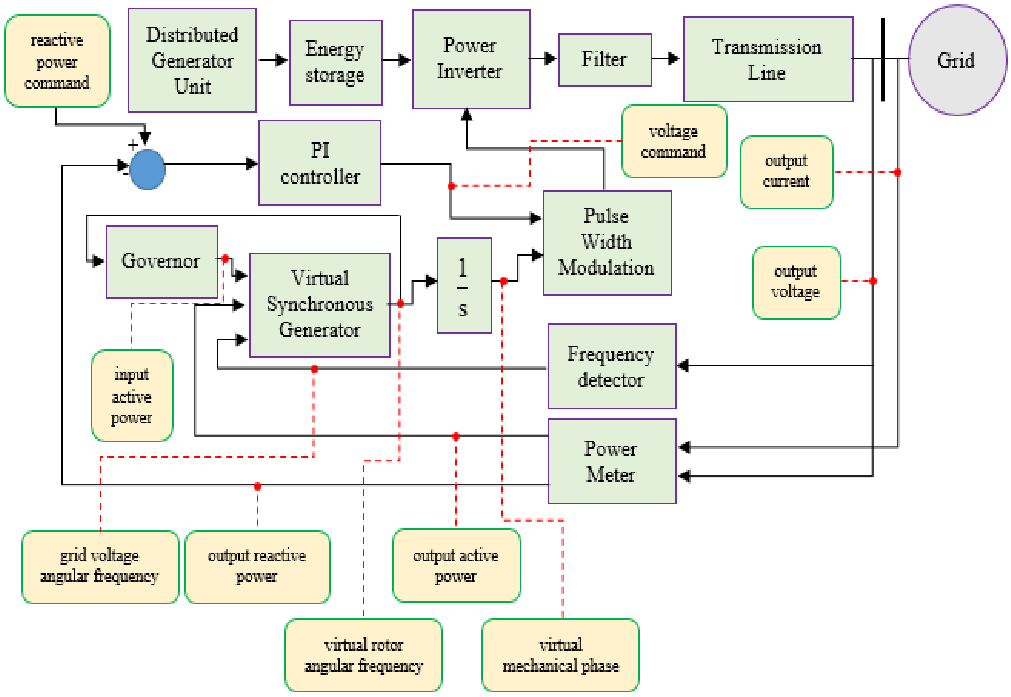

Fig. 1 Main circuit topology and structure of the virtual synchronous generator

The control block diagram of the VSG has two loops, including the active power loop and the reactive power loop, from which the phase information and the reference voltage amplitude are determined. The active power loop is determined based on the simulation of the oscillation equation and the governor of the synchronous generator to maintain frequency stability. The excitation regulator in the reactive power loop is used to regulate the reactive power and output voltage [51, 52].

The active power and reactive power control method is used in most control techniques for VSGs due to its simplicity. For grid connection operation, the reactive power control unit cannot provide the required power, and therefore a unit is needed to improve the performance of the reactive power unit [53, 54].

To simulate the mechanical motion of the VSG, there is no physical mechanical device in the control equation, so there are no mechanical power losses [55,56]. The virtual oscillation equation of the VSG is expressed in terms of the oscillation equation of the synchronous machine as follows:

$$\begin{cases} J_V \dfrac{d(\omega_v - \omega_g)}{dt} = \dfrac{P_{in}}{\omega_b} - \dfrac{P_{out}}{\omega_b} - K_D(\omega_V - \omega_g) \\ P_{in} = P_{out} - m_p(\omega_b - \omega_g) \\ Q_{out} = Q_{in} - m_q(V_g - V_r) \\ \dfrac{d\delta}{dt} = \omega_v - \omega_b \\ \dfrac{d\theta_m}{dt} = \omega_v \end{cases} \tag{1}$$

where K_D is the virtual damping factor, ω_g is the grid angular frequency at the point of common connection (grid voltage rotat-ional speed), ω_b is the base angular frequency and ω_V is the output angular frequency (virtual rotor angular freque-ncy). Also J_V is the virtual rotational moment of inertia, δ_V is the power angle and θ_m is the virtual mechanical phase. The input mechanical power (reference active power) and the active electrical power (output electrical power) are referred to as P_{in} and P_{out}, respectively. Also, Q_{out} is the output reactive power and Q_{in} is the reference reactive power, and V_g and V_r are the grid voltage and reference voltage, respectively. m_p is the active power-frequency droop factor and n_q is the reactive power-voltage droop factor.

3- Small signal model of parallel virtual synchronous generator

The main objective of using the VSG technique is to improve the stability of the power system based on renewable energy sources. Generally, based on the nature of the disturbance and the analysis, two types of small signal stability and transient stability are considered for the power system based on the synchronous generator.

The inverter forming the microgrid acts as a voltage source [57,58]. Fig. 2 shows the equivalent circuit of supplying a load on a common bus by two VSGs in a microgrid, whose virtual rotors oscillate together. The magnitude of the common load bus voltage is U_T. The magnitude of the output voltage of the two VSGs is E_1 and E_2, respectively, with phases δ_1 and δ_2. The resistive losses of the system are neglected and the equivalent impedance between the source of the VSGs with the common bus is considered as X_1 and X_2, respectively. The active output powers of each of the VSGs are determined from the following equation:

$$\begin{cases} P_{E1} = \dfrac{U_T E_1}{X_1} \sin \delta_1 \\ P_{E2} = \dfrac{U_T E_2}{X_2} \sin \delta_2 \end{cases} \tag{2}$$

The output reactive powers of VSGs are equal to:

$$\begin{cases} Q_{E1} = \dfrac{U_T E_1}{X_1} \cos \delta_1 - \dfrac{E_1^2}{X_1} \\ Q_{E2} = \dfrac{U_T E_2}{X_2} \cos \delta_2 - \dfrac{E_2^2}{X_2} \end{cases} \tag{3}$$

The reactive powers delivered to the common load from two VSGs can be determined from the following equation:

$$\begin{cases} Q_{L1} = \dfrac{U_T^2}{X_1} - \dfrac{U_T E_1}{X_1} \cos \delta_1 \\ Q_{L2} = \dfrac{U_T^2}{X_2} - \dfrac{U_T E_2}{X_2} \cos \delta_2 \end{cases} \tag{4}$$

As can be seen, the powers are a function of the phase difference between the grid voltage and the generator output voltage as well as the magnitude of the grid and VSG output voltages. If the magnitude of the load voltage and the fixed line reactance are taken into account, by linearizing the active power equations around the equilibrium point, the small-signal equations are determined as follows:

$$\begin{cases} \Delta P_{E1} = \underbrace{\dfrac{U_T E_{10}}{X_1} \cos \delta_{10}}_{K_{PF1}} \Delta\delta_1 + \underbrace{\dfrac{U_T}{X_1} \sin \delta_{10}}_{K_{PU1}} \Delta E_1 \\ \Delta P_{E2} = \underbrace{\dfrac{U_T E_{20}}{X_2} \cos \delta_{20}}_{K_{PF2}} \Delta\delta_2 + \underbrace{\dfrac{U_T}{X_2} \sin \delta_{20}}_{K_{PU2}} \Delta E_2 \end{cases} \tag{5}$$

where 0 represents the values of the quantities in the steady state, and Δ represents small changes in the variables. Ignoring resistance losses, the active power produced by the VSGs will be completely consumed by the load.

If the voltage changes of the VSGs are ignored, the changes in the electrical power produced by the VSGs can be expressed as follows:

$$\begin{cases} \Delta P_{E1} = \dfrac{K_{PF1} K_{PF2}}{K_{PF1} + K_{PF2}} (\Delta\delta_1 - \Delta\delta_2) \\ \qquad\qquad + \dfrac{K_{PF1}}{K_{PF1} + K_{PF2}} \Delta P_L \\ \Delta P_{E2} = -\dfrac{K_{PF1} K_{PF2}}{K_{PF1} + K_{PF2}} (\Delta\delta_1 - \Delta\delta_2) \\ \qquad\qquad + \dfrac{K_{PF2}}{K_{PF1} + K_{PF2}} \Delta P_L \end{cases} \tag{6}$$

where P_L represents the total load consumption. Fig. 3 shows the small signal model of parallel connection of two VSGs.

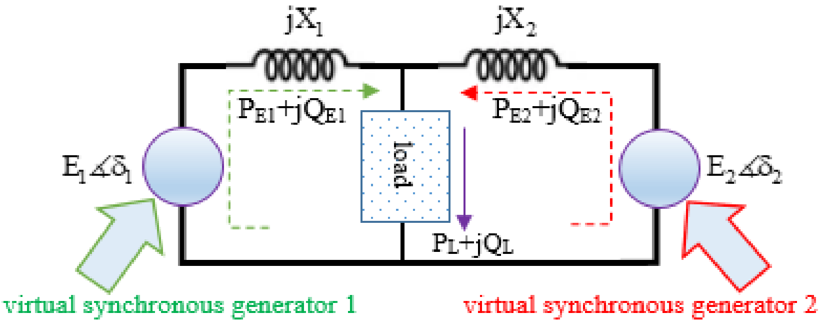

Fig. 2 Equivalent circuit connecting two virtual synchronous generators to a common load

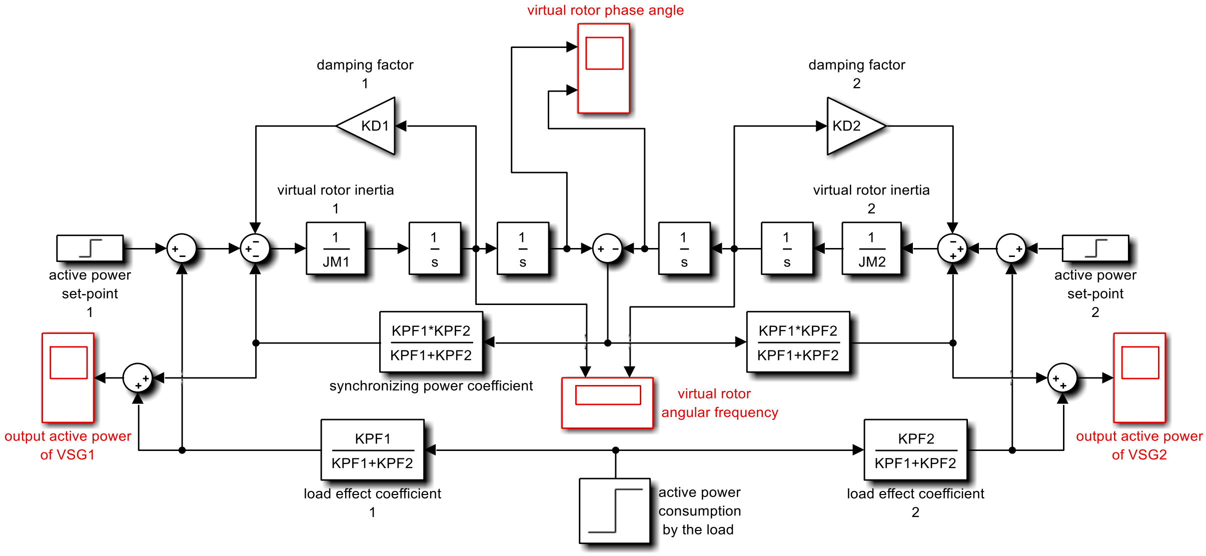

Fig. 3 Small signal block diagram of parallel connection of two virtual synchronous generators

According to the small signal model of parallel connection of two VSGs, the equations in the state space are expressed as follows by choosing three state variables and three independent inputs:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_{V1}\\ \Delta\omega_{V2}\\ \Delta(\delta_1-\delta_2)\end{bmatrix}=\begin{bmatrix}-\dfrac{K_{D1}}{J_{M1}} & 0 & -\dfrac{K_{PF1}K_{PF2}}{J_{M1}(K_{PF1}+K_{PF2})}\\ 0 & -\dfrac{K_{D2}}{J_{M2}} & \dfrac{K_{PF1}K_{PF2}}{J_{M2}(K_{PF1}+K_{PF2})}\\ \omega_b & -\omega_b & 0\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta\omega_2\\ \Delta(\delta_1-\delta_2)\end{bmatrix}$$

$$+\begin{bmatrix}\dfrac{1}{J_{M1}} & 0 & \dfrac{K_{PF1}}{J_{M1}(K_{PF1}+K_{PF2})}\\ 0 & \dfrac{1}{J_{M2}} & -\dfrac{K_{PF2}}{J_{M2}(K_{PF1}+K_{PF2})}\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta P_{M1}\\ \Delta P_{M2}\\ \Delta P_L\end{bmatrix} \quad (7)$$

$$\begin{bmatrix}\Delta P_{E1}\\ \Delta P_{E2}\end{bmatrix}=\begin{bmatrix}0 & 0 & \dfrac{K_{PF1}K_{PF2}}{K_{PF1}+K_{PF2}}\\ 0 & 0 & -\dfrac{K_{PF1}K_{PF2}}{K_{PF1}+K_{PF2}}\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta\omega_2\\ \Delta(\delta_1-\delta_2)\end{bmatrix}$$

$$+\begin{bmatrix}0 & 0 & \dfrac{K_{PF1}}{K_{PF1}+K_{PF2}}\\ 0 & 0 & \dfrac{K_{PF2}}{K_{PF1}+K_{PF2}}\end{bmatrix}\begin{bmatrix}\Delta P_{M1}\\ \Delta P_{M2}\\ \Delta P_L\end{bmatrix} \quad (8)$$

4- Simulation results

The intermittency of renewable energy sources has led to the importance of sustainability issues, especially in the field of microgrids, because these sources usually reduce the existing grid inertia. Virtual synchronous generator technology is an effective method to solve the problem of lack of rotational inertia in renewable energy-based power systems. In this section, the variations of the output electric power and the angular velocity changes of the virtual rotor for step changes in the load are shown.

Case 1- The virtual inertia of VSG1 is considered to be greater than VSG2. In this case, the damping coefficients are the same. Figs. (4) and (5) show the responses of the angular velocity changes of the virtual rotor for two virtual generators for step changes in the reference power 1 and the load, respectively. Figs. (6) and (7) show the responses of the output electric power changes for two virtual generators for step changes in the reference power 1 and the load, respectively.

The system modes in this case are -0.1262 and -0.0703±j0.3309, which has one real mode and two oscillatory modes, which indicates the stability of the response.

As can be seen, VSG2 produces more power than VSG1 with respect to load changes, but with a change in the reference signal, since it has occurred at the input of VSG1, VSG1 will produce more power.

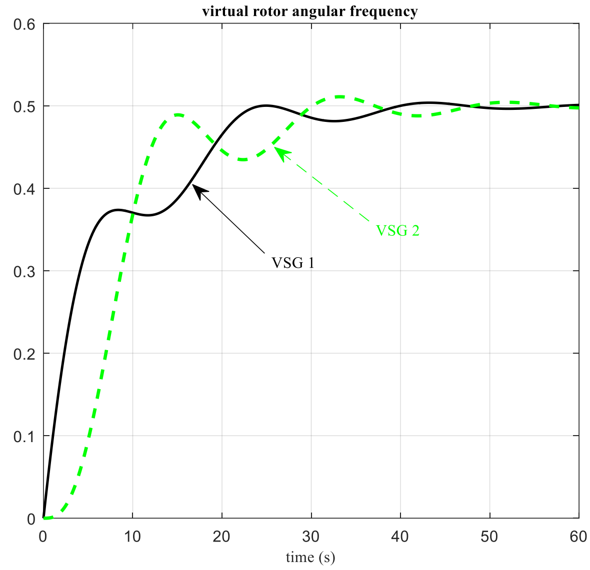

Fig. 4 Changes in the angular velocity of the virtual rotor for step changes in the active power reference 1 with different inertia coefficients

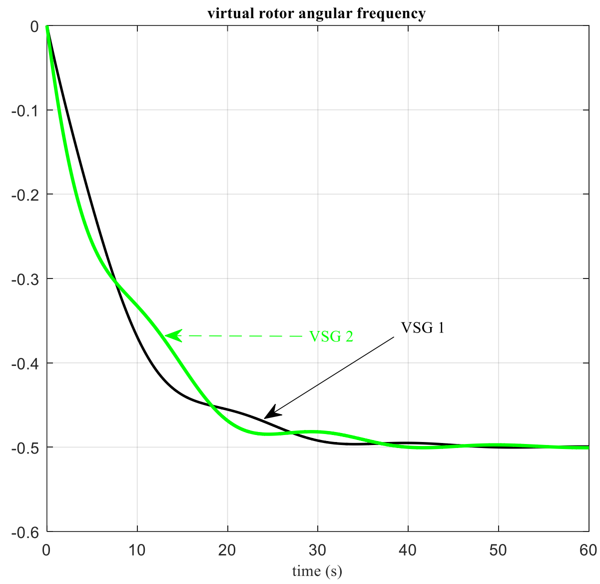

Fig. 5 Changes in the angular velocity of the virtual rotor for step changes in the consumed load with different inertia coefficients

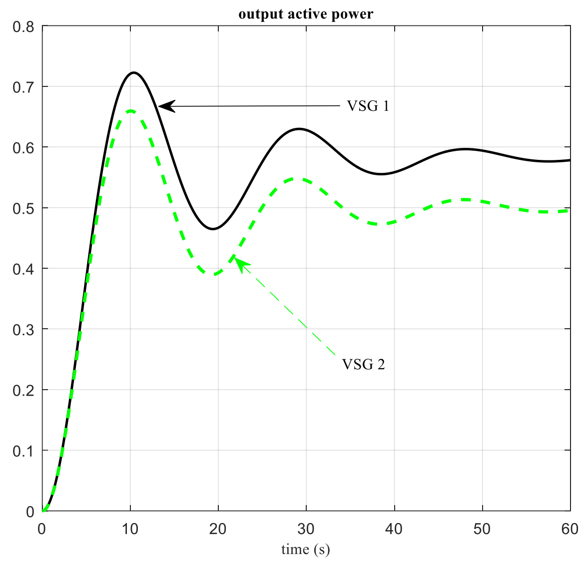

Fig. 6 Changes in the output electrical power for step changes in the active power reference 1 with different inertia coefficients

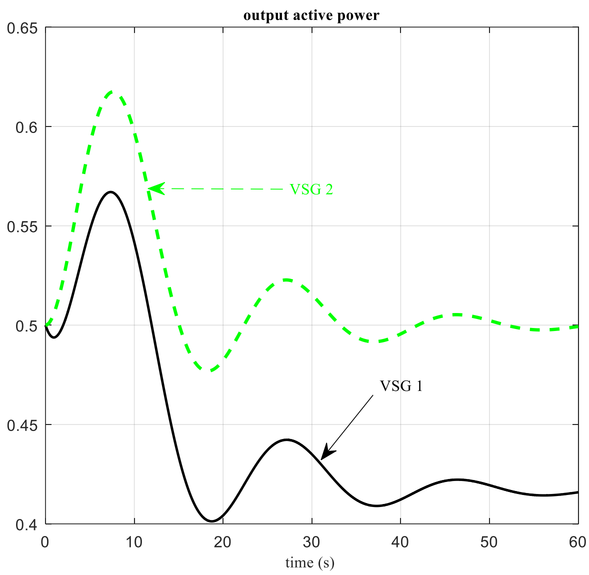

Fig. 7 Changes in the output electrical power for step changes in the consumed load with different inertia coefficients

In addition, the angular velocity of the virtual rotor in the steady state is the same for both step changes.

Case 2- In this case, the inertia value is considered the same for both VSGs, but the damping coefficient of VSG2 is greater than VSG1. Figs. (8) and (9) show the changes in the angular velocity of the virtual rotor and the changes in the output electrical power for changes in the consumed load.

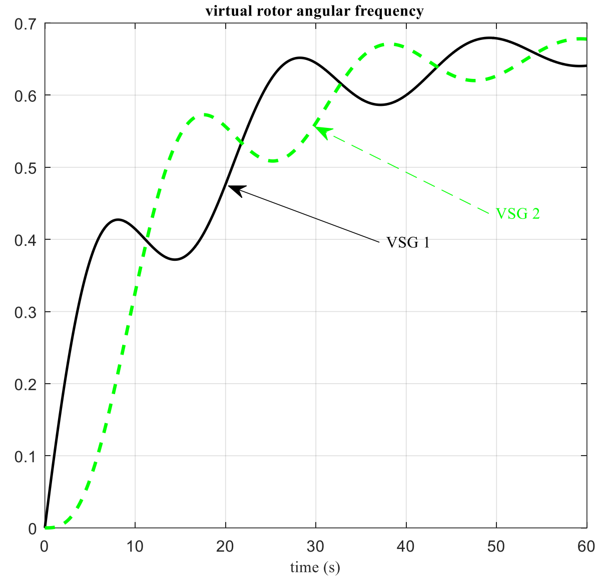

Fig. 8 Changes in the angular velocity of the virtual rotor for step changes in the active power reference 1 with different damping coefficients

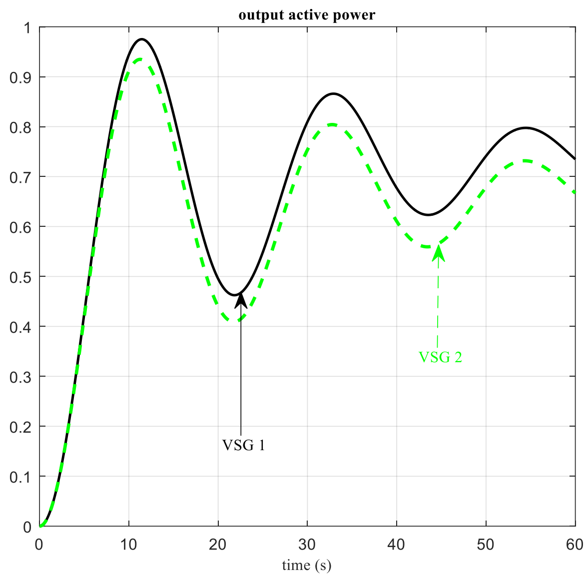

Fig. 9 Changes in the electrical power for step changes in the active power reference 1 with different damping coefficients

The system modes in this case are -0.0755 and -0.0372±j0.2908, which indicate the stability of the system. The oscillation mode is closer to the real and imaginary axes than before. As can be seen, the response time is slower than before.

5- Conclusion

The widespread integration of renewable energy sources into power systems has led to the supply of the increasing energy demand and the reduction of environmental problems. The separation of resources from the consumption loads, due to the use of power electronic inverters, reduces the inertia of power systems. The lack of inertia is one of the negative characteristics of microgrids based on renewable energy sources with power electronic converters, because it has a negative impact on the dynamic performance of the microgrid, which can cause instability and loss of coordination. The virtual synchronous generator is one of the most popular solutions for increasing the inertia of a microgrid. Inverter-based distributed generation sources, having the characteristics of a synchronous generator, can be used in the control and stability of the microgrid.

In this paper, parallel connection of virtual synchronous generators in microgrid system is studied. Small signal model is determined using linearized equations of the system. Dynamic performance of parallel VSGs can be different due to different virtual inertia possibilities. Simulation results for different moment of inertia and different damping coefficients of the system behavior are shown. Virtual synchronous generator with high inertia needs a long time to respond to load changes, but with smaller inertia the response is faster.

References

[1] Mesrinejad, F., Yaghoubi, S., Fani, B. (2022). Secondary frequency control for improved dynamic performance in interconnected power system. *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, 14(3), 47-54.

[2] Babaei, M., Jahangiri, M., Raeiszadeh, F., Aboutalebi, G.R., Jafari, A., Nariman, A. (2023). The feasibility of using solar heating in the Yazd hospital: A case study. *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, 15(2), 17-28.

[3] Fathollahi, A., Andresen, B. (2024). Deep deterministic policy gradient for adaptive power system stabilization and voltage regulation. *e-Prime- Advances in Electrical Engineering, Electronics and Energy*, 9, 100675.

[4] Shahgholian, G. (2020). An overview of hydroelectric power plant: Operation, modeling, and control. *Journal of Renewable Energy and Environment*, 7(3), 14-28.

[5] Wang, Z., Meng, F., Zhang, Y., Wang, W., Li, G., Ge, J. (2023). Cooperative adaptive control of multi-parameter based on dual-parallel virtual synchronous generators system. *IEEE Trans. on Energy Conversion*, 38(4), 2396-2408.

[6] Ghahramani, M., Heris, M.N., Zare, K., Ivatloo, B.M. (2016). Incorporation of demand response programs and wind turbines in optimal scheduling of smart distribution networks: A case study. *International Journal of Smart Electrical Engineering*, 5(4), 199-206.

[7] Mohamed, M.M., Zoghby, H.M., Sharaf, S.M., Mosa, M.A. (2022). Optimal virtual synchronous generator control of battery/supercapacitor hybrid energy storage system for frequency response enhancement of photovoltaic/diesel microgrid. *Journal of Energy Storage*, 51, 104317.

[8] Mortazi, A., Saeed, S., Akbari, H. (2023). Optimizing operation scheduling in a microgrid considering probabilistic uncertainty and demand response using social spider algorithm. *International Journal of Smart Electrical Engineering*, 12(2), 113-125.

[9] Hosseinipour, A., Hojabri, H. (2018). Virtual inertia control of PV systems for dynamic performance and damping enhancement of dc microgrids with constant power loads. *IET Renewable Power Generation*, 12(4), 430-438.

[10] Zhang, P., Zhao, H., Cai, H., Shi, J., He, X. (2016). Power decoupling strategy based on 'virtual negative resistor' for inverters in low-voltage microgrids. *IET Power Electronics*, 9(5), 1037-1044.

[11] Zhang, B., Yan, X., Li, S., Zhang, X., Han, J., Xiao, X. (2018). Stable operation and small-signal analysis of multiple parallel DG inverters based on a virtual synchronous generator scheme. *Energies*, 11(1), 203.

[12] Jaklair, L., Yesuratnam, G., Sarma, P. (2024). Control algorithm for renewable energy

standalone system with power quality and demand management. *Majlesi Journal of Electrical Engineering*, 18(1), 311-322.

[13] Suvorov, A., Askarov, A., Ruban, N., Rudnik, V., Radko, P., Achitaev, A., Suslov, K. (2023). An adaptive inertia and damping control strategy based on enhanced virtual synchronous generator model. *Mathematics*, 11(18), 3938.

[14] Cheema, K.M., Mehmood, K. (2020). Improved virtual synchronous generator control to analyse and enhance the transient stability of microgrid. *IET Renewable Power Generation*, 14(4), 495-505.

[15] Salama, H.S., Bakeer, A., Magdy, G., Vokony, I. (2021). Virtual inertia emulation through virtual synchronous generator based superconducting magnetic energy storage in modern power system. *Journal of Energy Storage*, 44, 103466.

[16] Shahgholian, G., Ebrahimi-Salary, M. (2012). Effect of load shedding strategy on interconnected power systems stability when a blackout occurs. *International Journal of Computer and Electrical Engineering*, 4(2), 212-216.

[17] Shahgholian, G., Moazaami, M., Honarvar, M.A. (2024). Small signal stability analysis of dynamic behavior of gas turbine power plant with secondary control loop in electric power system. *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, 16(1), 23-35.

[18] Fathollahi, A., Andresen, B. (2024). Enhancing transient stability in multi-machine power systems through a model-free fractional-order excitation stabilizer. *Fractal and Fractional*, 8(7), 419.

[19] Shahgholian, G., Moazzami, M., Dehghani, M. (2025). A brief review of the application and control strategies of alternating current microgrids in the power system. *Technovations of Electrical Engineering in Green Energy System*, 4(2), 17-34.

[20] P. Saxena, N. Singh, A.K. Pandey, "Enhancing the dynamic performance of microgrid using derivative controlled solar and energy storage based virtual inertia system", Journal of Energy Storage, vol. 31, Article Number: 101613, Oct. 2020.

[21] Wu, W., Chen, Y., Luo, A., Zhou, L., Zhou, X., Yang, L. (2017). A virtual inertia control strategy for dc microgrids analogized with virtual synchronous machines. *IEEE Trans. on Industrial Electronics*, 64(7), 6005-6016.

[22] Zheng, F., Su, M., Liu, B., Liu, W. (2023). Adaptive virtual inertia control strategy for a grid-connected converter of dc microgrid based on an improved model prediction. *Symmetry*, 15(11), 2072.

[23] Lu, S., Zhu, Y., Dong, L., Na, G., Hao, Y., Zhang, G., Zhang, W., Cheng, S., Yang, J., Sui, Y. (2022). Small-signal stability research of grid-connected virtual synchronous generators. *Energies*, 15(19), 7158.

[24] Suvorov, A., Askarov, A., Bay, Y., Maliuta, B., Achitaev, A., Suslov, K. (2023). Comparative small-signal stability analysis of voltage-controlled and enhanced current-controlled virtual synchronous generators under weak and stiff grid conditions. *International Journal of Electrical Power and Energy Systems*, 147, 108891.

[25] Rajaguru, V., Annapoorani, K.I. (2023). Virtual synchronous generator based superco-nducting magnetic energy storage unit for load frequency control of micro-grid using african vulture optimization algorithm. *Journal of Energy Storage*, 65, 107343.

[26] Alipoor, J., Miura, Y., Ise, T. (2015). Power system stabilization using virtual synchronous generator with alternating moment of inertia. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 3(2), 451-458.

[27] Ding, X., Cao, J. (2024). Deep and reinforc-ement learning in virtual synchronous gener-ator: A comprehensive review". *Energies*, 17(11), 2620.

[28] Zheng, T., Chen, L., Guo, Y., Mei, S. (2018). Comprehensive control strategy of virtual syn-chronous generator under unbalanced voltage conditions. *IET Generation, Transmission and Distribution*, 12(7), 1621-1630.

[29] Fang, J., Tang, Y., Li, H., Li, X. (2018). A battery/ultracapacitor hybrid energy storage system for implementing the power managem-ent of virtual synchronous generators. *IEEE Trans. on Power Electronics*, 33(4), 2820-2824.

[30] Wang, R., Chen, L., Zheng, T., Mei, S. (2017). VSG-based adaptive droop control for frequ-ency and active power regulation in the MTDC system. *CSEE Journal of Power and Energy Systems*, 3(3), 260-268.

[31] Hlaing, H.S., Liu, J., Miura, Y., Bevrani, H., Ise, T. (2019). Enhanced performance of a stand-alone gas-engine generator using virtual synchronous generator and energy storage system. *IEEE Access*, 7, 176960-176970.

[32] Rathore, B., Chakrabarti, S., Srivastava, L. (2021). A self-regulated virtual impedance control of VSG in a microgrid. *Electric Power Systems Research*, 197, 107289.

[33] Wang, H., Yang, C., Liao, X., Wang, J., Zhou, W., Ji, X. (2023). Artificial neural network-based virtual synchronous generator dual droop control for microgrid systems. *Computers and Electrical Engineering*, 111, 108930.

[34] Liang, J., Fan, H., Cheng, L., Rong, S., Li, T., Yu, T., Wang, L. (2024). Control strategy for improving the frequency response characteristics of photovoltaic and energy storage systems based on VSG control. *Energy Reports*, 11, 2295-2305.

[35] Jiang, W., Zhou, B. (2022). A virtual synchronous generator control strategy for microgrid based on harmonic current bypass control. *International Transactions on Electrical Energy Systems*, 1, 2516777.

[36] Liu, J., Miura, Y., Bevrani, H., Ise, T. (2017). Enhanced virtual synchronous generator control for parallel inverters in microgrids. *IEEE Trans. on Smart Grid*, 8(5), 2268-2277.

[37] Bo, Z., Xiangwu, Y., Yibin, H., Zhengnan, L., Xiangning, X. (2017). Stability control and inertia matching method of multi-parallel virtual synchronous generators. *Transactions of China Electrotechnical Society*, 32(10), 42-52.

[38] Mohamed, S.Y.A., Yan, X., Abdo, A.M.A. (2021). Parallel operation of virtual synchr-onous generators in a microgrid. *Proceeding of the IEEE/ICCCEEE*, Khartoum, Sudan, 1-6.

[39] Chen, M., Zhou, D., Wu, C., Blaabjerg, F. (2021). Characteristics of parallel inverters applying virtual synchronous generator control. *IEEE Trans. on Smart Grid*, 12(6), 4690-4701.

[40] Gao, X., Zhou, D., Anvari-Moghaddam, A., Blaabjerg, F. (2024). An adaptive control strategy with a mutual damping term for paralleled virtual synchronous generators system. *Sustainable Energy, Grids and Networks*, 38, 101308.

[41] Abou-Hussein, W.M., Dabour, S.M., Hamad, M.S., Rashad, E.M. (2023). Model predictive control based virtual synchronous generator for parallel-connected three-phase split-source converters in islanded ac microgrids. *Energy Reports*, 9, 1696-1706.

[42] Yang, Q., Yan, L., Chen, X., Chen, Y., Wen, J. (2023). A distributed dynamic inertia-droop control strategy based on multi-agent deep reinforcement learning for multiple paralleled VSGs. *IEEE Trans. on Power Systems*, 38(6), 5598-5612.

[43] Wang, Y., Chen, S., Yang, M., Liao, P., Xiao, X., Xie, X., Li, Y. (2025). Low-frequency oscillation in power grids with virtual synchronous generators: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 207, 114921.

[44] Zhou, W. Xiaosong, Z. Xufeng, Y., Wei, X. (2020). Review on virtual synchronous generator technologies. *Proceeding of the IEEE/ACDC*, 744-751.

[45] Frasetyo, M.B., Wijaya, F.D., Firmansyah, E. (2021). Review on virtual synchronous generator model and control for improving microgrid stability. *Proceeding of the IEEE/ICEES*,Chennai, India, 397-402.

[46] Liu, Y., Hao, M., He, Y., Zang, C., Zeng, P. (2019). Review and applications of virtual synchronous machines technologies. *Proceeding of the IEEE/ISGT*, Chengdu, China, 593-598.

[47] Li, H., Wang, K., Chen, Z., Peng, H., Tan, M. (2021). Parameters design in active power control of virtual synchronous generator consi-dering power-angle characteristic nonlinearity. *International Journal of Electrical Power and Energy Systems*, 130, 106952.

[48] Shadoul, M., Ahshan, R., AlAbri, R.S., Al-Badi, A., Albadi, M., Jamil, M. (2022). A comprehensive review on a virtual-synchr-onous generator: topologies, control orders and techniques, energy storages, and applications. *Energies*, 15(22), 8406.

[49] Li, J., Wen, B., Wang, H. (2019). Adaptive virtual inertia control strategy of VSG for micro-grid based on improved bang-bang control strategy. *IEEE Access*, 7, 39509-39514.

[50] Sang, W., Guo, W., Dai, S., Tian, C., Yu, S., Teng, Y. (2022). Virtual synchronous generator, a comprehensive overview. *Energies*, 15(17), 6148.

[51] Yan, X., Mohamed, S.Y.A., Li, D., Gadalla, A.S. (2019). Parallel operation of virtual synchronous generators and synchronous generators in a microgrid. *The Journal of Engineering*, 16, 2635-2642.

[52] Liu, A. Liu, J., Wu, Q. (2023). Coupling stability analysis of synchronous generator and virtual synchronous generator in parallel under large disturbance. *Electric Power Systems Research*, 224, 109679.

[53] Cheema, K.M. (2020). A comprehensive review of virtual synchronous generator. *International Journal of Electrical Power and Energy Systems*, 120, 106006.

[54] Fani, B., Shahgholian, G., Alhelou, H.H., Siano, P. (2022). Inverter-based islanded mic-rogrid: A review on technologies and control. *e-Prime- Advances in Electrical Engineering, Electronics and Energy*, 2, 100068.

[55] Awda, Y., Alowaifeer, M. (2024). Adaptive optimization of virtual synchronous generator based on fuzzy logic control and differential evolution. *Ain Shams Engineering Journal*, 15(4), 4, 102606.

[56] Shi, T., Sun, J., Han, X., Tang, C. (2024). Research on adaptive optimal control strategy of virtual synchronous generator inertia and damping parameters. *IET Power Electronics*, 17(1), 121-133.

[57] Chen, J., O'Donnell, T. (2019). Analysis of virtual synchronous generator control and its response based on transfer functions. *IET Power Electronics*, 12(11), 2965-2977.

[58] Yang, D.Q., Li, M.J., Ma, T., Ni, J.W., Han, Z.Y. (2025). Study on adaptive VSG parameters and SOC control strategy for PV-HESS primary frequency regulation. *Energy*, 314, 133909.

[59] Serban, I., Ion, C.P. (2017). 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*, 89, 94-105.

[60] Ren, B., Li, Q., Fan, Z., Sun, Y. (2023). Adaptive control of a virtual synchronous generator with multiparameter coordination. *Energies*, 16(12), 4789.