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Analysis of voltage and frequency stability of electric power system network with photovoltaic-based generation penetration

Rusilawati[1,*], Irfan[2], Gusti Eddy Wirapratama[3], Istiyo Winarno[4]
[1,3]Teknik Elektro, Universitas Islam Kalimantan Muhammad Arsyad Al Banjari
[2,4]Teknik Elektro, Universitas Hang Tuah
[1,3]Jl. Adhyaksa, No. 2, Kayutangi, Banjarmasin 70124, Indonesia
[2,4]Jl. Arif Rahman Hakim, No. 150, Keputih, Surabaya 60111, Indonesia
[*]Corresponding email: habsyi.sila@gmail.com

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Abstract — The operation of distributed generation with renewable energy sources integrated with distribution networks through microgrids poses challenges in terms of operation and control. The drastic increase in the use of distributed generation creates problems in the form of voltage and frequency stability that will be disturbed due to rapid changes in generation and loading levels. If this condition is left unchecked, it could harm system security and reliability in terms of voltage and frequency stability which will be disrupted because of frequent variations in power production and loading levels. This study investigates voltage and frequency stability in microgrids because of the penetration of distributed generation with photovoltaic renewable energy sources in the power system using the virtual synchronous generator control technique. The virtual synchronous generator is a control alteration that enhances the capabilities of the power system so that voltage and frequency stability can be preserved and improved. The virtual synchronous generator control method with additional damping controllers that increase inertia with additional virtual inertia is used to simulate the speed of restoration of voltage and frequency stability of the power system due to the penetration of photovoltaic-based power plants. The simulation results show that at the time of penetration of photovoltaic-based power plants in the power system, there is a momentary instability in voltage and frequency, but it is immediately dampened by virtual synchronous generator control and can be quickly restored so that the stability of voltage and frequency is maintained.

Keywords – distributed generator, renewable energy, voltage stability, frequency stability, virtual synchronous generator control

I. INTRODUCTION

The demand for electrical energy is increasing quickly in accordance with growth in the economy. In the development of electric power systems, electric energy service providers are required to be able to supply electrical energy on demand with good quality. Because conventional energy resource reserves, especially fossil fuel, are rapidly diminishing, power generation utilizing renewable energy resources has become one of the most exciting issues to research in recent years. Furthermore, traditional fossil fuels emit a high level of pollution and contribute to an increase in the Glasshouse effect. Renewable energy sources include wind, solar, and clean water-based power generating sources, on the other hand, are pollution-free. These problems lead to a new trend of electrical energy generation at the distribution level using non-conventional/renewable energy generation such as wind power, solar cells, fuel cells, mini-hydro, and others. Therefore, fuels with renewable energy-based energy sources can replace conventional fossil fuels for power generation such as oil, coal, and natural gas [1].

Clean and fast-growing renewable energy sources have considerable availability and are not costly [2]. However, the uncertain nature of renewable energy sources poses challenges regarding operation and control when integrated with existing grids. If left uncontrolled, this can have a negative impact on the security and reliability of the system [3], [4]. The increased penetration of variable generation into power system management and control has a significant impact on frequency control. Because renewable energy sources inject uncertainties into the power system, a greater spinning reserve is required to adjust for generation and demand imbalances [5]–[7].

The usage of Distributed Generation (DG) can improve overall system efficiency, minimize transmission losses, decrease pollution, and assure the continued operation of electrical energy distribution. However, the drastic increase in the use of DG creates problems in the form of voltage and frequency stability that will be disturbed due to rapid changes in generation and loading levels [8], [9]. In the case of an imbalanced condition, a proper control approach can recover the stability of the system. In operation, DG is linked to the distribution network via a microgrid.

In the research conducted on reference [8], [10] the control scheme for microgrids based on droop control is discussed. However, in contrast to Synchronous Generators (SGs), droop control-based DGs still lack inertia, which is adversely affecting the frequency dynamics [9]. To overcome the lack of inertia, a control technique that effectively generates virtual inertia and damping through an electronic inverter is developed. The development of electronic inverters based on special control techniques is called Virtual Synchronous Generator (VSG) [11]–[13]. During disturbances, the VSG inertia constant could dampen frequency oscillations. To improve frequency stability, a damping coefficient and inertia constant adaption control are used [14], [15]. The VSG may operate in both grid-connected and islanded modes. The VSG experiences various stability issues during power system or microgrid disturbances, depending on the nature of the disturbance [16]–[18].

The stability of voltage and frequency in the event of penetration of power plants with PV sources in the power system network must be controlled. In this study, the authors proposed the Virtual Synchronous Generator (VSG) control technique with an additional damping controller. This proposed method could increase inertia which impacts the stability of voltage and frequency of the systems. The VSG control approach is used in simulations to assess the recovery rate of voltage and frequency stability of the power system according to the penetration of PV-based power plants.

II. RESEARCH METHODS

This section discusses distributed generation, microgrid, virtual synchronous generator, structure of the VSG, VSG control operation, and VSG for PV system.

A. Distributed Generation

The term ”distributed generation” (DG) refers to a small-scale power-producing technology positioned near load centers. The DG energy sources could be classified as renewable (wind, solar, hydro, biomass) or non-renewable (diesel, steam, fuel cell). Because of its distributed location, DG can be connected with the distribution system to meet the load demand. The advantages of DG technology include improving the voltage profile and efficiency of electric power distribution. However, the addition of DG can also have a negative impact on frequency and voltage due to rapid changes in generation levels when disturbances occur [8].

B. Microgrid

A microgrid is a unified control consisting of several DGs and interconnected loads. Microgrids can operate through two modes of operation, namely grid-connected and disconnected from the main grid, namely islanding [8], [19]. The goal of microgrids is to deliver electric power sustainably, economically, and safely with intelligent monitoring, control, and recovery technologies [20].

Microgrids integrate with power systems and information systems, having the capability of delivering electrical power back to the larger network during failures in the grid or power outages. Microgrid networks are more sensitive due to the lack of inertia, so when load changes occur, frequency deviations can result, which can degrade the stability of the microgrid [17].

C. Virtual Synchronous Generator

DG is based on renewable energy sources connected to the main power system through electronic inverters [21]. Compared to normal synchronous generation, the electronic inverter responds quickly, and the control is quite flexible. In the case of a disturbance, synchronous generators offer the required inertia and damping for stabilizing the power system. Electronic inverters, on the other hand, lack inertia and damping properties. The absence of inertia and damping in electronic inverters causes severe stability problems when a fault or disturbance occurs [11], [16].

Addressing the disadvantage of these electronic inverters [22], a special control technique was developed that effectively generates virtual inertia and damping through an electronic inverter. Virtual Synchronous Generator (VSG) is an electronic inverter with a specific control technique. VSG was designed to duplicate the dynamic behaviors of a synchronous generator. VSG functions, however, have restrictions, such as fluctuations in active and reactive power regulation and rapid frequency variations. VSGs are more adaptable and simpler to operate than synchronous generators. VSG characteristics can be modified in real time, providing greater flexibility than synchronous generators.

VSGs are designed to integrate and enhance the stability of power systems based on renewable energy sources. A simple VSG, however, cannot ensure the stability of renewable energy source-based electric power systems. Hence, various modifications and refinements are made in VSG control to improve the stability of the system [13].

D. Structure of the VSG

Fig. 1 depicts the DG's block diagram, which includes the VSG structure. In Fig. 2 the simple structure of a VSG can be seen.

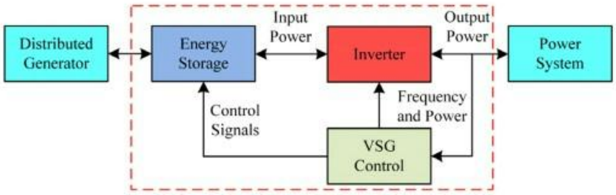

Fig. 1. Distributed Generator's Block Diagram including VSG structure.

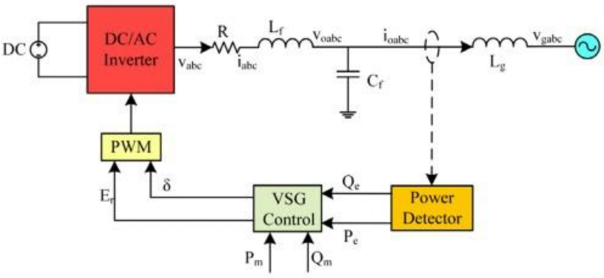

Fig. 2. Simple structure of the VSG.

VSG consists of DG unit, energy storage, DC/AC converter, filter circuit, governor, and grid [11], [16]. While the electricity from the DG and storage of energy is supposed to represent the prime mover's input torque, the DC/AC converter is believed to be an electromechanical energy transformer connecting the stator and rotor. The fundamental component of the electrical voltage midpoint thus represents the electromotive force of the VSG. The value of the resistance and inductance of the filtering unit indicates the impedance of the stator winding.

According to Fig. 2, V_{abc} dan i_{abc} are the inverter's alternating current side voltage and current, respectively. V_{oabc} dan i_{oabc} are the LC filter voltage and current, V_gabc is the grid voltage. While R, L_f and C_f are filter resistance, inductance, and capacitance, respectively. L_g is the gridline inductance, E and δ are the internal potential amplitude and phase angle of the VSG, V and θ are the voltage amplitude and phase angle of the VSG terminals. P_e, P_m, Q_e, and Q_m is the active power and reactive power generated by the VSG.

VSGs are typically installed between distributed sources of energy and electrical power systems, as seen in Fig. 1. As a result, specific control mechanisms that imitate the electromagnetic and mechanical movements of a synchronous generator are an important aspect of VSG development. It is also in charge of active power and frequency modulation, as well as reactive power and voltage management.

The simple swing equation of the SG is used as the core part of the VSG, as described in (1).

$$J\frac{d\omega}{dt} = T_m - T_c - D(\omega - \omega_t)\frac{d\delta}{dt} = \omega \qquad (1)$$

where ω is virtual angular frequency, ω_r is reference angular frequency, T_m is mechanical torque, T_e is electromagnetic torque, δ is power angle, D is damping coefficient, and J is moment of inertia of the rotor.

The electrical formulation of the synchronous generator's stator is simulated without taking consideration of the electromagnetic connectivity between the stator and rotor while modeling the electromagnetic features of SG for VSG, and can be expressed in (2).

$$L_f\frac{di_{abc}}{dt} = e_{abc} - V_{abc} - Ri_{abc} \qquad (2)$$

The active power loop of the VSG simulates the SG's main frequency regulation, damping, and inertia to determine the reference phase and frequency of the modulated signal. The reactive power loop, which simulates the voltage regulation of the SG, calculates the modulating signal amplitude. The VSG is built around the general and basic swing equation of the SG, and is expressed in (3).

$$P_m - P_e = 2J\frac{d\omega}{dt} - D(\omega - \omega_t) \qquad (3)$$

where P_m is inverter input power and P_e is inverter output power.

The coefficient of virtual damping was crucial in keeping the VSG's speed equal to the grid frequency. Eq. (4) describes the mathematical formulas for the VSG's active power loop, which includes the VSG fundamental governor.

$$J\frac{d\omega}{dt} = \frac{P_m}{\omega} - \frac{P_e}{\omega} - D(\omega - \omega_t) \qquad (4)$$

The mathematical equation for the VSG reactive power loop can be expressed in (5).

$$K\frac{dE_r}{dt} = Q_m - Q_e + k_q(V_r - V) \qquad (5)$$

where K is inertia coefficient of reactive power - voltage of the reactive power loop, E_r is virtual electromotive force, Q_m is reactive power reference, Q_e is reactive power output, K_q is eactive power coefficient-voltage droop, V is output voltage amplitude, and V_r is voltage amplitude rating.

E. VSG Control Operation

The input/output control of VSG is attained by the corresponding working mechanism of the inverter on its interface. The control method is the joint control of active and reactive power control, voltage and frequency control, and droop control. In general, the strategy of applying control to the system depends on the type of operation of the power system.

The characteristics of the inverter and VSG are almost the same, the only difference is that the VSG replicates the characteristics of the SG through its control algorithm and has the further benefit of additional virtual inertia to the system [17]. There are two classifications of VSG control algorithms: active and reactive power control and voltage and frequency control.

The VSG's active and reactive power loops are depicted in Fig. 3. The active power-frequency control strategy is represented in Fig. 4, and the reactive power-voltage control approach is depicted in Fig. 5.

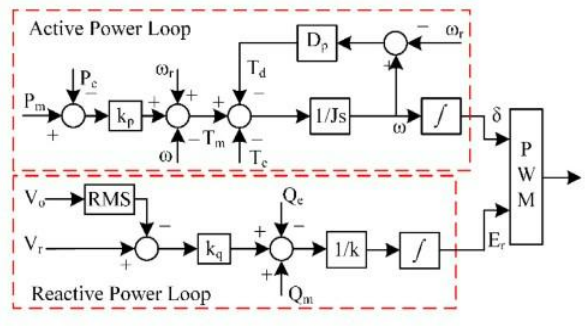

Fig. 3. Active power and reactive power loops of the VSG.

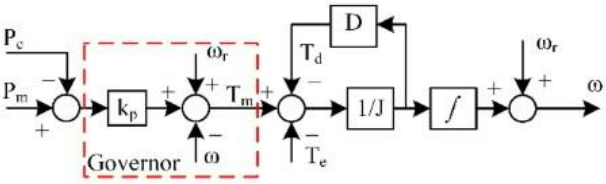

Fig. 4. VSG structure for active power and frequency control with simple governor.

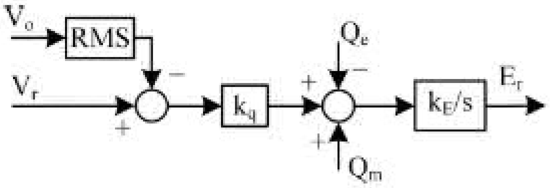

Fig. 5. VSG control for reactive power and voltage control.

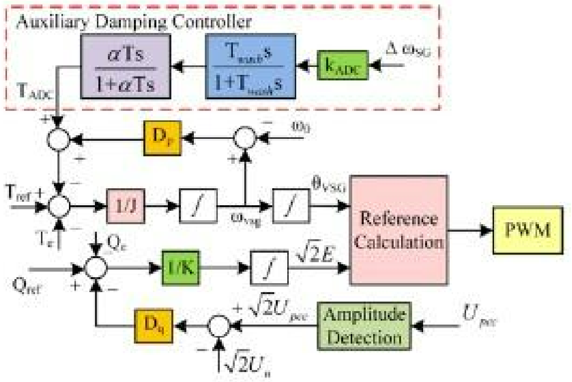

Fig. 6. VSG with additional damping control.

Currently, most VSG control techniques utilize active power and active reactive power control methods due to their simplicity [11], [16], [23]. The advantage of this method is the ability to distribute active power according to its capacity when the VSG is operated in parallel. When operating in the grid connection model, the reactive power controller unit failed to meet the power demand, so an additional unit is needed to increase the reactive power controller functions. Thus, it can provide the desired reactive power supply to the system.

Furthermore, as compared to active power management, reactive power control can easily be impacted by line impedance, load variations, and other factors, causing control results to depart from the needed characteristics and, eventually, leading to reactive power distribution inaccuracy. To suppress the impedance and load fluctuation effects, various control modifications are introduced. For example, adaptive parameter estimation and selection techniques, and virtual impedance control methods to reduce output voltage. These techniques effectively control and get a better effect for VSG reactive voltage control.

1) Frequency control - active power

According to (3), active power control could be accomplished by adjusting the frequency change. To suppress frequency fluctuations, the DG can modify its reference power in response to frequency changes. The damping unit, contrary, causes the DG to decrease oscillation.

2) Voltage control - reactive power

The reactive power-voltage control structure is equivalent to the traditional SG control system. The value of K_q determines the characteristics of reactive power-voltage gain. According to (5), reactive power is gradually managed by reducing its impact on the system under specific situations. This control loop incorporates proportional and integral controllers, which control the output voltage based on the changed reference value. It should be mentioned that the primary elements for replicating the SG characteristics are the energy storage system and the electronic inverter. In addition, an extra damping controller is used to inhibit the system's frequency oscillation. Fig. 6 depicts the VSG with an additional damping control.

F. VSG for PV system

Distributed power sources, such as PV are mostly connected to the power distribution grid through electronic inverters [24]. In general, PV power systems are categorized as low-voltage and medium-voltage distribution power systems. When multiple PV power systems are connected to each other or to the grid, there will be special difficulties on the power quality and stability of the power system [1], [11].

Particularly, the VSG of a PV power system can demonstrate a frequency dynamic response similar to that of the SG. However, unlike the SG, the power converter is not able to absorb/deliver any kinetic energy, thus requiring an extra energy storage system. Therefore, it is required the implementation and coordination of energy storage system control in the VSG of PV power systems.

Fig 7 shows the application of VSG in a distributed power system with RE. The grid-connected PV through DC/DC converter with MPPT and energy storage system is illustrated in Fig. 8 [1], [25]. The MPPT mode controls the PV to maximize the power output. The energy storage system is applied to smoothen the active power output and reduce the negative impact on the grid.

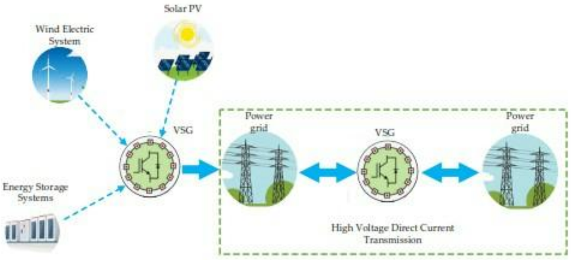

Fig. 7. VSG application on distributed power system with RE.

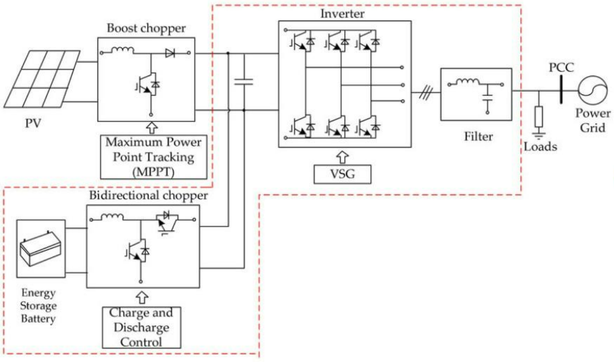

Fig. 8. Solar PV system with MPPT and energy storage system.

III. RESULT

To investigate the effect of VSG control on voltage and frequency stability during the penetration of PV-based systems in the power system, simulations were made using MATLAB/SIMULINK. In Fig. 9 and Fig. 10, it can be seen the voltage and frequency response of the grid when PV penetration occurs in the system.

In Fig. 11 and Fig. 12, voltage and frequency responses of the grid can be clearly depicted when PV penetration occurs, and load is applied.

In Fig. 13 and Fig. 14, it can be seen the voltage and frequency response of the grid during PV penetration in the system with VSG and without inertia.

In Fig. 15 and Fig. 16, it can be seen the voltage and frequency response of the grid when PV penetration occurs in a system with VSG and inertia.

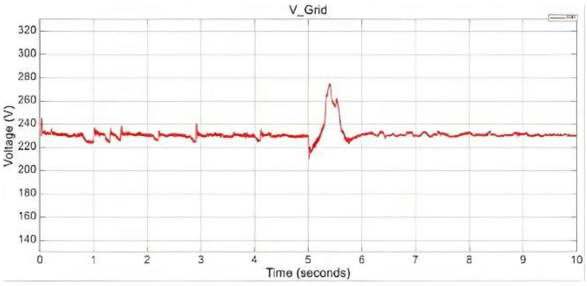

Fig. 9. Grid voltage response during PV penetration.

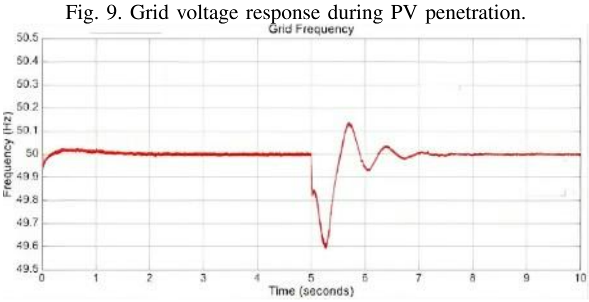

Fig. 10. Grid frequency response during PV penetration.

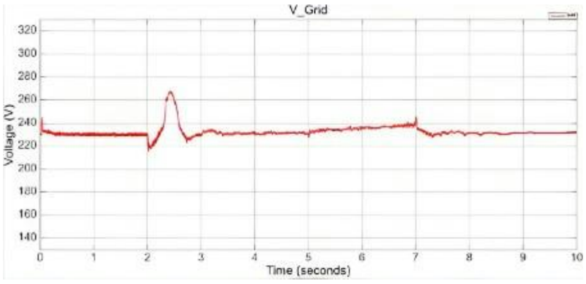

Fig. 11. Grid voltage response during PV penetration and load addition

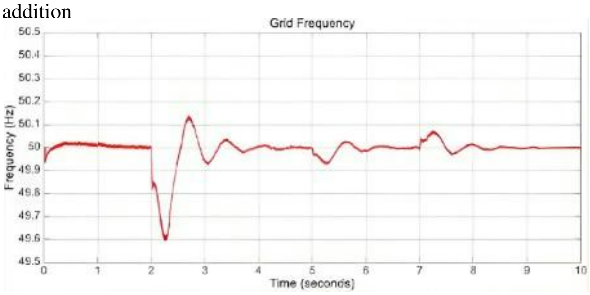

Fig. 12. Grid frequency response during PV penetration and load addition.

IV. DISCUSSION

In the research conducted on reference [8], [10], the control scheme for microgrid based on droop control is discussed. However, in contrast to Synchronous Generators (SGs), droop control based DGs still lack inertia, adversely affecting the frequency dynamics. Using VSGs with additional damping controllers that can increase inertia with additional virtual inertia has been proven to reduce voltage and frequency fluctuations caused by the penetration of PV sources in the power system.

From Fig. 9 and Fig. 10, it can be observed the voltage and frequency response of the grid when PV penetration occurs in the system. At the 5th second, the amplitude of voltage and frequency were affected significantly, instability condition, by the penetration of the PV.

From Fig. 11 and Fig. 12, voltage and frequency responses of the grid can be clearly depicted when PV penetration occurs, and load is applied. At the 2nd

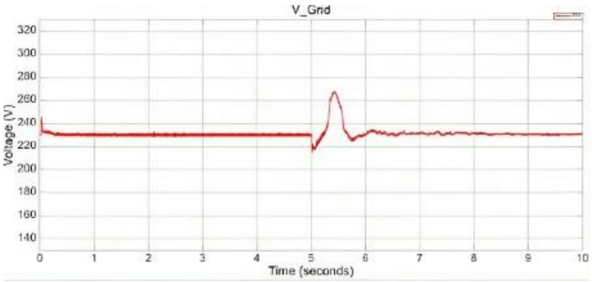

Fig. 13. Grid voltage response during PV penetration with VSG and without inertia.

Fig. 14. Grid frequency response during PV penetration with VSG and without inertia.

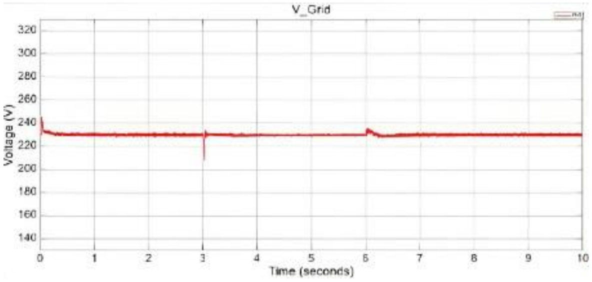

Fig. 15. Grid voltage response during PV penetration with VSG and inertia.

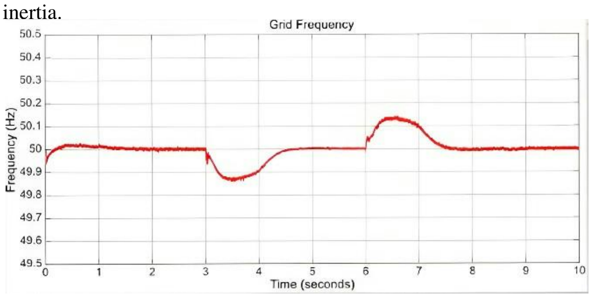

Fig. 16. Grid frequency response during PV penetration with VSG and inertia.

second, as the result before, the amplitude of voltage and frequency fluctuated during the penetration. At the 5th and 7th second, the load connected to the system. This load addition also affected the amplitude of voltage and frequency, out from stability condition.

From Fig. 13 and Fig. 14, the voltage and frequency response of the grid during PV penetration in the system with VSG and without inertia can be observed. Although VSG has been added to the system, the voltage and frequency still fluctuate, as be seen in the 5th second. Combining PV penetration with VSG can provide active voltage control and help mitigate voltage fluctuations caused by intermittent PV generation. On the other hand, the absence of inertia can make the grid voltage response more sensitive to changes in power injections.

Fig. 15 and Fig. 16, illustrate the voltage and frequency reaction of the grid when PV penetration occurs in a system with VSG and inertia. The voltage and frequency fluctuations caused by PV penetration are well dampened, as depicted at the 3rd and 5th seconds. This occurs due to the addition of VSG with inertia. The proposed method could stabilize the fluctuating voltage and frequency during the PV penetration.

V. CONCLUSION AND FUTURE WORK

This research introduced the Virtual Synchronous Generator (VSG) control technique with an additional damping controller. The VSG control can provide additional virtual inertia to control the stability of voltage and frequency during the penetration of PV-based power plants into the power system network. The results showed that during the penetration of PV-based power plants into the power system, there was a momentary instability in voltage and frequency. However, by implementing VSGs and inertia-enhancing technologies, PV penetration can be managed more effectively, enabling smoother grid integration, and maintaining grid stability, both in terms of voltage and frequency. Hence, the stability of voltage and frequency was well-maintained.

In future works, the authors will develop advanced control techniques for VSGs, such as the Hybrid PI-Fuzzy control method, which hopefully could duplicate the inertia and damping behavior of synchronous generators more precisely. The challenging thing in the research is the investigation of how these control strategies can be optimized to address both short-term frequency stability and longer-term voltage stability.

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