Unbalanced voltage control of virtual synchronous generator in isolated micro-grid

Y Z Cao*, H N Wang and B Chen

School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China

*Email: 814390474@qq.com

Abstract. Virtual synchronous generator (VSG) control is recommended to stabilize the voltage and frequency in isolated micro-grid. However, common VSG control is challenged by widely used unbalance loads, and the linked unbalance voltage problem worsens the power quality of the micro-grid. In this paper, the mathematical model of VSG was presented. Based on the analysis of positive- and negative-sequence equivalent circuit of VSG, an approach was proposed to eliminate the negative-sequence voltage of VSG with unbalance loads. Delay cancellation method and PI controller were utilized to identify and suppress the negative-sequence voltages. Simulation results verify the feasibility of proposed control strategy.

1. Introduction

Micro-grid that using wind, solar and other renewable energy as main source is an effective local power supply, which has broad application prospects in the mountain area and island [1]. However, isolated micro-grid often has no synchronous power supply to support its voltage and frequency. Therefore, the virtual synchronous generator(VSG) control is usually adopted in the isolated micro-grid inverter [2-3]. The existing VSG works as voltage source, and the output voltage is usually open-loop controlled. When unbalanced loads connect to the isolated micro-grid, the unbalance degree of output voltage is usually higher than national standard—2%.

The circuit topology of the neutral-splitting circuit or the three-phase four-leg circuit has solved the problem brought by unbalance loads. But the applications are not common in existing micro-grid inverter products, as this type of topology increases the cost of the system and introduces the problem of neutral point voltage balance control. For the control of unbalance voltage in isolated micro-grid, the existing research mainly focused on the compensation of negative-sequence voltage [4-5]. Reference [6] derived universal transformation from synchronous to stationary reference frame, then proposed the concept of virtual composite impedance to control the positive- and negative-sequence voltage respectively. References [7-8] pointed that the negative-sequence voltage caused by unbalance loads can be controlled indirectly by controlling negative-sequence admittance. Reference [9] proposed a virtual negative impedance control method to compensate the voltage drop on the inverter output impedance, which effectively reduced the voltage unbalance degree. However, the existing relevant papers had no analysis of the generation mechanism of VSG output voltage imbalance, and the unbalanced voltage control method remains to be further studied.

This paper aims at solving the electrical power quality problem of isolated micro-grid inverter operating with VSG control strategy under unbalanced loads situation. On the basis of the positive-
and negative-sequence equivalent circuit of VSG and negative-sequence voltage depressing methods, an improved VSG voltage control algorithm has been proposed. Simulation results have verified that using this control strategy can promote the ability of carrying unbalanced load and improve the power supply quality.

2. Basic principle of VSG
The typical main circuit topology of three-phase three-wire inverter is shown in Figure 1.

![Figure 1. Topology of VSG main circuit.](image)

2.1. VSG ontology model
The motion equation of the rotor and the electrical equation of the stator are respectively shown in equation (1), which using the mathematical language to describe the rotary synchronous generator electromagnetic changes and mechanical motion.

\[
\begin{align*}
T_m - T_e &= P_m - P_e = f \frac{d\omega}{dt} - D(\omega - \omega_s) \\
\mathbf{u}_{abc} &= E_0 \sin \theta_{abc} - L_{SG} \frac{\mathbf{d}i_{abc}}{dt} - r_{SG} \mathbf{i}_{abc}
\end{align*}
\]

In equation (1), \(\omega_s\) is the synchronous angular velocity of the AC bus; \(E_0\) is the open-circuit voltage amplitude of the synchronous generator; \(L_{SG}\) is the synchronous reactance, and \(r_{SG}\) is the stator resistance.

The excitation equation of the synchronous generator is shown in equation (2), where \(i_{f0}\) is the excitation current required to synchronize the generator to establish the rated no-load electromotive force when the rotor is running at rated speed.

\[
i_f = i_{f0} + \Delta i_f
\]

But in VSG, the excitation current is not an intuitive controllable variable, which is not easy to set the parameters. In the case of neglecting the saturation of the magnetic circuit, the open-circuit voltage \(E_0\) and the excitation current \(i_f\) is approximately proportional relationship [4]. Therefore, we can see that the no-load EMF \(E_0\) is: \(E_0 = \omega_0 M_f i_{f0}\), \(M_f\) is the inter-rotor mutual inductance. By multiplying both sides of equation (2) by the constant term \(\omega_0 M_f\), we can obtain equation (3):

\[
\omega_0 M_f i_f = \omega_0 M_f i_{f0} + \omega_0 M_f \Delta i_f
\]

That is the same expression as equation (4):

\[
E_0 = \frac{E_{fe} + \Delta E_f}{\omega_0} \times \omega = \frac{E_{fe}}{\omega_0} \times \omega
\]

Thus, the adjustment of the excitation current \(i_f\) can be converted into a direct adjustment to the open-circuit voltage \(E_0\). The excitation process of real synchronous generator has a certain hysteresis, so join the first-order inertia link to make sure that the excitation system of VSG is closer to the excitation system of real synchronous generator. Since the realization of the synchronous reactance is behind the combined of EMF, it is placed outside the VSG ontology model. Together with virtual speed regulator and virtual excitation regulator, the VSG ontology model can be shown in Figure 2.
2.2. Realization of synchronous reactance

The synchronous reactance is an important parameter in synchronous generator. In order to simulate the synchronous generator accurately, the synchronous reactance must be introduced as a control parameters of VSG. If the equation in (1) is rewritten as a current integral form, as shown in equation (5), the output can the stator current of synchronous generator.

\[ i_{abc} = \frac{1}{L_{SG}} \left( e_{abc} - u_{abc} - r_{SG}i_{abc} \right) dt \]  

By using the stator current as the reference current of VSG, and introducing current closed-loop, the output current of VSG can be consistent with the output current of synchronous generator, which ensuring the VSG can accurately simulate the running characteristics of synchronous generator.

3. Negative-sequence voltage control of VSG

There is a large amount of single-phase loads in micro-grid. The load current presents asymmetry when common VSG connects to these loads in island mode, which leads to output voltage unbalanced.

3.1. Analysis of VSG under unbalance loads

Based on symmetric component method, we can know that three-phase unbalanced phasors can be decomposed into three sets of symmetric phasors: positive-sequence, negative-sequence and zero-sequence component. For the three-phase inverter without neutral line, the zero-sequence is usually neglected.

According to the deduction and analysis in reference [10], we can obtain positive- and negative-sequence equivalent circuit of VSG in island mode, as shown in Figure 4.

3.2. The extraction of negative-sequence component

In order to suppress the negative-sequence component, we need to extract it from unbalanced voltages first. Three-phase asymmetric voltage can be decomposed according to equation (6).
\[ u_a \]
\[ u_b = U_{m+} \begin{bmatrix} 
\cos(\alpha + \varphi_+ - 120') \\
\cos(\alpha + \varphi_+ + 120')
\end{bmatrix} + U_{m-} \begin{bmatrix} 
\cos(\alpha + \varphi_- - 120') \\
\cos(\alpha + \varphi_- + 120')
\end{bmatrix} \]

where \( U_{m+} \), \( U_{m-} \) respectively means the positive- and negative-sequence peak value of fundamental voltage. And \( \varphi_+\varphi_- \) respectively means the initial phase angle of the positive- and negative-sequence of fundamental wave voltage. Transform the positive- and negative-sequence components into \( \alpha-\beta \) axis, then equation (7) and (8) are obtained.

\[ \begin{bmatrix} 
\frac{1}{2} - \frac{1}{\sqrt{3}} \\
0
\end{bmatrix} \begin{bmatrix} 
u_{\alpha+} \\
u_{\beta+}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix} 
\frac{\sqrt{3}}{2} \\
-\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix} 
u_{\alpha+} \\
u_{\beta+}
\end{bmatrix} = \begin{bmatrix} 
\cos(\alpha + \varphi_+) \\
\sin(\alpha + \varphi_+)
\end{bmatrix} \]

\[ \begin{bmatrix} 
\frac{1}{2} - \frac{1}{\sqrt{3}} \\
0
\end{bmatrix} \begin{bmatrix} 
u_{\alpha-} \\
u_{\beta-}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix} 
\frac{\sqrt{3}}{2} \\
-\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix} 
u_{\alpha-} \\
u_{\beta-}
\end{bmatrix} = \begin{bmatrix} 
\cos(-\alpha + \varphi_-) \\
-\sin(-\alpha + \varphi_-)
\end{bmatrix} \]

We can find that \( u_{\alpha+} \) and \( u_{\beta+} \) have the cosine-sine function relationship with the same amplitude and frequency. Thus, the delay cancellation method[11] can be used to acquire the \( u_{\alpha-},u_{\beta-} \) component, where they are still AC values in the \( \alpha-\beta \) axis. In this paper, the positive- and negative-sequence components are transformed into the d-q axis rotating coordinate to control. The control diagram of negative-sequence component extraction method is shown in Figure 5.

**Figure 5.** Control diagram of negative-sequence component extraction method.

In the above figure, \( \theta \) is the angle between d-axis and a-axis, \( R(\theta) \) represents the transformation matrix of positive-sequence from \( \alpha-\beta \) axis to d-q axis, while \( R(-\theta) \) represents the negative one. In order to achieve 90° phase shift, the SOGI phase shift system is adopted, and its transfer function can be reorganized as equation (9):

\[ \begin{align*}
D(s) &= \frac{u'_a}{u_a} = \frac{k \cos}{s^2 + k \cos + \omega^2} \\
Q(s) &= \frac{j u'_a}{u_a} = \frac{k \omega^2}{s^2 + k \cos + \omega^2}
\end{align*} \]

When \( k = 1, \omega = 100\pi \), \( D(s) \) has a gain of 1dB at 50Hz and the phase offset is 0°, while \( Q(s) \) has a gain of 1dB and the phase offset is 90° at the same frequency.

### 3.3. Unbalance voltage control strategy

In order to suppress the negative-sequence voltage and increase the unbalance load capacity of VSG, the unbalance voltage control strategy for VSG is designed (shown in Figure 6).
Figure 6. Unbalance voltage control structure diagram of isolated VSG.

The measured output terminal voltage $u_{abc}$ are calculated through delay cancellation method and thus the positive- and negative-sequence components in the α-β axis are obtained. The negative-sequence component $u_{Cα}$ and $u_{Cβ}$ are transformed into d-q axis to achieve the direct-current negative-sequence components $u_{Cd}$ and $u_{Cq}$. According to the classical control theory, in the synchronous rotating coordinate system, the negative sequence output voltage can track the reference quantity without static error using PI controller. The reference DC negative-sequence components $u_{Cd}$ and $u_{Cq}$ are set to 0 and the PI controller output values are added on the current loop reference instructions $i_d^*$ and $i_q^*$ as compensations. This improved VSG control can suppress the negative-sequence voltages to zero.

4. Simulation results

The simulation was performed in Matlab/simulink environment to verify the feasibility of proposed unbalance voltage control strategy. Simulation parameters are shown in Table 1.

| Block name         | Parameter value                                      |
|--------------------|------------------------------------------------------|
| Inverter           | $U_{dc}=600V$; LC Filter: L=0.35mH, C=50μF; Switching frequency: $f=6000Hz$; Rated capacity: $P_N=100kW$ |
| Current loop       | PI regulator: $k_p=1.2, k_i=60$                     |
| NSV control        | PI regulator: $k_p=2.4, k_i=120$                    |
| Simulation duration| 1s (intercept displaying 0.5~0.6s)                  |
| Load               | $P=90kW, Q_r=30kvar$                                |
| Unbalance condition| (1) Inserting 5Ω load between A and C phase (2) B phase load out of running |

Unbalance degree is usually adopted to indicate how bad the unbalance condition is. It is defined as the amplitude ratio of negative-sequence and positive-sequence component. Unbalance degree is expected to keep as small as possible.

The output voltage and load current waveform under unbalance condition(1) can be seen in Figure 7. When inserting 5Ω load between A and C phase, the output voltage of common VSG become unbalanced distinctly. The unbalance degree of output voltage comes to 7.5%, which is higher than relevant standard. In contrast, the improved VSG outputs three-phase balanced voltage, whose unbalance degree is 0.17%.
Figure 7. Comparison of simulation results under unbalance condition(1).

Figure 8 shows the output voltage and load current waveform under unbalance condition(2). The unbalance degree of output voltage comes to 12.4% when B phase load is out of running, which is too much higher than 2%. In contrast, the improved VSG outputs three-phase balanced voltage, whose unbalance degree is 0.21%.

Figure 8. Comparison of simulation results under unbalance condition(2).

By comparing the simulation results, we can draw a conclusion that the proposed unbalance voltage control strategy can make VSG adapt to various kind of unbalance loads, even the worst condition: one phase load out of running. The unbalance degree of output voltage can be kept under 0.5%.

5. Conclusion

In isolated micro-grid, the output voltage unbalance degree of common VSG is difficult to fit the relevant technical standards because of the existence of a large number of asymmetric loads. In this paper, an improved VSG voltage control algorithm has been proposed based on the positive- and negative-sequence equivalent circuit of VSG and negative-sequence voltage depressing methods. The simulation results verify the feasibility and effectiveness of the proposed VSG unbalance voltage control strategy. However, the problem of voltage unbalance in multiple VSG co-governed island mode is still to be further studied.

References
[1] Robert H Lasseter 2007 Microgrids and Distributed Generation Intelligent Automation & Soft Computing 133(3) pp 225-34
[2] Sakimoto K and Miura Y 2011 Stabilization of a power system with a distributed generator by a Virtual Synchronous Generator function Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on IEEE pp 1498-1505
[3] Zhong Q C and Weiss G 2011 Synchronverters: Inverters That Mimic Synchronous Generators IEEE Transactions on Industrial Electronics 58(4) pp 1259-67

[4] Liu J and Yushi M 2016 Parallel operation of a synchronous generator and a virtual synchronous generator under unbalanced loading condition in microgrids IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia) pp 3741-8

[5] Liu Q W and Tao Y 2014 Voltage unbalance and harmonics compensation for islanded microgrid inverters IET Power Electronics 7(5) pp 1055-63

[6] Wang Y C and Luo A 2015 An unbalanced voltage compensation method for parallel inverters in microgrids Proceedings of the CSEE 35(19) pp 4956-64(in Chinese)

[7] Alipoor J and Miura Y 2014 Voltage sag ride-through performance of virtual synchronous generator Power Electronics Conference pp 3298-305

[8] Zhao X and Wu X H 2015 A direct voltage unbalance compensation strategy for islanded microgrids IEEE Applied Power Electronics Conference and Exposition (APEC) pp 3252-9

[9] Savaghebi M and Jalilian A 2013 Autonomous voltage unbalance compensation in an islanded droop-controlled microgrid IEEE Transactions on Industrial Electronics 60(4) pp 1390-1402

[10] Zeng Z and Shao W H 2017 Unbalanced Voltage Control of Virtual Synchronous Generator in Islanded Micro-grid Proceedings of the CSEE 37(2) pp 372-80

[11] Karthikeyan S S and Kumar R S 2012 Design and analysis of controller for three-phase UPS system Electrical, Electronics and Computer Science (SCEECS) pp 1-4