Inverter Control Strategy Based on Virtual Synchronous Generator

Dong Xie*
College of Electrical Engineering, Tongling University, Anhui, 244000, China
*Corresponding author(E-mail: XDY@tlu.edu.cn)

Dajin Zang
College of Electrical Engineering, Tongling University, Anhui, China

Peng Gao
College of Electrical Engineering, Tongling University, Anhui, China

Abstract
In view of the shortcomings of droop control based microgrid inverter control method, the Virtual Synchronous Generator(VSG) based inverter control strategy is proposed. By realizing the ontology algorithm and designing the speed governor and excitation regulator, the VSG based inverter control method mimicked the operating characteristics and control characteristics of synchronous generator, thus the microgrid inverter could stably operate under the condition of islanding and grid-connected, with good synchronization control and power sharing control characteristics. By the hierarchical control of frequency and voltage, the reliability and flexibility of microgrid inverter control were improved. Simulation and experiment results show that the proposed inverter control strategy can guarantee the stability of the voltage and frequency of the microgrid system, and in islanding operating mode the load can be distributed proportionally according to the capacity of inverter, so the power balance of the system is maintained, and the control requirements of the microgrid inverter are met.

Key words: Inverter control, Virtual Synchronous Generator, Speed governor, Excitation controller.

1. INTRODUCTION
Because of the growing demand for energy, the traditional fossil energy reserves have been difficult to meet the needs of human beings. On the other hand, the fossil energy will cause serious environmental pollution in the process of exploitation, transportation and use. Therefore, Distributed Generation(DG), which is based on wind, solar and other clean renewable energy, has been rapid developed. Distributed power source directly connected to the large power grid will bring many problems such as voltage disturbance. Compared with the simple distributed power source, microgrid can achieve large-scale utilization of renewable energy, and can improve power supply reliability and power quality, so currently microgrid is a hot topic Xisheng Tang, Wei Deng, and Zhiping Qi (2014) and Jing Wang, (2015).

Microgrid is a collection of various micro power supply, energy storage unit, load and monitoring and protection device, and microgrid inverter is the key to the integration of the microgrid system. At present, the research on the control strategy of the microgrid inverter is focused on the droop control and its improvement. The disadvantage of droop control is the complexity in mode switching, and droop control can only reflect the external characteristics of synchronous generator, but can’t realize the synchronous generator characteristics such as large inertia and large output inductance, while large inertia is in favor of the frequency stability of microgrid system and large output inductance is beneficial to parallel operation control when microgrid inverter is in islanding mode. Therefore, the characteristics of synchronous generator are very favorable for constructing microgrid which is based on small inertia, low output impedance inverter. In addition, in the power system, each synchronous generator is equipped with a speed governor and an excitation regulator to realize a balanced allocation of active and reactive loads between synchronous generators and to maintain the stability of the system voltage and frequency Xiaqiang Guo, Zhigang Lu, (2014) and Fanghong Guo, (2015).

In summary, a algorithm can be added to the control of microgrid inverter to make it have the operating characteristics of synchronous generator. At the same time, the corresponding controller is designed according to the principle of speed governor and excitation regulator of synchronous generator. This is a novel microgrid inverter control strategy, which is based on virtual synchronous generator. This control strategy can easily learn from the mature power system control and scheduling theory to design the control structure and energy management system of microgrid, and can improve the flexibility and reliability of microgrid control. In the existing literature on VSG based control strategy, literature Torres M, and Lopes L.A.C (2011) proposed the idea of VSG based current control, its disadvantage is that the voltage and frequency of microgrid can’t be supported in islanding operation mode and the inverters can only work in grid-connected mode. Literature
Debin Zhu (2012) described an improved voltage control type VSG-based control strategy, but did not give a specific design process, didn’t give the specific method of multi parallel inverter active and reactive power sharing control. Based on the above literature, this paper expounds the control principle and design method of VSG, and analyzes and calculates the power sharing control strategy of islanding operation mode inverters, the simulation and experiment results verify the correctness of the theoretical analysis.

2. PRINCIPLE AND DESIGN FOR VSG

2.1. VSG Control Principle

Here an single-phase VSG is used to analyze its control principle, the corresponding schematic diagram is shown in Fig. 1. The main circuit uses a single phase bridge voltage type inverter circuit, $L_1$ is the filter inductor, $C$ is the filter capacitor, inductor $L_2$ make the output impedance of VSG to be inductive impedance in order to achieve the power control. The VSG output power $P_e$ is calculated by detecting the current $i_o$ which flows through $L_2$ and the filter capacitor terminal voltage $u$. The VSG input mechanical power instruction $P_m$ is obtained from the speed governor, and the excitation electromotive force (e.m.f.) instruction $E_0$ is given by the excitation regulator. Then the VSG ontology algorithm Calculates the filter capacitor terminal voltage instruction $u_{st}$ according to $P_e$, $P_m$, $E_0$ and $i_l$. Finally, after the PWM control and driving circuit, the inverter power switch devices are controlled, so that the VSG can simulate the basic operation and control features of the synchronous generator.

![Figure 1. Schematic Diagram of Virtual Synchronous Generator](image)

2.2. VSG Ontology Algorithm

VSG is to simulate the electromechanical transient characteristics of synchronous generator by introducing its rotor motion equation and stator electrical equation. Synchronous generator in different applications has second-order, third-order, five-order, and other mathematical model, the second-order model is used to construct the VSG ontology algorithm, which not only reflects the operation characteristics of synchronous generator, but also avoids the complicated electromagnetic coupling relationship, and facilitates the output power decoupling control of VSG. Assuming that non-salient pole type of synchronous generators is adopted, the number of pole pairs is 1, does not consider eddy current and hysteretic loss, the second-order mathematical model of synchronous generator is as follows Qinghai Heng, Jing Lu, (2015).

$$P_m - P_e - D\Delta \omega = J\omega \frac{d\Delta \omega}{dt}$$

(1)

$$U = E_0 - I(r_s + jx_s)$$

(2)

These two formulas are rotor motion equation and stator electrical equation of synchronous generator. In Eq. 1, $P_m$ is the rotor input mechanical power of synchronous generator, $P_e$ is the stator electromotive power, $J$ and $D$ are rotary inertia and damping coefficient respectively, $\omega$ is the electrical angular frequency, and $\Delta \omega$ is the difference between the rated value and the actual value of electric angular frequency. In Eq. 2, $E_0$ is the excitation induced e.m.f. of stator windings, $U$ is the stator winding terminal voltage, $I$ is the stator current, $r_s$ and $x_s$ are the stator armature resistance and synchronous reactance respectively. The synchronous generator has small $r_s$ and big $x_s$, which is helpful for the power control and suppressing the current mutation, while its $J$ and $D$ are relatively large, which makes the speed of synchronous generator change slowly, and it is conducive to the stability of the system frequency. According to the mathematical model of synchronous generator, the structure diagram of VSG ontology algorithm is shown in Fig. 2.
The parameters $P_m$, $P_e$, $D$, $J$, $\omega$, $E_0$, $U$, $I$, $r_s$, $x_t$ in Fig. 2 have the same physical meanings as those of synchronous generator, when we design these parameters, they can be selected according to the same power level synchronous generator. Actually, $D$ and $J$ can be flexibly configured, without the limitation of synchronous generator actual manufacturing process. Considering that the equivalent output resistance of the inverter main circuit is very small, in the VSG ontology algorithm it is convenient to calculate the power using the VSG output power instead of electromagnetic power $P_e$.

2.3. Design Of VSG Controller

In power system, the synchronous generators use the speed governor to adjust the frequency fluctuation caused by the change of active load. The speed governor regulates the turbine valve or hydraulic turbine guide vane according to the deviation of actual angular frequency and reference angular frequency, to change the output mechanical power of prime motor, meet the active load demand and maintain the stability of the system frequency. Sokolski Pawel, Rutkowski Tomasz A., (2015).

For synchronous generator, active power-frequency characteristic is shown in the following formula.

$$P_{ref} - P = -K_{ao}(\omega_{ref} - \omega)$$  \hspace{1cm} (3)

Where $K_{ao}$ is the frequency adjustment factor of synchronous generator. Similarly, the speed governor of VSG also adjusts its input mechanical power to obtain the power balance between VSG and load, so that the frequency stability of the microgrid system is maintained.

VSG needs to switch between grid-connected and islanding operation modes based on the actual system working conditions. When the mode is being switched, we should take the synchronization control to prevent the large current impact due to voltage amplitude, voltage phase and voltage frequency of both sides of the grid-connected switch are out of sync. The speed governor structure which has mode switching and synchronization control is shown in Fig. 3(b). When VSG is in islanding operation mode, the switches $K_1$, $K_2$, $K_3$ are disconnected, the speed governor use proportional(P) regulator to adjust the frequency, which can quickly adjust the frequency deviation caused by the load fluctuation to guarantee frequency stability; when VSG is in grid-connected operation mode, $K_1$ switch into the connected state, $K_2$ and $K_3$ remain disconnected state, the difference between VSG output active power and the active power instruction is regulated by proportional-integral (PI) regulator to obtain frequency adjusting value $\Delta\omega_p$, then $\Delta\omega_p$ adds frequency instruction $\omega_{ref}$ to generate new frequency command $\omega'_{ref}$, so that the VSG can output active power according to the active power instruction; when the synchronization control is being carried out, $K_2$ and $K_3$ are in connected state while $K_1$ is in disconnected state, connecting $K_2$ so that the phase difference between VSG output voltage and the grid voltage can be regulated by PI regulator to get frequency adjusting value $\Delta\omega_k$, then $\Delta\omega_k$ adds frequency instruction $\omega_{ref}$ to generate new frequency command $\omega'_{ref}$, in order to achieve phase synchronization, connecting $K_3$ so that the frequency regulator is changed from P to PI, which can realize the frequency control without steady-state error. 

Fig. 3(a) is the structure diagram of the VSG speed governor. Where $\omega$ and $\omega_{ref}$ are actual value and reference value of system angular frequency, $P_{ref}$ is the active power instruction of VSG, $P_m$ is the input mechanical power of VSG, the physical meaning of $K_{ao}$ is the same as that of synchronous generator. As can be seen from Fig. 3(a), VSG and synchronous generator has the same active power-frequency characteristic.

![Figure 2. Block Diagram of VSG Ontology Algorithm](image)

![Figure 3. Structure diagram of VSG Speed Governor](image)
to meet the requirement of frequency synchronization. Fig. 3(b) shows that just control the on-off of \( K_1 \), \( K_2 \) and \( K_3 \) can achieve the operation mode switching and synchronization control, which is very flexible and convenient. Moreover, in both grid-connected and islanding modes, the VSG adopts voltage type control, which ensures the reliability and continuity of mode switching.

In power system, synchronous generator uses the excitation regulator to adjust the output voltage variation caused by the reactive load fluctuation. Excitation regulator automatically adjusts the excitation current according to the deviation of actual output voltage and reference output voltage, and then change the excitation induced e.m.f. of stator winding, to maintain the stability of stator terminal voltage, and achieve the system reactive power balance Sokolski Pawel, Rutkowski Tomasz A., and Duzinkiewicz Kazimierz (2015).

According to the control principle of synchronous generator excitation regulator, the structure diagram of VSG excitation regulator is shown in Fig. 4(a). Where \( U \) and \( U_{\text{ref}} \) are the actual value and reference value of VSG output voltage, \( U_0 \) is the VSG stator voltage, \( E_0 \) is the VSG stator excitation induced e.m.f., \( K_s \) is the VSG voltage regulation coefficient. Fig. 4 (a) shows that compared with the synchronous generator, the VSG excitation regulator has similar principle to regulate its output voltage, so they have the same voltage regulation characteristic, which is conducive to the output voltage stability and reactive power balance.

The VSG excitation regulator structure which has mode switching and synchronization control is shown in Fig. 4(b). When VSG is in islanding operation mode, the switch \( K_1 \) and \( K_2 \) is broken, the VSG output voltage stability is maintained by the fast P regulation; when VSG is in grid-connected operation modes, \( K_1 \) switch into the connected state and \( K_2 \) remains disconnected state, the difference between the output reactive power of VSG and the reactive power instruction is regulated by PI regulator to obtain voltage adjustment value \( \Delta U_0 \), then \( \Delta U_0 \) adds voltage instruction \( U_{\text{ref}} \) generate new voltage command \( U'_{\text{ref}} \), so that the VSG can output reactive power according to the reactive power instruction; when the synchronization control is being carried out, \( K_1 \) is disconnected and \( K_2 \) is closed which means the voltage control is changed from P regulation to PI regulation, so that the VSG can meet the voltage amplitude synchronization requirement through no steady-state error voltage control. Similar to Fig. 3(b), the operation mode switching and synchronization control can flexibly implement through breaking or connecting \( K_1 \) and \( K_2 \).

![Figure 4. Structure diagram of VSG Excitation regulator](image)

### 3. VSG POWER SHARING CONTROL UNDER ISLANDING OPERATION MODE

#### 3.1. VSG Active Power Sharing Control

In islanding operation mode, the parallel VSGs share the load according to each VSG capacity, this is the VSG power sharing control Tan K.T., Peng X.Y., So P.L., Chu Y.C., and Chen M.Z.Q. (2012). According to VSG ontology algorithm and its speed governor structure, the structure diagram of VSG frequency closed-loop control is shown in Fig. 5.

![Figure 5. Block Diagram of VSG Frequency Closed Loop Control](image)

VSG frequency instruction \( \omega_{\text{ref}} \) is usually equal to its reference frequency \( \omega_0 \), from Fig. 5 we can obtain the following transfer function formula.

\[
\frac{\omega - \omega_{\text{ref}}}{P_{\text{ref}} - P} = \frac{\Delta\omega}{\Delta P} = \frac{1}{J\omega S + D + K_w}
\]

(4)

The frequency regulation of speed governor increases the system damping, so the damping coefficient \( D \) can be set to 0, then Eq. 4 is simplified as

\[
\frac{\Delta\omega}{\Delta P} = \frac{1}{J\omega S + K_w}
\]

(5)

When the VSG equivalent output impedance and line impedance are inductive, the output active power of VSG is approximated to
Where $U$ is the output voltage of VSG, $U_{com}$ is the parallel bus voltage, $\delta$ is the phase difference between $U$ and $U_{com}$ (i.e., the power angle), $X$ represents the sum of VSG equivalent output impedance and line impedance.

Based on the above analysis, the closed-loop regulation structure of VSG active power is shown in Fig. 6.

![Figure 6. Block Diagram of VSG Active Power Closed Loop Control](image)

It can be obtained from Fig. 6:

$$P_e = \frac{U U_{com}}{X} \cdot P_n(s) + \frac{(J \omega + K_u) U U_{com}}{X} \cdot [e(s) - \omega_{com}(s)]$$  \hspace{1cm} (7)

According to Eq. 7, in the steady state, the output active power of VSG should be

$$P_s = P_{ref} + K_u \cdot (\omega_0 - \omega_{com})$$  \hspace{1cm} (8)

Eq. 8 shows that to achieve the active power sharing control, for each VSG its frequency adjustment coefficient $K_u$ and its active capacity $P_s$ should meet the following formula.

$$P_1 \frac{K_u}{K_{u1}} = P_2 \frac{K_u}{K_{u2}} = \ldots = P_k \frac{K_u}{K_{uk}}$$  \hspace{1cm} (9)

### 3.2. VSG Reactive Power Sharing Control

According to VSG ontology algorithm and its excitation regulator structure, in order to achieve the VSG reactive power dispatch, for each VSG the output voltage instruction $U_{ref}$ should be

$$U_{ref} = U_0 + \frac{X_0}{K_u U_0} Q_{ref}$$  \hspace{1cm} (10)

Where $U_0$ is the reference value of VSG output voltage, $X_0$ is the VSG equivalent output impedance, $K_u$ is the VSG voltage regulation factor, $Q_{ref}$ is the VSG output reactive power instruction. According to Eq. 10, the corresponding voltage regulation characteristics is

$$U - U_0 = -\frac{X_0}{3(1 + K_u) U_0} (Q - Q_{ref}) = -n(Q - Q_{ref})$$  \hspace{1cm} (11)

Where $n$ is the reactive power-voltage regulation factor of VSG. To ensure the VSG can share the reactive load in proportion to its reactive capacity, the $n_k$ value of each VSG and its reactive capacity $Q_k$ need to meet the following formula.

$$n_1 Q_1 = n_2 Q_2 = \ldots = n_k Q_k$$  \hspace{1cm} (12)

When the sum of VSG equivalent output impedance and line impedance are inductive, the output reactive power of VSG is approximated to

$$Q = \frac{U(U - U_{com})}{X}$$  \hspace{1cm} (13)

In Eq. 13, the meaning of the parameters are the same as those in Eq. 6. If the sampling delay is not considered, the closed loop regulation structure of the VSG reactive power can be obtained by the above analysis, as shown in Fig. 7.

![Figure 7. Block Diagram of VSG Reactive Power Closed Loop Control](image)
According to Fig. 7, in the steady state, the VSG output reactive power is

\[ Q = \frac{nU}{X + nU} \cdot Q_{ref} + \frac{U}{X + nU} (U_0 - U_{ref}) \]  

(14)

Eq. 14 shows that in the steady state, the size of VSG output reactive power is related to the sum of VSG equivalent output impedance and line impedance. In order to make the parallel VSGs can share the reactive load according to their capacity, in addition to setting the \( n \) value by Eq. 12, it must also meet the following requirements.

\[ \frac{X_1}{n_1} = \frac{X_2}{n_2} = ... = \frac{X_k}{n_k} \]  

(15)

4. FREQUENCY AND VOLTAGE CONTROL OF MICROGRID SYSTEM BASED ON VSG

4.1 Microgrid Secondary Frequency Regulation And Secondary Voltage Regulation

In islanding operation mode, the VSG speed governor controls the system frequency is called primary frequency regulation, and the VSG excitation regulator controls the system voltage is called primary voltage regulation. According to the above mentioned control structures of speed governor and excitation regulator of VSG, it can be seen that the VSG adjusts the frequency and voltage using the proportional (P) regulators. In the steady state, if there is unplanned load power, the system frequency and voltage will have some control deviation. Therefore, the secondary regulation of frequency and voltage is necessary, so that the VSG output power can make up for the unplanned load power, to achieve the zero-error control of frequency and voltage.

The easiest way of secondary regulation is to change the P regulation in the speed governor and excitation regulator of the VSG to the PI regulation, to achieve no-deviation regulation for frequency and voltage. The disadvantage of this decentralized regulation is that each VSG is prone to an endless PI adjustment, so that its output power repeatedly oscillates, which is not conducive to the stability of the microgrid system. To this end, the microgrid central control unit can be used to carry out the secondary regulation.

The centralized secondary frequency regulation is to detect the frequency deviation \( \Delta \omega \) of a certain point in microgrid, the active power total adjustment amount \( \Delta P \) is obtained after the PI regulation, and then the active power adjustment amount \( \Delta P_k \) of each VSG is calculated according to certain distribution rule (such as according to the size of the frequency adjustment coefficient \( K_{\omega} \)). The \( \Delta P_k \) is superimposed with the planned active power \( P_{ref} \) to obtain the VSG active power command value \( P_{refk} \). The centralized secondary frequency regulation can effectively avoid the problem of endless regulation and oscillation caused by the decentralized secondary frequency regulation, and each frequency regulation unit can reasonably share the load power fluctuations according to the distribution rule. The control structure of the centralized secondary frequency regulation is shown in Fig. 8.

![Figure 8. structure diagram of centralized secondary frequency regulation](image)

The voltage of each node in the microgrid varies with the line impedance, and it is difficult to control the voltage of all nodes. In view of the fact that the majority of the loads obtain voltage via the hub bus, a realistic secondary voltage regulation method is to control the voltage of the hub bus to ensure the power supply quality. It may be assumed that there is only one hub bus in the microgrid, comparing the actual voltage detection value
$U$ of the hub bus with its given value $U_{ref}$, according to the voltage deviation, the reactive power total adjustment amount $\Delta Q$ is obtained by the PI regulation, and then the reactive power adjustment amount $\Delta Q_k$ of each VSG is calculated according to certain distribution rule (such as according to the size of the reactive power-voltage regulation factor $n$), then the $\Delta Q_k$ is superimposed with the planned reactive power $Q_0k$ to obtain the VSG reactive power command value $Q_{refk}$. The control structure of the centralized secondary voltage regulation is shown in Fig. 9.

4.2 Hierarchical Control Of Frequency And Voltage In Microgrid System

When the number of microgrid inverters is large, the central controller of microgrid is required to control the inverters to maintain the stability of the system frequency and voltage. In order to meet the rapidly changing needs of the load on energy, the hierarchical control of the frequency and voltage of the microgrid system is carried out by combining the slow adjustment of the central controller and the quick adjustment of the microgrid inverter itself, which is an effective means to maintain the stable operation of the system.

The VSG based hierarchical control of the frequency and voltage of the microgrid is shown in Fig. 10. In the hierarchical control structure, each layer is connected with two-way communication lines, the main functions of each layer are as follows:

The first layer is the local control of microgrid, which is realized by the microgrid inverter, it’s the lowest layer of the hierarchical control structure. This layer performs the corresponding functions according to the control commands sent by the second layer, mainly including the VSG pre-parallel control, the VSG grid-connected control and the primary regulation of frequency and voltage in islanding operation mode. The inverters in this layer have a certain ability to operate independently, which can quickly regulate the voltage and frequency of the microgrid, requiring fast response and short regulation cycle.

The second layer is the system-level control of the microgrid, the main functions include microgrid pre-parallel control, islanding detection, non-error control of the tie-line power in grid-connected mode, secondary frequency regulation and secondary voltage regulation in islanding operation mode etc. The control period of this layer is longer than that of the first layer, shorter than the third layer, and the control information of the microgrid is required to be transmitted to the other two layers.

The third layer is also the system-level control of microgrid, which is mainly used for energy management and optimal economic operation. According to the power generation forecasting of distributed generators in the microgrid, the load demand forecast and the power market information, the planned active power and reactive power at a certain time are provided for each distributed generator, to minimize the system cost and loss and to maximize the operation benefit, this layer has the longest regulation cycle.

In islanding operation mode, the hierarchical control structure is represented by a plurality of distributed generators as a main control unit. Relative to the single main control unit of the master-slave control structure, the dependency of the hierarchical control on the main control unit is Weak, and it’s system reliability is higher.

![Figure 10. structure diagram of microgrid hierarchical control](image-url)
5. SIMULATION AND EXPERIMENT VERIFICATION

To verify the effectiveness of the VSG based microgrid inverter control strategy, a VSG simulation model consisting of two single phase inverters has been constructed to performed Matlab simulation. The simulation parameters are set as follows: VSG DC supply voltage \( U_{dc} \) is 400V, the filter inductance \( L_1 \) and the line inductance \( L_2 \) are all 1mH, the filter capacitor \( C \) is 30\( \mu \)F, the reference values of the system frequency and voltage amplitude are 311.127V and 314.1593rad/s respectively, the VSG stator armature resistance \( r_s \) is 0 and the synchronous reactance \( x_s \) is 5mH, the damping coefficient \( D \) is 0 and the rotary inertia \( J \) is 0.6 kg*m^2. The frequency adjustment coefficients are \( K_{ω1}=0.5 \times 10^4 \) and \( K_{ω2}=10^5 \), reactive power-voltage regulation factors are taken as \( n_1=n_2=10^4 \), the specified values of active power are \( P_{ref1}=1000W \) and \( P_{ref2}=2000W \), and the specified values of reactive power are \( Q_{ref1}=750Var \) and \( Q_{ref2}=750Var \).

The simulation results are shown in Fig. 11, firstly sets VSG in islanding operation mode, at first VSG1 alone supplies power to the load, the initial active load is set to 3000W and the initial inductive reactive load set to 1500Var; at the moment of 1 second the VSG2 starts synchronization control, when the output voltages of VSG1 and VSG2 reach the synchronization requirements in the amplitude, frequency and phase, the VSG2 is put into operation to supply the load together with VSG1; at the moment of 3 second the load changes, the active load suddenly increases 1500W and the reactive load increases 500Var; at the moment of 4 second the synchronization control is started, when the two VSGs meet the grid-connected requirement, their operation mode will switch from islanding mode to grid-connected mode.

Fig. 11(a) are the output active power simulation waveforms of the two VSGs. As can be seen from the waveforms, at the very start the VSG1 alone supplies power to the load, the initial active load is set to 3000W and the initial inductive reactive load set to 1500Var; at the moment of 1 second the VSG2 starts synchronization control, when the output voltages of VSG1 and VSG2 reach the synchronization requirements in the amplitude, frequency and phase, the active load suddenly increases 1500W and the reactive load increases 500Var; at the moment of 4 second the synchronization control is started, the two VSGs meet the grid-connected requirement, their operation mode will switch from islanding mode to grid-connected mode.

Fig. 11(b) are the output reactive power simulation waveforms of the two VSGs. It can be seen that at initial stage the VSG1 alone affords 1500Var reactive load. After VSG2 putting into operation, because the two VSGs’ reactive instructions and their reactive-voltage regulation factor \( n \) are the same, their reactive power outputs before and after the load mutation are all the same, which shows that the microgrid system can achieve its reactive power sharing control. After the grid-connected mode, from Fig. 4(b) we know that due to the introduction of voltage adjusting value \( ∆U_0 \), the reactive outputs of the two VSGs are finally stabilized at their specified values.

Fig. 11(c) and Fig. 11(d) are the simulation waveforms of VSG frequency instructions and output voltage magnitude instructions. It can be seen from the comparison of Fig. 11(a) and Fig. 11(c) that the two VSGs adjust their frequency instructions based on the change of active load, so as to change their active power outputs to match the active load size. Similarly, by the comparison of Fig. 11(b) and Fig. 11(d), we can see that the two VSGs adjust their output voltage amplitude instructions based on the change of reactive load, thus their reactive power outputs are adjusted to match the reactive load size. It shows that the VSG speed governor and the VSG excitation regulator can simulate respectively active power-frequency and reactive power-voltage characteristic of synchronous generator, which can control the stability of the system voltage and frequency and can maintain the balance of active and reactive power.

Fig. 11(e) reflects the effect of VSG synchronization control, the two voltages in this figure are respectively the voltage of point of common coupling (PCC) and the grid voltage. It can be seen that because the synchronization control is carried out at the moment of 4 seconds, at first the two voltage waveforms are not completely overlap due to their difference of amplitude, frequency and phase; by the synchronization control the two voltages gradually achieve synchronization, the voltage waveforms are also coincident, which shows that the VSG can switch the inverter operation mode very well.

To further verify the VSG based control strategy, an experiment platform has been set up, the experiment system consists of two single phase inverters, and the central hardware is TMS320F28335 DSP. The system parameters are as follows: DC power supply voltage is 200V, the filter inductor is 0.7mH, the filter capacitor is 30\( \mu \)F, the line additional inductance is 0.5mH, the specified values of output voltage and active power of the two inverters are 100V and 1000W respectively. The frequency adjustment factor \( K_{ω} \) and reactive power-voltage regulation factor \( n \) of the two VSGs are the same, the experimental results are shown in Fig. 12.

Fig. 12(a) are the test waveforms for VSG mode switching and grid-connected mode power dispatch, the load is 2000W/0Var. Firstly, the two VSGs operate in islanding mode, then implement the synchronization control, and then transfer to the grid-connected mode after the synchronization requirements are met. After the
grid-connected mode, the two VSGs operate for some time under the 1000W active power instructions and then increase 500W the power specified values respectively. Fig. 12(a) is the output voltage and output current waveforms of one of the VSGs, it shows that the VSG can implement mode switching and in the grid-connected mode it can dispatch its output power. However, after switching to grid-connected mode, we also see that the VSG output active power is less then its specified value 1000W, the reason is that the grid frequency is slightly greater than the rated value of 50Hz, by the VSG regulating its active output according to the active power-frequency characteristic, the active power output of VSG is reduced, it shows that VSG has the function of regulating the system frequency.

Fig. 12(b) are the VSG output voltage and grid voltage waveforms after the implementation of synchronization control. As we can see that the two voltages gradually realize the synchronization, which shows the effect of synchronization control.

Fig. 12(c) are the load mutation test waveforms for the two VGSs parallel operating under islanding mode, the load at a certain instant suddenly increased from 700W/0Var to 1000W/0Var. From Fig. 12(c) we can see that the output currents of the two VSGs increase with the increase of load and can re-enter into steady state rapidly, which shows that the VSG has fast dynamic response and good current-sharing control.

**Figure 11.** the Waveforms of Simulation Verification

**Figure 12.** the Waveforms of Experiment Verification
6. CONCLUSION

Aiming at the shortcoming of the microgrid inverter droop control, a VSG based new control strategy is proposed in this paper. By ontology algorithm, this control strategy can simulate the operation characteristics of synchronous generator such as large rotational inertia and high output inductance. By designing the speed governor and excitation regulator of VSG, it can mimic the control characteristics of synchronous generator, thereby improving the control performance of microgrid inverter. The simulation and experiment results show that the VSG based microgrid inverter control strategy has a good synchronization control and power sharing control characteristics and can maintain the stability of voltage and frequency in islanding and grid-connected mode, which can meet the control requirements of microgrid inverter.

ACKNOWLEDGEMENTS

This work is supported by the natural science foundation project of Anhui Province(160805ME120), the university natural science research project of Anhui Province (KJ2015A245), and Research Fund of Tongling University (2014txyrc03)

REFERENCES


