

Microgrid Control Strategy Based on Battery Energy Storage System-Virtual Synchronous Generator (BESS-VSG)

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Abstract—With more and more renewable energy resources integrated into the power grid, the system is losing inertia because power electronics-based generators do not provide natural inertia. The low inertia will cause the microgrid to be more sensitive to disturbance and thus a small load change may result in a severe deviation in frequency. Based on the basic VSG algorithm, which is to mimic the characteristic of the traditional synchronous generator, the frequency can be controlled to a stable value faster and more smoothly when there is a fluctuation in the PV power generation and/or load change. However, characteristic of the VSG depends on the system structure in consideration of multiple generations, such as Synchronous Generator (SG), PV and Battery Energy Storage System (BESS), which greatly increases the complexity of applying VSG in practical power system. Furthermore, with BESS-VSG, Maximum Power Point (MPP) operation of PV is guaranteed. In addition, an adaptive VSG method is developed for a microgrid system, and the corresponding simulation in Matlab/Simulink shows the effectiveness of the adaptive VSG method.

Keywords—Microgrid, virtual synchronous generator, inertia, frequency control.

I. INTRODUCTION

Renewable energy has been paid more and more attention due to limited conventional fossil fuels. In addition, the environmental problem is also severe and urgent to be solved. According to the latest data from Energy Information Administration (EIA) in April 2019, the renewable energy capacity exceeded that of coal for the first time in the United States, which marks the arrival of the next generation of electricity.

In 2001, the concept of Microgrid was proposed by Consortium for Electric Reliability Technology Solutions (CERTS). Since then, a lot of different definitions have emerged; however, a typical microgrid includes distributed power generators (such as PV and wind power), energy storage and loads. Accordingly, some basic methods including control, protection and energy management for Microgrid were proposed in [1]. As one of the benefits, Microgrid can provide the electricity and/or heat, connect and disconnect from the grid to run in either grid-connected mode or islanded mode [2].

With a lot of Distributed Generators (DGs) as power supply in Microgrid, it has the following characteristics: 1) Flexibility: Since microgrid can run in either grid-connected mode or

islanded mode, it is flexible to supply to or import power from the main grid and can disconnect from the main grid when there is an event happening in the main grid; 2) Compatibility: As additional power supply for the main grid in grid-connected mode, it can help balance the load demand during peak times when the power grid is not capable of meeting load demands; 3) Economy: Besides the benefits of using the natural energy as the resources of microgrid, those DGs can be built near the location of the load with reduced power loss due to less power flowing needed in transmission lines [3].

In order to achieve stable output of the renewable energy, Microgrid needs a smart switch and reliable inverter controller to complete the synchronization with grid during transition [4]. Some traditional control methods including decoupled real power and reactive control for the power electronics-based resources have been used. Other methods include decoupled frequency and voltage control.

However, with a high penetration of renewable energy resources, the issues of frequency stability occur gradually. More specifically, in Microgrid, lots of renewable energy generators replace the traditional generators and result in insufficient capacity for primary/secondary control, leading to frequency fluctuation of the microgrid due to the uncertainty of renewable energy [5]. Furthermore, the whole system is losing inertia because power electronics-based generators do not provide natural inertia [6]. The low inertia will cause the microgrid to be more sensitive to the disturbance and thus a small load change may result in a severe deviation in frequency, which deteriorates the stability of the microgrid [7].

In order to mitigate these disadvantages, the concept of Virtual Synchronous Generator (VSG) was proposed [8]. The VSG technique can mimic the characteristics of the traditional synchronous generators with damping and inertia by using appropriate control algorithm. A complete VSG model with consideration of mechanical and electromagnetic transient state was proposed in [9]. The theoretical stability analysis by using a small signal model with parallel VSGs was introduced in [10]. Furthermore, the comparison of dynamic characteristics between Droop control and VSG control in inverter-based distributed generators was demonstrated in [11]. Also, considering distributed cooperative control for distributed renewable energy generators, some distributed control methods of VSG for Microgrid can be found in [12][13]. On the other

hand, wind turbine has inherent advantage for VSG because of the stored energy in the blades of the wind turbine and thus does not need the battery necessarily to exchange energy during the operation of VSG. In [14], it introduces the main popular control methods for variable speed wind turbines (VSWTs). Furthermore, VSG with multiple virtual rotating masses for permanent magnet synchronous generator-variable speed wind turbine generators (PMSG-WTG) to achieve better performance under changing wind speed was proposed in [15]. Nevertheless, PV is frequently considered in some areas where solar energy is abundant. In such a case, Battery Energy Storage System is almost always used as the medium for exchanging the energy when VSG algorithm is adopted. When battery is used in a PV microgrid, the battery optimization considering demand response can help improve system economic performance as illustrated in [16]. Since the performance of the frequency regulation is directly related to system inertia, the VSG characteristic can be improved if the moment of inertia is changed during the system operation. The method of adaptive moment of inertia was firstly proposed in [17]. Then, in order to pursue better dynamic index, both inertia and damping factors were considered and developed for the adaptive VSG control algorithm [18], wherein stability of the adaptive VSG algorithm is proved by Lyapunov function. For the design of the corresponding VSG parameters, [19] proposed a dual-adaptivity inertia control strategy to determine the range of the adaptivity. [20] also provides some guidelines on how to obtain some key control parameters for a VSG system. However, characteristic of the VSG is greatly influenced by many factors such as the system structure considering multiple generations, such as Synchronous Generator (SG), PV and Battery Energy Storage System (BESS). In this situation, it is hard to guarantee the performance of VSG in such a system; furthermore, the complexity of applying VSG is increased as well in practical power system. Another aspect of applying VSG in PV microgrid system is whether MPP operation is maintained well in such situation.

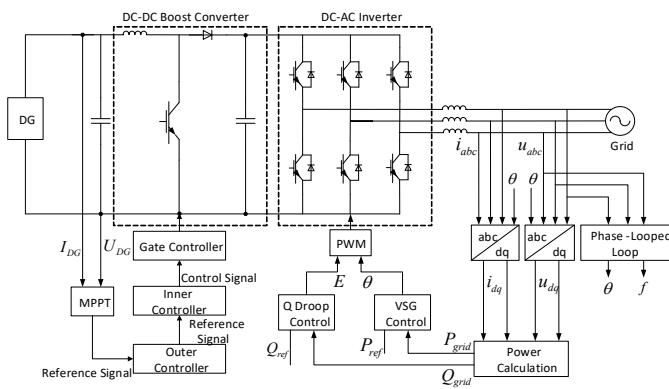


Fig. 1. Typical structure of DG system with VSG control

To address those mentioned issues, in this paper the adaptive VSG algorithm is applied in a modified IEEE-14 bus system including SG, PV and BESS. The novelty and contributions of this paper are summarized as follows:

1) The model for a microgrid with diversified generation including SG, PV and BESS is built and adaptive VSG

algorithm is applied with well-designed system and VSG parameters.

2) While maintain the performance of VSG system, the MPP of the PV system is guaranteed, ensuring the maximum benefit of the system.

The rest of the paper is organized as follows. Section II introduces the BESS-VSG control system including the basic VSG algorithm and the adaptive VSG algorithm. Then, some simulation cases are studied in Section III. Finally, the conclusions are summarized in Section IV.

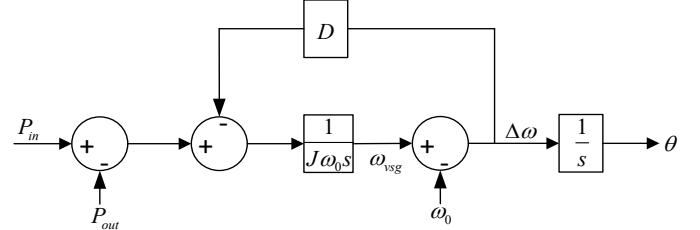


Fig. 2. Structure of VSG algorithm

II. BESS-VSG CONTROL SYSTEM

A. Basic VSG Algorithm

As mentioned previously, the principle of VSG algorithm is to control DG so that the characteristic of the traditional synchronous generator is mimicked. Typical structure of a DG system including VSG control is shown in Fig. 1; besides the active power VSG algorithm, the reactive power or voltage can be controlled by using Droop Control. In this paper, only the VSG active power control is studied. VSG algorithm is based on the swing equation of the synchronous generator. The VSG mathematical model is implemented by using control blocks. The swing equation is shown as follows:

$$P_{in} - P_{out} = J\omega \frac{d\omega}{dt} + D\Delta\omega \quad (1)$$

where P_{in} is the input power of the synchronous generator;

P_{out} is the electromagnetic power of the stator; J is the moment of inertia; ω is the rotor angular velocity; D is the damping coefficient; and $\Delta\omega = \omega - \omega_0$; ω_0 is the reference grid angular velocity, which is $2\pi 60$ in the United States. With the same principle, VSG algorithm has the similar formula:

$$P_{in} - P_{out} = J\omega_{vsg} \frac{d\omega_{vsg}}{dt} + D\Delta\omega \quad (2)$$

where ω_{vsg} is the virtual angular velocity of the VSG; $\Delta\omega = \omega_{vsg} - \omega_0$; and all other parameters have been explained in (1).

Since $\omega_{vsg} \approx \omega_0$, the following can be obtained:

$$P_{in} - P_{out} = J\omega_0 \frac{d\omega_{vsg}}{dt} + D\Delta\omega \quad (3)$$

By using Laplace Transformation on (3), it is obtained:

$$P_{in} - P_{out} = J\omega_0 s\omega_{vsg} + D(\omega_{vsg} - \omega_0) \quad (4)$$

Based on (4), the control blocks can be created as shown in Fig. 2.

B. Adaptive VSG Algorithm

The typical power-angle curve for power system is shown in Fig. 3.

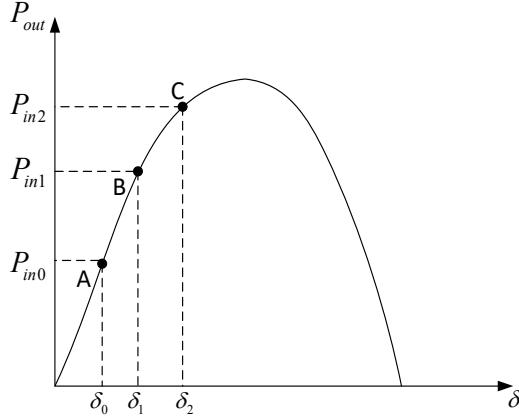


Fig. 3. Typical power-angle curve of a synchronous generator

Assume that the system is operating at point A initially, and it is stable. For example, if the input power increases to point B, P_{in1} , the operating point will follow the curve from A to B

because in this period, $\Delta\omega > 0$, and $\frac{d\omega_{vsg}}{dt} > 0$, which is

defined as an acceleration segment. However, the goal is to alleviate the oscillation of the frequency when the load or generation changes. In this way, a big J can be used to reduce the acceleration; otherwise a small J should be used.

For those four segments, the control strategy can be summarized as Table I [18]:

ADAPTIVE INERTIA DURING SYSTEM TRANSIENTS

$\Delta\omega$	$d\omega_{vsg} / dt$	Status	J Value
$\Delta\omega > 0$	$d\omega_{vsg} / dt > 0$	Accelerating	Big J
$\Delta\omega > 0$	$d\omega_{vsg} / dt < 0$	Decelerating	Small J
$\Delta\omega < 0$	$d\omega_{vsg} / dt < 0$	Accelerating	Big J
$\Delta\omega < 0$	$d\omega_{vsg} / dt > 0$	Decelerating	Small J

In addition, the relationship between P_{out} , the line impedance X , the amplitude of electromotive force E , the amplitude of the grid voltage U_{grid} and the angle of VSG θ can be expressed as:

$$P_{out} = \frac{3EU_{grid}}{X} \sin \theta \quad (5)$$

Combining (5) and (4), the small signal transfer function model from P_{in} to ω_{vsg} can be obtained as:

$$\frac{\omega_{vsg}}{P_{in}} = \frac{Xs}{J\omega_0 Xs^2 + DXs + EU_{grid}} \quad (6)$$

By using Laplace inverse transformation, (6) can be expressed as [19]:

$$\omega_{vsg}(t) = P_{in} \left(\sqrt{\frac{EU_{grid}}{J\omega_0 X}} / \sqrt{1 - \frac{D^2 X}{4J\omega_0 EU_{grid}}} e^{-\frac{D}{2J\omega_0}t} \right) \times \sin \left(\sqrt{\frac{EU_{grid}}{J\omega_0 X}} \sqrt{1 - \frac{D^2 X}{4J\omega_0 EU_{grid}}} t \right) \quad (7)$$

Therefore, the frequency dynamics is influenced by the inertia and damping. By using control theory knowledge, the ideal response of frequency when there is a step change in real power with an adaptive inertia algorithm is shown in Fig. 4. For big inertia, the fluctuation of the frequency change is smaller, but the response speed is also slow. In contrast, for the small inertia, the response speed is fast, but the fluctuation of the frequency change is also larger. It can be observed that the adaptive VSG algorithm takes the advantages of both small inertia and big inertia during respective segments, which has small fluctuation for the initial ascent stage with big inertia and has fast response speed for the deceleration stage with small inertia.

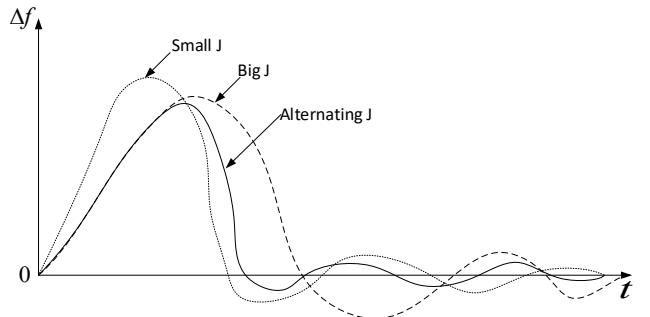


Fig. 4. Ideal response of frequency deviation when there is a step change in real power with adaptive inertia VSG [19]

III. RESULTS

A. System Structure and Scale

The model of the test system is built in Matlab/Simulink, which is shown in Fig. 5, wherein the two green blocks represent the two traditional synchronous generators G1 and G2 with typical Droop control; the yellow one represents the PV system with variable solar irradiation and temperature; the cyan one represents the BESS-VSG system to share the load and provides some extra inertia to the whole system; and the middle block represents the IEEE-14 bus transmission network. Inside the PV block, there are MPPT and Voltage Source Converter (VSC), which work together to ensure system stability as shown in Fig. 6. Besides, the BESS-VSG diagram is shown in Fig. 7. The parameters of the system are listed in Table II.

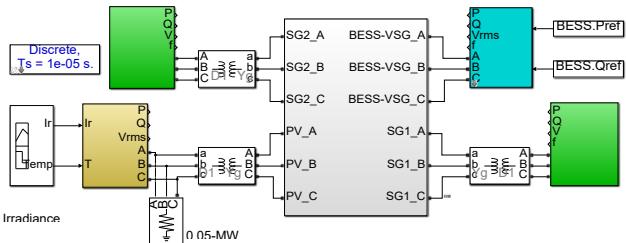


Fig. 5. Overall model of the system in Matlab/Simulink

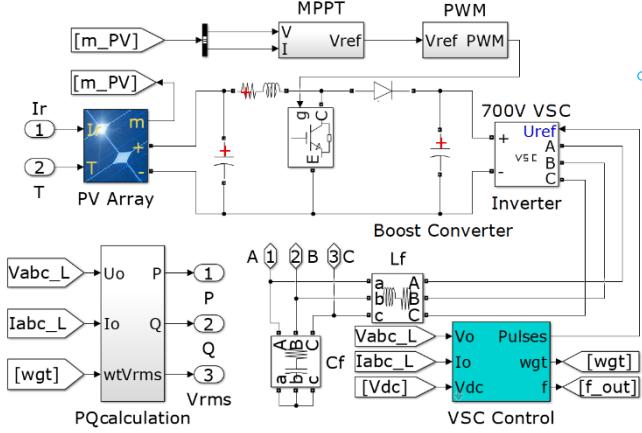


Fig. 6. Diagram of PV subsystem

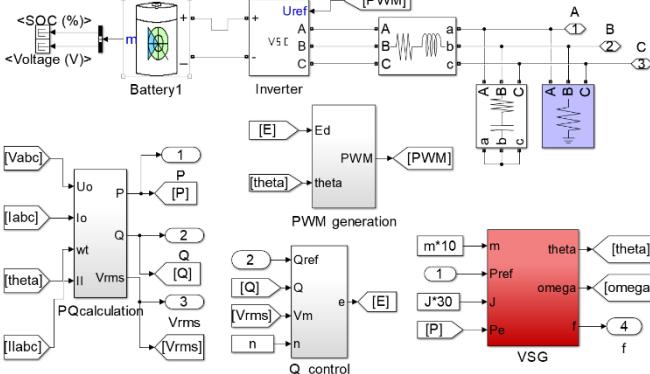


Fig. 7. Diagram of BESS-VSG subsystem

B. Case Studies

1. Case 1: Grid-connected mode to Islanded mode

Case 1 shows the transients from the grid-connected mode to islanded mode. In this case, the circuit breaker between the infinite power supply and the transmission lines is set to be closed at time 0s, opened at time 3s. The results are shown in Fig. 8. And the real power of G1 maintains at about 0.73 pu, which is 1.46 MW with a base power for G1 as 2 MW. G2 maintains at about 0.5 pu, which is 1.5 MW with its base power of 3MW. PV system reaches the MPP at about 0.1 MW with changing irradiance and temperature from 0s to 2.1s.

TABLE II
SYSTEM PARAMETERS

Parameter	Value
DG bus voltage U_{dg}	380 V
Microgrid voltage U_{grid}	10 kV
System frequency f	60 Hz
Apparent Power S_{SG1}	2 MVA
Apparent Power S_{SG2}	3 MVA
Apparent Power S_{PV}	1 MVA
Apparent Power $S_{BESS-VSG}$	1 MVA
Constant J	0.0014 p.u.
Big J	0.0014 p.u.
Small J	5.62e-5 p.u.
Damping D	5e-4 p.u.

From time 0s to time 3s, the system is running at grid-connected mode, and it is stable at 60 Hz. Then, at time 3s, the real power and frequency of each generation has a little fluctuation because the main power supply is removed but the system finally reaches stable state at about 60 Hz (with steady state error) at about 10s. Therefore, both grid-connected and islanded mode are proved to be stable for this system.

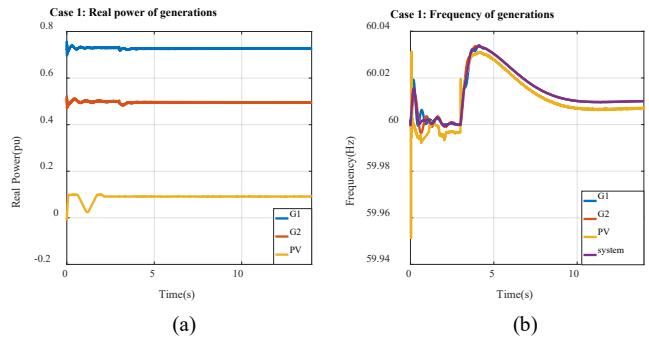


Fig. 8. Case 1: Grid-connected mode to Islanded mode. (a) Real power of generations. (b) Frequency of generations.

2. Case 2: Islanded mode: load increases without VSG

Case 2 is for islanded mode operation, and the aim is to observe how frequency changes when the load increases without any extra generation. The results are shown in Fig. 9. In this case, at time 5s, there is a load increase with 0.2 MW, 0.05 MVar. From the figures, the synchronous generators increase their generations because of the inherent characteristic of the traditional SG. However, it is not enough to balance the increased load. Then the frequency decreases suddenly, and the slope in this period is very steep. The lowest frequency (nadir) approaches to about 59.72 Hz, which is harmful to the power system. Finally, under the coordination of generators and loads, the system is running at a new stable point, but the frequency is

lower than 60 Hz. This is also the reason why the VSG technique is used to help the system return to the original state.

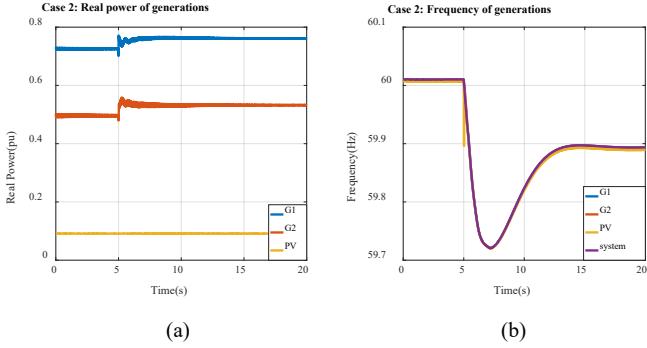


Fig. 9. Case 2: Islanded mode: load increases without VSG. (a) Real power of generations. (b) Frequency of generations.

3. Case 3: Islanded mode: load increases with constant VSG

Based on Case 2, the VSG is added to supply the increased load. VSG control with inertia $J = 1.4 \times 10^{-3} \text{ pu}$ results in very good performance and the results are shown in Fig. 10. In combination with VSG algorithm, the simulated system can guarantee the MPP operation of the PV, which also shows the robustness of the MPPT technique of the PV system.

For the same condition, with the BESS-VSG technique, the lowest point of the frequency is about 59.85 Hz when the load increases, which is allowable in real power system. Finally, the system is running at a new stable point at frequency about 60.01 Hz.

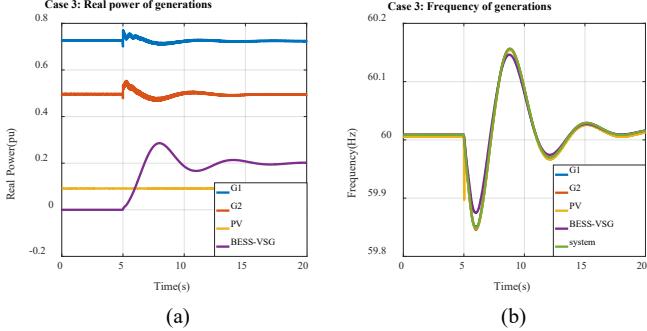


Fig. 10. Case 3: Islanded mode: load increases with constant VSG. (a) Real power of generations. (b) Frequency of generations.

4. Case 4: Islanded mode: load increases with adaptive VSG

In order to enhance the performance of making the frequency drop curve smoother, the adaptive VSG technique is used in the same scenario with Case 2 and Case 3. And the $Big J = 1.4 \times 10^{-3} \text{ pu}$, $Small J = 5.62 \times 10^{-5} \text{ pu}$. The results are shown as Fig. 11.

To observe the improvement of the performance directly, comparison between the results of the constant VSG and the adaptive VSG are shown in Fig. 12.

5. Case 5: Islanded mode: PV drops

In order to test the feasibility of the VSG algorithm when PV generation drops, another case is set up. Note that, the output power of PV is 0.1 MW, but there is a 0.05 MW load

next to the PV generation, which means that the injected power to the Microgrid is 0.05 MW. Therefore, when $t=5$ s, a severe situation happens with the PV generation dropping to 0, and then the reference input power of the BESS-VSG is set to be 0.05 MW. The results are shown in Fig. 13, Fig. 14, and Fig. 15 for simulation case without VSG, with constant VSG and with adaptive VSG, respectively. Based on the comparison results, it can be seen that adaptive BESS-VSG can better help the system get back to its normal frequency.

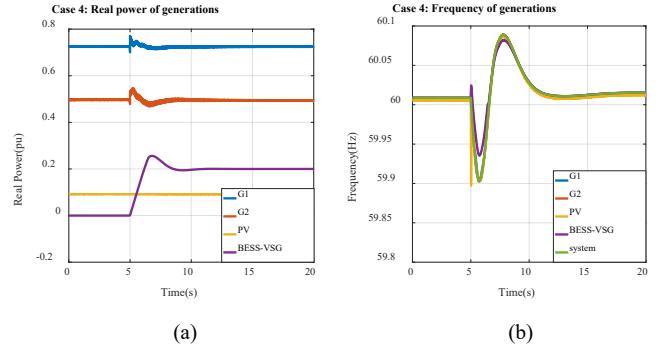


Fig. 11. Case 4: Islanded mode: load increases with adaptive VSG. (a) Real power of generations. (b) Frequency of generations.

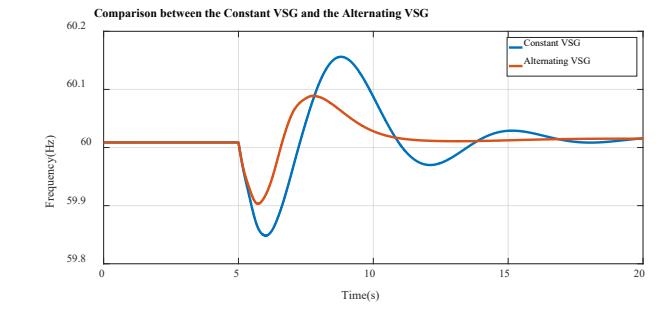


Fig. 12. Comparison between the Constant VSG and the Adaptive VSG

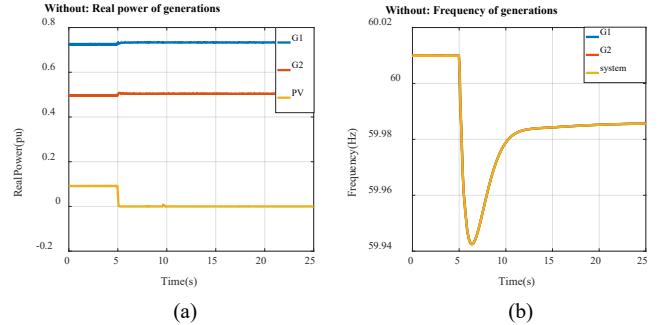


Fig. 13. Case 5: Islanded mode: PV drops without VSG. (a) Real power of generations. (b) Frequency of generations.

IV. CONCLUSION

Solving frequency control problem is the most important way to guarantee the stability of microgrid power system. Also, renewable energy such as PV is more and more popular in today's power system. This paper aims to make the PV based microgrid behave like a traditional power system during islanded mode operation in consideration of SG and BESS in such a multiple generation system. The frequency stability

performance is enhanced by the developed adaptive VSG method. The conclusions of this paper are given as follows:

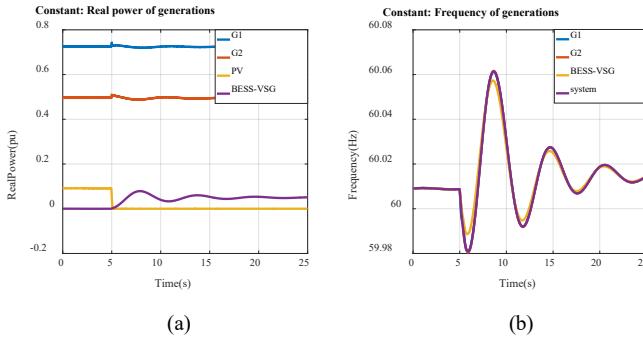


Fig. 14. Case 5: Islanded mode: PV drops with constant VSG. (a) Real power of generations. (b) Frequency of generations.

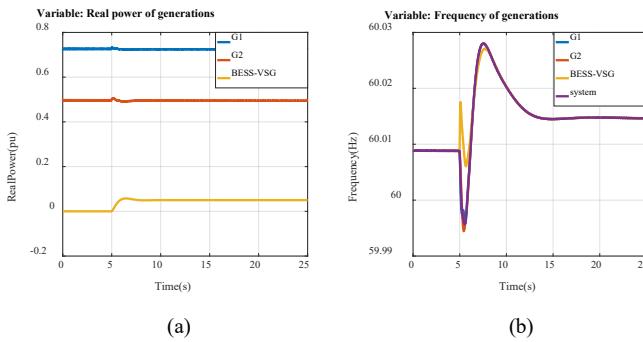


Fig. 15. Case 5: Islanded mode: PV drops with adaptive VSG. (a) Real power of generations. (b) Frequency of generations.

1. The PV system maximizes its performance by using the MPPT Algorithm under changing weather conditions.
2. The PV based microgrid system is synchronous with the grid based on the same frequency due to the dual loop controller for inverter and it can run in either grid-connected mode or islanded mode.
3. In combination with the BESS-VSG system, the MPP of PV is guaranteed.
4. The developed adaptive VSG technique can be embedded into the multiple generation system including SG, PV and BESS, showing the feasibility of alleviating the frequency dip problem due to load increase and PV generation reduction.

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BIOGRAPHY

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