Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 6, December 2025, pp. 4279~4289
ISSN: 2302-9285, DOI: 10.11591/eei.v14i6.9733

Influence of installing a virtual synchronous generator control on Lombok Island power grid with high penetration of PV plants

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Article Info

Article history:

Received Dec 17, 2024
Revised Oct 1, 2025
Accepted Oct 14, 2025

Keywords:

Clean energy technology
Dynamic stability
Indonesia
Photovoltaic
Virtual synchronous generator

ABSTRACT

Indonesia is a country with several islands, and providing clean energy in islanded power systems connected to a single main grid would be economy challenging. On the other hand, absence of inertia, system strength, and damping value in islanded power systems due to inverter interfaced renewable energy (RE) resources can cause significant decline of power system stability. The primary concern with integrating large scale photovoltaic (PV) power plant in an islanded power system is maintaining frequency and voltage stability. This research investigates the application of virtual synchronous generator (VSG) in Lombok's Islanded power system, considering high penetration of PV. A thorough time domain simulation is performed with a detailed modelling of power system in Lombok Island to study the dynamic voltage and frequency stability. The simulation results show that the VSG improves both frequency and voltage stability in transient and steady state stages, ensuring smoother operation and faster stabilization time. It is found that the frequency deviation can be curtail up to 0.5% and the steady state can be increased up to 0.1%.

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1. INTRODUCTION

Lombok is part of Indonesia's West Nusa Tenggara province, which has immense renewable energy (RE) potential due to its abundant natural resources. But apparently, Lombok is still relying on diesel-powered generators, steam power plants, and gas-fired power plants for its electricity, where *Perusahaan Listrik Negara* (PLN) plays a major role as an electricity supplier. Accounted in 2021, the electricity consumption in Lombok accounted for 1,603 GWh. Meanwhile, based on the data published by the Minister of Energy and Mineral Resources of the Republic of Indonesia, by 2021, the installed capacity of solar energy was only 20.82 MW and the capacity of micro hydro was 15.95 MW [1].

According to the primary data source released by *Badan Pusat Statistik* (BPS), electricity demand in Lombok is projected to increase rapidly to 4,745 GWh by 2030, with an annual growth rate of 7.2% [1]. In response, the Indonesian government has prioritized the expansion of renewable energy sources (RESs) to meet future demand. Referring to the National Energy Plan, West Nusa Tenggara is obligated to establish a regional energy plan (RUED) to create a shared vision of energy priorities and RESs target goals.

With a predicted annual growth rate of 2-3%, the RUED aims to integrate 35% of RESs into the power system of West Nusa Tenggara by 2025 and 50% of RESs by 2050 [2]. However, the rising integration of photovoltaic (PV) and wind generation at the distribution Lombok's grid level caused frequency and voltage instabilities. The reason is because the Lombok grid system operates independently and has relatively weak electrical grids. This issue has become the main reason for restricting the capacity of RES generations in Lombok to only 5 MW each. Therefore, to solve this problem while ensuring the stable operation of the Lombok power system during penetration of RESs, virtual synchronous generator (VSG) can be suggested as a solution.

The fundamental concept of VSG is discussed in [3], [4], where the primary goal of VSG is essentially to take the mathematical model used by synchronous generator (SG) and apply the SG's behaviour into the electronic inverter control loops [5]. Furthermore, in [6] the researchers integrate the swing equation into the VSG power control loop. The swing equation is a cornerstone for the VSG's operation as it helps predict how the generator will respond to power changes caused by faults and disturbances in the grid. Furthermore, references [7]-[11] suggest that power system based on power electronic interfaces can improve frequency stability because of rapid response capability of VSGs compared to conventional SGs.

Additional controllers such as virtual inertia control is essential to enhance the performance of VSG as reported in [12]. It is reported that virtual inertia can give VSG a better control signal for providing virtual inertia to the system. Research effort in [13] also shows the efficacy of virtual inertia control for enhancing the frequency response of power system. It is reported from the research that adding virtual inertia control on VSG could reduce the low inertia on the power system with renewable power generation. Essentially, VSGs offer fast frequency regulation and power equilibrium [14]. Nonetheless, this could significantly impact the inertia on frequency regulation compared with traditional power systems.

The main contributions of this research are outlined as follows: i) this paper investigates the inclusion of VSG application on the Lombok power system, while considering the high penetration of PV plants and ii) compared with the implementation of RES in the microgrid of Lombok in [15]-[17], this study provides RESs especially PVs generation system equipped with VSG control, therefore increasing the stability of the Lombok power system. The remaining parts of this paper are as follows. Section 2 describes the fundamental structure and control method of VSG and the applied method for VSG on Lombok's power system. Section 3 presents the simulation results of the PV generations (PVG) under several control scenarios in the Lombok Island. Section 4 highlights the conclusions and contributions of the research.

2. METHOD

2.1. Fundamental structure and control method of virtual synchronous generator

To address the issue of low system inertia due to the expansion of inverter based RESs penetration, the implementation of VSG has been proposed. VSG emulates characteristics of traditional SGs such as inertia and damping, thereby enhancing system resilience and stability. By adjusting their control parameters to meet operational needs, VSGs provide a flexible and effective solution for maintaining grid stability during increasing penetration of RESs [18].

Generally, the VSG system comprises several key components: energy storage system (ESS), inverter, and an appropriate control method, as depicted in Figure 1. These components are essential for virtually emulating the characteristics of a SG, including the rotor and stator actions that produce a magnetic field to generate electricity. Within the VSG, the ESS functions as a rotor, while the inverter emulates the behaviour of an SG by providing the necessary additional power based on control signals from the VSG algorithm. Moreover, the VSG manages controlling active power and frequency modulation, as well as reactive power and voltage regulation. This approach effectively supports the management of a significant portion of RESs within the current islanded microgrid infrastructure [19].

The basic principle behind VSG involves integrating the swing equation of the traditional generation into the power electronic control loops, allowing the VSG to mimic that behaviour. This modification enables the adjustment of the output frequency and power angle based on the deviation from a specified power reference. As a result, the converter can mimic the dynamic behaviour of SGs. The working method of this approach is when the occurrence of disturbance results in frequency deviations and rate of change of frequency (RoCoF) that exceed frequency operating standards justifiable limits [20].

In the implementation of VSG, the swing equation is seen as a key component which includes the damping constant (D). The equations can be written as (1):

$$P_m - P_e = \frac{2H}{f_0}\frac{d\Delta f}{dt} + D\frac{\Delta f}{f_0} \quad (1)$$

where P_m and P_e represent electrical power output of the generator and mechanical power input to the generator respectively, f_0 represents nominal frequency (Hz), and H represents inertia constant [21].

According to (1), the active power control loop in the VSG can be depicted in Figure 2. The angular frequency of VSG (ω) is equal to the reference frequency ω_{ref}, then the transfer function from ΔP_e to $\Delta\omega_{grid}$ is obtained as (2) [22]:

$$\frac{\Delta\omega_{grid}}{\Delta P_e} = -\frac{1}{H_{syn}+D_{syn}} \quad (2)$$

It can be seen from (2) that the main parts of the VSG control are virtual inertia and virtual damping. Virtual inertia value is determined using a derivative technique to measure the rate of change of frequency (RoCoF or df/dt). This technique allows the VSG to adjust inertia compensation as additional power to meet the system's setpoint during disturbances, reducing rotor speed deviation, and frequency undershoot or overshoot.

Similarly, the virtual damping control is designed to swiftly stabilize the system according to the frequency deviation calculation. The virtual damping concept is based on the damper windings in SGs, which can effectively suppress post-disturbance frequency oscillations, thereby enhancing system stability.

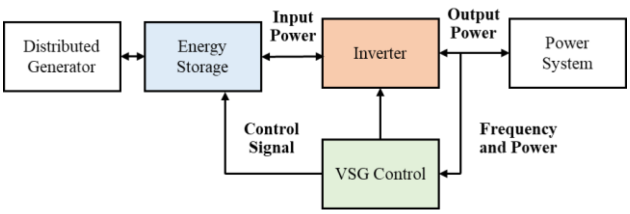

Figure 1. Block diagram of power system equipped with VSG structure

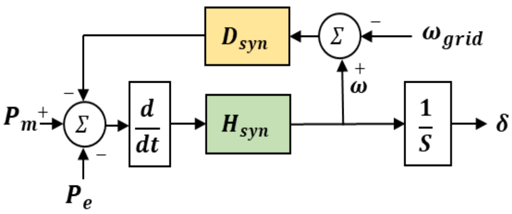

Figure 2. Active power and frequency loop control of the VSG

2.2. Dynamic modelling of virtual synchronous generator control

Within the battery energy storage system (BESS) frame controller, the VSG configuration as a frequency control is depicted in Figure 3. A frequency measurement control block consists of a phase-locked loop (PLL) which functions to detect variations in system frequency (frequency deviations) and RoCoF. When the system frequency and RoCoF occur larger than acceptable limit, the VSG's algorithm calculates the required inertia and damping value to be applied to the grid and delivers the additional power transfer using (2). In this study, the value used for virtual inertia (H_{syn}) and virtual damping (H_{syn}) were both 100. This value is based on the practical scenarios of application of VSG at rote 20 kV power system [23].

The output signal of VSG will be used as an input for PQ-control. The outputs from the PQ-control module comprise active and reactive reference currents. Noting that the illustrated topology in this study uses a direct-quadrature (d-q) based current control methodology. In d-q control, the d-axis current reference can be computed as given in (3) [24]:

$$I^{*}d = \frac{2}{3}\left(\frac{V_d P_{VSG} - V_q Q}{{V_d}^2 + {V_q}^2}\right) \quad (3)$$

In this context, V_d and V_q represent the measured grid voltage components's, along the d-axis and q-axis respectively. Because only active power is managed, the q-axis current reference Iq and the reactive power Q are designated as zero. The reference current input from PQ control will be regulated by the charge controller. The battery unit's charge controller primarily consists of limit constraint. The function of limit constraint is to avoid battery degradation caused by deep cycles of charge or discharge; therefore, the system on chip (SOC) can be kept within a tolerable range between 20%-80%. This study used LiFePO4 lithium batteries with individual cell capacity of 80 Ah. The battery power capacity used in this system accounted for 20 MW. However, the setpoint of active power can be adjusted beyond this range to reduce the output power of the battery, preventing it from making any sudden change in system. In result, the limiter can keep the battery output stable, along with the system action in avoiding abrupt changes during power shortages. Current references as the output from charge controllers are generated for the input of current controller (PWM). The current controller relies on feedback from the grid current to generate gate signals to operate the inverter.

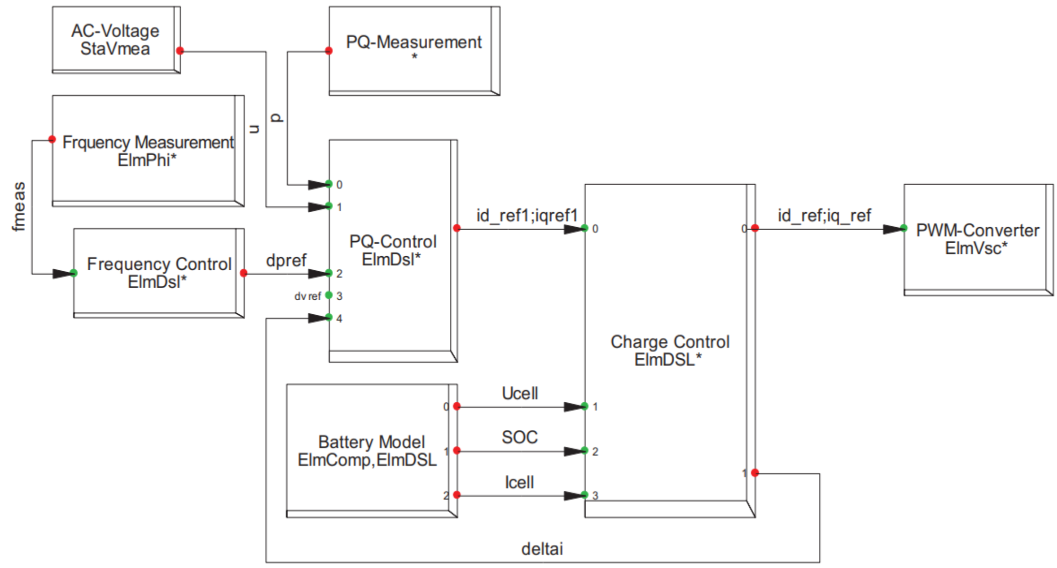

Figure 3. Block diagram of BESS frame controller

2.3. Lombok power system architecture

Originally, Lombok had a 150 kV main grid system covering the entire island, extending from Mataram to East Lombok and Tanjung. This main grid of Lombok supplied electricity to all the regencies, starting from Mataram City, West Lombok Regency, Central Lombok Regency, East Lombok Regency and lastly to North Lombok Regency [25].

Figure 4 illustrates the Lombok Island interconnected power system where some modifications have been made due to the integration of VSG into the Sengkol busbar. The power system contains various types of generation systems, and different types of loads. The main generations consist of 4 diesel power plants (PLTD), 2 microhydro power plants (PLTMH), 1 steam power plant (PLTU), and 3 PV plants. The generated energy is consumed by 9 different loads. The system has a total capacity of the PV plants for 15 MW, where each PV plant in each bus has a rating of 5 MW from the total of 15 different buses. Detailed data of Lombok power system is available on the supplementary data.

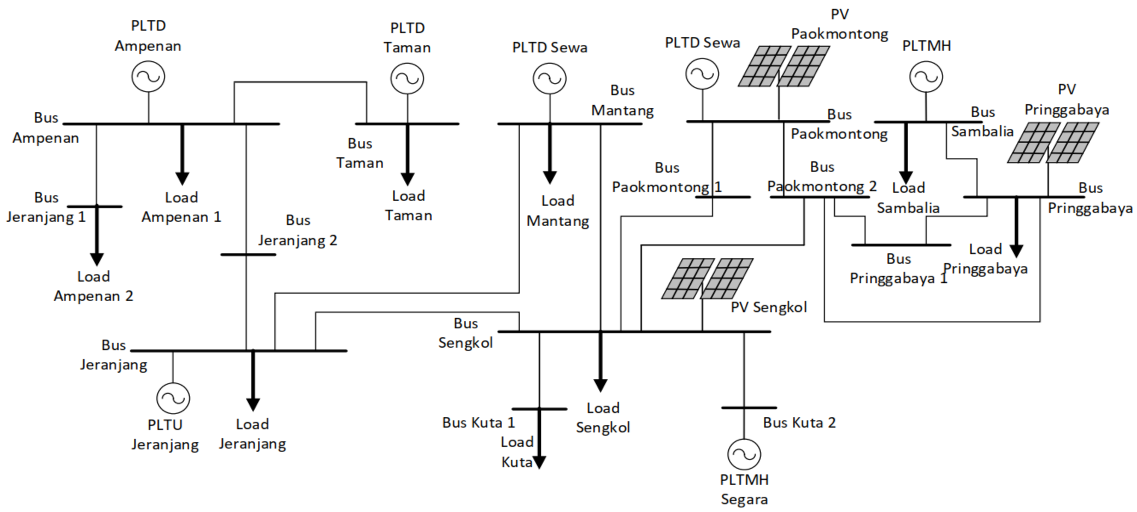

Figure 4. Lombok 150 kV network including PVG-VSG

3. RESULTS AND DISCUSSION

In this study, to validate the effectiveness of the proposed VSG control method, the Lombok power system was augmented with PVG based VSG units as shown in Figure 4. Two test the performance of VSG, two different case studies are carried out. In the first case study, the system is being exposed by the disconnecting event on Paokmotong. The second case study is investigating the performance of the system against line loss between the Sengkol and Mantang buses. Table 1 shows the comparison of different scenarios considered in this research. As shown in Table 1, the difference between BESS and VSG is on the frequency control, where the BESS uses generic droop control while VSG uses virtual rotor and virtual damping controller.

Table 1. Scenarios comparison

Note	Scenario 1	Scenario 2	Scenario 3
Additional devices	No additional devices	Generic BESS	VSG
Capacity of additional devices	-	20 MWh	20 MWh
PQ control	-	Generic PQ control	Generic PQ control
Frequency control	-	Generic droop controller	Virtual rotor and virtual damping controller
PWM converter	-	Generic PWM converter	Generic PWM converter
Charger control	-	Generic charger control	Generic charger control
Battery model	-	Generic battery mode	Generic battery model

3.1. Case 1: disconnection of the Paokmontong diesel power plant

Figures 5 and 6 illustrate the frequency response at the Ampenan and Jeranjang buses, respectively. The disconnection of the Paokmotong diesel power plant reduces system inertia and damping properties, leading to a significant deterioration in RoCoF. This leads to an increase in frequency deviation and a longer settling time for stabilization. In the existing condition (scenario 1), the system frequency experiences a severe drop, resulting in a large frequency nadir (lowest point), and a prolonged recovery period. Meanwhile, BESS implementation (scenario 2) offers some improvement, it can curtail frequency deviation by 0.5% during critical conditions and increase the steady-state value by 0.1%. However, this improvement comes at the cost of a slightly extended settling time (2.7 seconds longer). On the other hand, The VSG integration (scenario 3) demonstrates superior performance than other scenarios, scenario 1 and scenario 2. VSG offers faster power response in supplying additional power during generation dispatch, thus effectively reduces frequency deviation by up to 0.6%. Moreover, VSG impacted on power system faster stabilization time, made it reaching steady-state 17.6 seconds quicker compared to other scenarios. This can be happening due to the ability to response to grid changing due to their virtual synchronous generation controller. Different with traditional droop control that consist of proportional controller only. The VSG controller consist of virtual inertia and virtual damping control that make the BESS converter could response the grid fluctuations faster compared to droop controller.

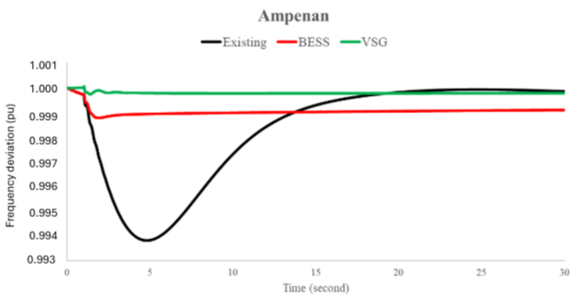

Figure 5. Frequency response on the Ampenan bus

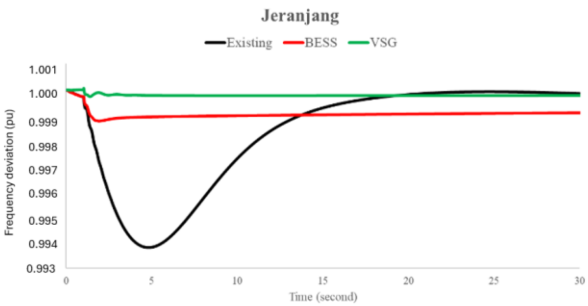

Figure 6. Frequency response on the Jeranjang bus

The observation continuously investigates other measures of frequency, RoCoF, as depicted in Figures 7 and 8. The results show the implementation of BESS (scenario 2) resulting in a 40% reduction of RoCoF compared to the absence of additional equipment in the existing condition of power system (scenario 1). Whereas for the implementation of VSG (scenario 3), it only impacted on a 10% reduction of RoCoF from the existing condition. The usage of BESS (scenario 2) gives the system a better response during the transient state, which resulting in lower RoCoF value compared to the VSG implementation (scenario 3). This can be happened due to the capabilities for VSG to used RoCoF as the input of the controller. Different with droop control that used frequency grid as the controller input, VSG used RoCoF as the input controller so that make the system can response the frequency changing faster than regular droop controller. However, the RoCoF of VSG experience overshoot due to the sensitivity of the controller. It is important to design the controller of VSG more detailed.

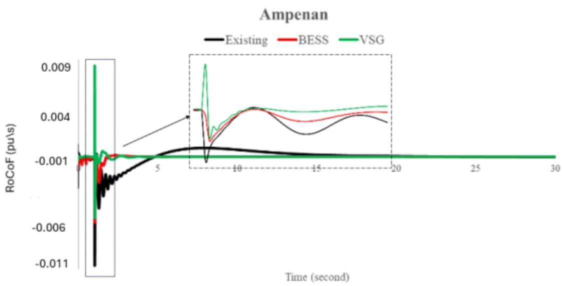

Figure 7. RoCoF response on the Ampenan bus

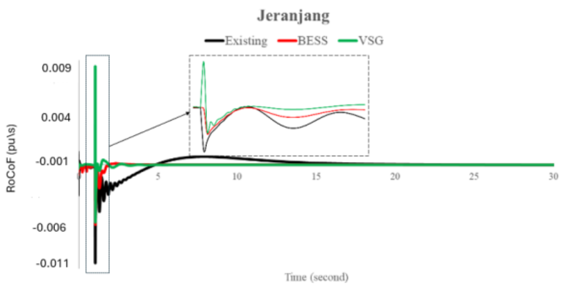

Figure 8. RoCoF response on the Jeranjang bus

The examination on disconnection of Paokmontong diesel power plant also analyzed dynamic voltage stability of the Ampenan and Jeranjang buses (Figures 9 and 10). Nothing that the improvement of dynamic voltage stability response during generator dispatch is primarily due to PVG-based inverter application replacing some power from SG-based diesel plants. While PVG-based inverter application has the benefit of faster response, this substitution may have varying effects, potentially reducing system inertia and damping, leading to increased voltage oscillations during significant disturbances. This is shown in the implementation of BESS (scenario 2), which demonstrably reduces voltage deviation by up to 1.3% and elevates steady-state voltage levels by 2.1%. Moreover, by using this scenario voltage stabilization also accelerates at the Jeranjang bus by 1.6 seconds, while the Ampenan bus experiences slightly delayed stabilization (0.5 seconds longer). Notably, both voltage responses still exhibit a longer settling time despite achieving a new equilibrium point.

Meanwhile, with the implementation of VSG (scenario 3), which is already equipped with virtual inertia and damping control, more damped response was observed, thus exhibiting superior performance compared to (scenario 2). As a result, impacting on smaller voltage amplitudes and faster settling time. Voltage deviations at both buses are reduced to 1.4%, and the stabilization time decreases significantly by 11.4 seconds. Furthermore, VSG integration leads to a 2.4% increase in the steady-state voltage values. These results clearly demonstrate the superior stabilizing effect of VSG control compared to BESS.

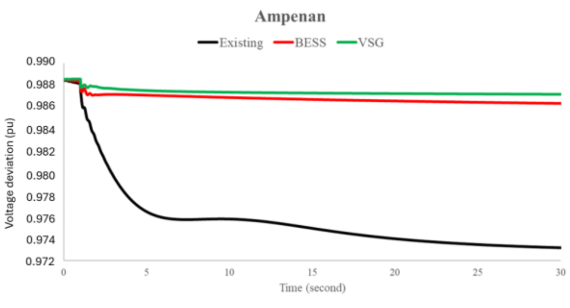

Figure 9. Voltage response on the Ampenan bus

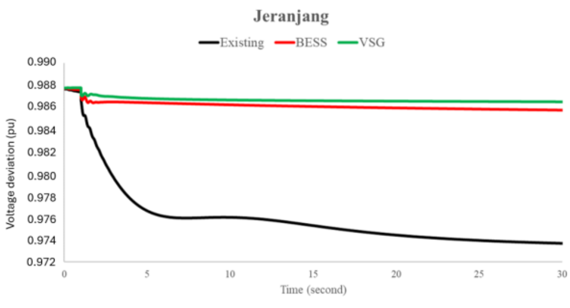

Figure 10. Voltage response on the Jeranjang bus

Rate of change of voltage (RoCoV) were also obtained in the observation of voltage response at the Ampenan and Jeranjang buses, as illustrated in Figures 11 and 12. Figures 11 and 12 also presents results, showing that the implementation of BESS (scenario 2) may reduce RoCoV by 5.19% at the Ampenan bus and 5.85% at the Jeranjang bus compared to the existing condition (scenario 1). Using VSG on the other hand, presents remarkable response in decreasing RoCoV by up to 11.11% at the Ampenan bus and 13.45% at the Jeranjang bus compared to the existing condition (scenario 1). Unlike conventional BESS control, which primarily responds to power imbalances, VSG emulates the inertial and damping characteristics of synchronous machines. As a result, VSG not only delivers fast power support but also introduces virtual inertia that slows the rate of voltage changes and enhances damping during transients. This inertia-based response leads to smoother voltage dynamics, thereby significantly reducing RoCoV compared to both the existing condition and the BESS-only case. These findings confirm that while BESS contributes to improved voltage stability, VSG provides a more robust solution by combining fast power injection with virtual inertia and damping effects, making it more effective in mitigating abrupt voltage fluctuations.

It is concluded that by applying inverter-based generation with the right control such as VSG control can significantly benefit the power system. This control reduces generator stress, leading to higher efficiency and increased spinning reserve. The fast control response of VSG is capable of restoring system stability after disturbance, resulting in dampened voltage fluctuations and faster stabilization.

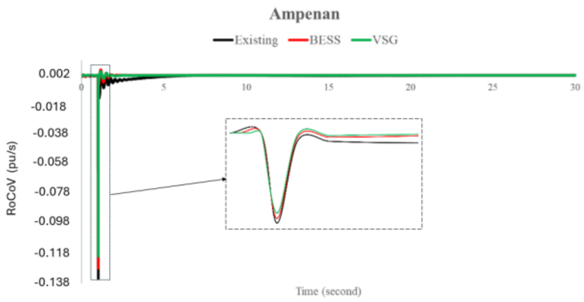

Figure 11. RoCoV response on the Ampenan bus

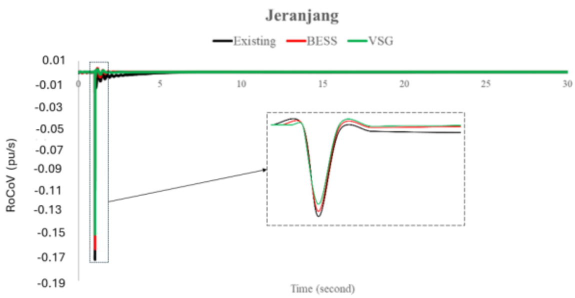

Figure 12. RoCoV response on the Jeranjang bus

3.2. Case 2: disconnection of the line disconnected between the Sengkol and Mantang

To investigate the broader impact of the VSG application, another case was simulated. This case involved a line disconnect between the Sengkol and Mantang buses at the first second, simulating a line discharge event. Similar to the previous case (Paokmotong power plant disconnection), the system's frequency and voltage responses at the Ampenan and Jeranjang buses were analyzed to assess the effectiveness of VSG under this case. It is found that the key effect of VSG implementation unit (scenario 3) as detailed in Figures 13 and 14, demonstrably improves the frequency response at both the Ampenan and Jeranjang buses compared to scenario 1 (existing condition) and scenario 2 (BESS implementation). This can be happening due to the ability to response to grid changing due to their virtual synchronous generation controller. Different with traditional droop control that consist of proportional controller only. The VSG controller consist of virtual inertia and virtual damping control that make the BESS converter could response the grid fluctuations faster compared to droop controller.

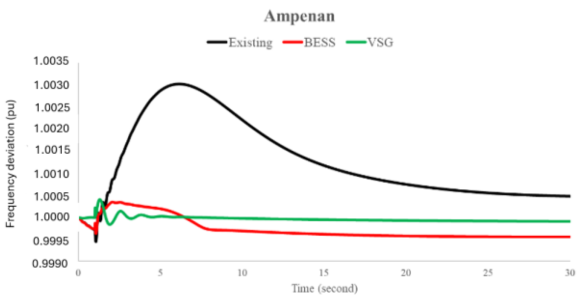

Figure 13. Frequency response on the Ampenan bus due to disconnected between the Sengkol and Mantang

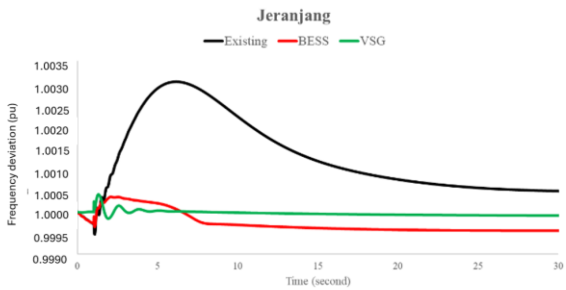

Figure 14. Frequency response on the Jeranjang bus disconnected between the Sengkol and Mantang

Further analysis was carried out on the RoCoF which shown in Figures 15 and 16. According to the frequency response results, it shows that by using BESS (scenario 2) and VSG (scenario 3) can enhance RoCoF during the disconnection of line between two buses (Sengkol and Mantang bus). This enhancement reaches up to 130% with BESS and up to 270% with VSG utilization compared from the existing condition (scenario 1). This can be happened due to the capabilities for VSG to used RoCoF as the input of the controller. Different with droop control that used frequency grid as the controller input, VSG used RoCoF as the input controller so that make the system can response the frequency changing faster than regular droop controller. However, the RoCoF of VSG experience overshoot due to the sensitivity of the controller. It is important to design the controller of VSG more detailed.

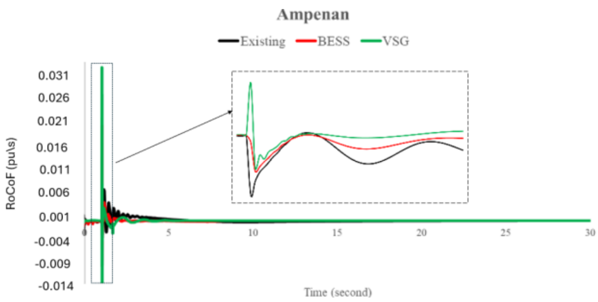

Figure 15. RoCoF response on the Ampenan bus disconnected between the Sengkol and Mantang

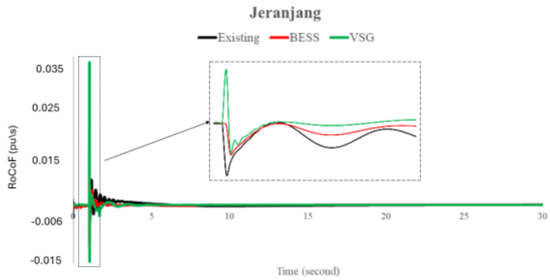

Figure 16. RoCoF response on the Jeranjang bus disconnected between the Sengkol and Mantang

Next observations focused on the voltage response of the Ampenan and Jeranjang buses. Based on the result of the simulation, the PVG-based inverter application responds faster than conventional generators. This rapid response, whether through BESS or VSG control, significantly helps the Lombok power system in regaining stability after disturbances to its equilibrium point. A comparative analysis was conducted to evaluate the impact of various system configurations on the voltage response. The findings demonstrate that both BESS and VSG units (as detailed in Figures 17 and 18) offer significant improvements compared with the existing condition (scenario 1). These enhancements include reduced voltage deviations, faster settling times, and improved voltage profiles during steady-state operation. While both technologies effectively mitigate voltage excursions, BESS exhibits a slight advantage in terms of voltage deviation, particularly at the Ampenan bus. Additionally, BESS achieves marginally faster voltage stabilization compared with VSG integration.

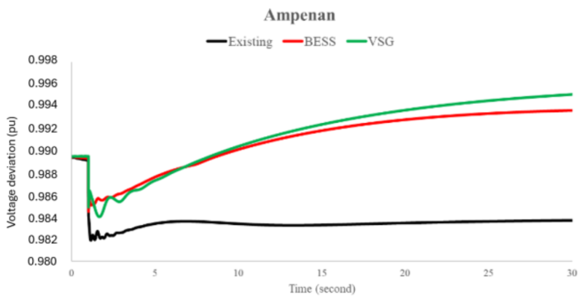

Figure 17. Voltage response on the Ampenan bus disconnected between the Sengkol and Mantang

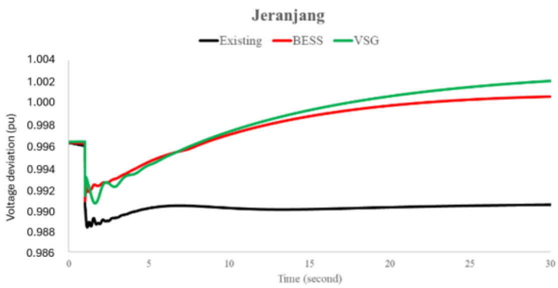

Figure 18. Voltage response on the Jeranjang bus disconnected between the Sengkol and Mantang

The observations of RoCoV response, depicted in Figures 19 and 20. Utilization of BESS (scenario 2) may offer superior response by providing lower RoCoV, up to 5.07% lower than the existing condition (scenario 1), but the utilization of VSG (Scenario 3) surpassed both scenarios by giving a better response. The implementation of VSG can reduce RoCoV by up to 10.77% from the existing condition.

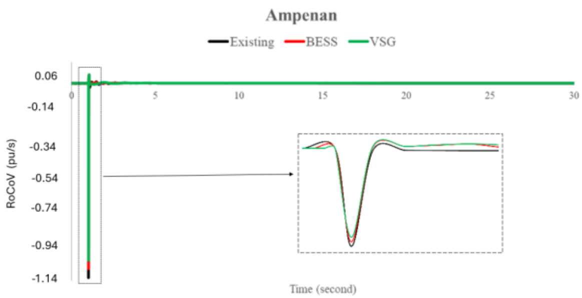

Figure 19. RoCoV response on the Ampenan bus disconnected between the Sengkol and Mantang

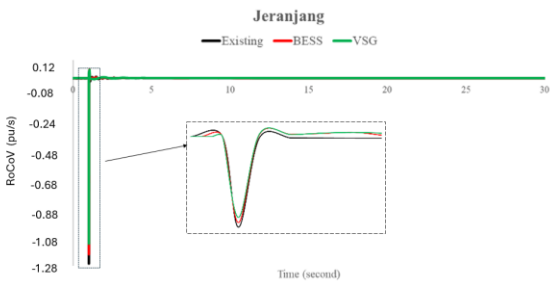

Figure 20. RoCoV response on the Jeranjang bus disconnected between the Sengkol and Mantang

4. CONCLUSION

The application of VSG is presented in this paper. The purpose of this research is to investigate the influence VSG as additional devices in Lombok power systems. To investigate the efficacy of adding VSG in Lombok power systems, two different events are conducted in this research. The event is disconnected of Paokmotong diesel power plant. Paokmotong plant disconnection weakens frequency and voltage regulation. However, VSG integration in Lombok's power system emerges as a compelling solution, improving both aspects. It reduces frequency deviation and settling time through fast power response, while also enhancing voltage dynamics (including RoCoV) with damped response and faster settling times due to reduced generator stress. But in change, higher value of virtual inertia dan damping within the VSG parameter led to higher RoCoF.

In another case (line disconnect between two buses), VSG application significantly enhances frequency response at observed buses. It reduces RoCoF, maximum frequency deviation, and settling time compared with other scenarios. Both PVG with BESS and VSG control offer significant improvements in voltage stability compared to conventional generation. They achieve this by providing faster response to disturbances, resulting in reduced voltage deviations, faster settling times, and improved steady-state voltage profiles. While both are effective, VSG demonstrates advantage in terms of voltage dynamic during transient state, it can curtail RoCoV value with twice rate of BESS implementation. Thus, in change, BESS demonstrates faster voltage stabilization. Further research needs to be conducted by designing the VSG controller based on artificial intelligence to get better performance. In addition, another testing such as multi-event robustness testing, parameter sensitivity testing will also be considered as the future study.

FUNDING INFORMATION

This research is funded by Universitas Airlangga through International Research Network (IRN) with Grant Number 1678/UN3.LPPM/PT.01.03/2023.

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
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So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [initials: HS], upon reasonable request.

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