Parallel Stability Analysis of Generator and Inverter in Independent Micro grid

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Abstract. In the independent micro grid system, the generator set and the new energy grid connected inverter are both important components of the system. To solve the problem of stability of the parallel of the inverter and synchronous generator, this paper studied the droop control and the virtual synchronous machine control principle, analyzed their similarities and differences and essential characteristics; established the small signal model of the parallel system of the inverter generator set, analyzed the stability of different structural systems. It Comed to conclusion that the stability of the virtual synchronous machine control in the parallel system was stronger, and the system simulation model was built by Matlab / Simulink software to verify the theoretical analysis results.

1. Introduction
The independent micro grid has the characteristics of simple structure and high efficiency. It has a wide application prospect in remote mountainous areas away from the grid, base posts and other places [1, 2]. Its structure is shown in Figure 1. By controlling the mode change-over switch on the AC bus, the system can complete the transformation of operation states such as grid connection, power distribution and load switching [3-5]. However, due to the different nature and structure of new energy generation inverter and generator set, how to realize the stable grid connection and operation of inverter and generator set has become the key problem to be solved. In view of this problem, literature [6] proposes that voltage source control is used when the inverter and generator are separately powered under various working conditions, and electricity is used when the inverter is parallel to the diesel generator flow source control, so as to achieve stable parallel operation. But there are some problems in this method, such as the complexity of control mode and the impact of mode switching. In literature [7], virtual synchronous machine control is directly used to realize the grid connection of inverter and diesel engine, but why such a control method is used is not mentioned. Through the analysis of control structure in literature [8], the differences between virtual synchronous machine control and droop control are obtained, but only the structural characteristics of the two control modes are analyzed independently, and the differences between the two control modes in the parallel system of generator unit and inverter are not analyzed.

It can be seen that there are differences in the current inverter control methods for the generator inverter parallel system, lacking systematic theoretical analysis. In this paper, by analyzing the characteristics of different control modes of the parallel system, the small signal model of the system is established, and the parallel stability problem is grouped in detail, and verified by simulation.
2. Brief introduction of inverter control method

The independent micro grid requires that the new energy inverter can stabilize the frequency and voltage of the bus in independent operation, and can realize the reasonable distribution of power in parallel operation. Among the current inverter control methods, droop control and VSG control can meet the requirements of power distribution without communication and bus voltage and frequency support [9-11]. Therefore, these two control methods are selected as the research content of this paper, and the structure diagram is shown in Figure 2. The two control methods are similar in structure, but they have their own characteristics in specific application. In this paper, firstly, the characteristics and similarities and differences between droop control and VSG control are analyzed, and then the strategy of improving system stability is studied by small signal analysis. Finally, the above conclusions are verified by simulation.

3. Comparative analysis of droop control and VSG control

Inverter control is divided into modulation layer, control layer and function layer [12-14]. Among them, the modulation layer controls the working state of the inverter by outputting SPWM modulation wave signal; the control layer adopts voltage and current double closed-loop PI control; the function layer is the core algorithm of the inverter to realize various kinds of control. In this paper, the characteristics of functional layer in inverter control are studied.

\[
\begin{align*}
\omega &= \omega_n + k_p (P_n - P) \\
E &= E_n + k_q (Q_n - Q)
\end{align*}
\]

(1)

\(E_n, \omega_n\) is rated voltage and frequency, \(P_n, Q_n\) is rated active power and reactive power, and \(k_p, k_q\) is active frequency and reactive voltage droop coefficient.

When the pole pairs are 1, the traditional synchronous generator has the following power frequency equation:

Figure 1. Structure diagram of independent micro grid

Figure 2. Inverter control schematic diagram
Where $P_m$ is the mechanical power input by the generator, $P_e$ is the electrical power output by the generator, $J$ is the inertia constant, $\theta$ is the phase angle of the excitation electromotive force, $\delta$ is the angle between the excitation electromotive force and the voltage at the stator end, $\omega_n$ is the rotor speed. VSG control is based on this equation, adding the influence of damping winding [15]. When the speed $\omega_n$ is near the synchronous speed point $\omega_0$, it is approximately considered that $\omega_n$ is equal to $\omega_0$, and the motion equation can be simplified as follows:

$$\frac{P_m}{\omega} - \frac{P_e}{\omega} - D_0 \Delta \omega = J_0 \frac{d \Delta \omega}{dt}$$

(3)

It is further sorted into the standard form of inertia link:

$$\omega_0 - \omega = \frac{-m}{(\tau s + 1)} (P_{ref} - P)$$

(4)

$$\begin{cases} 
\tau = \frac{J \omega_0}{D \omega_0 + K_\omega} \\
\omega_0 = \frac{1}{D \omega_0 + K_\omega}
\end{cases}$$

(5)

Combining formula 3-1, it can be seen that in the droop control and VSG control, the function of $k_p$ and $\frac{1}{Js + D}$ is the same. In the steady state, according to the terminal value theorem, there are:

$$\omega = \omega_0 + \frac{1}{D} (P_m - P_e)$$

(6)

If $k_p = \frac{1}{Js + D}$, the effect of VSG control and droop control is the same, which means that droop control and VSG control can achieve frequency power droop in steady state, which has good performance of grid connection; in dynamic process, when there is change of $P_m - P_e$, that is, when the system faces power mutation, $\frac{1}{Js + D}$ is equivalent to inertia link, and the response of droop control is compared, the frequency change output of the two controls is:

![Figure 3. Inverter control power frequency response curve](image)

As shown in Figure 3, the droop control is equivalent to the proportional control and the VSG control is equivalent to the inertia control. In the face of sudden power change, the initial and final values of the
two are the same, but the VSG control change is more smooth, which is similar to that of the traditional synchronous generator when the load changes, the first is the rotating energy of the rotor to balance the load fluctuation, so the frequency will not change abruptly [16]. When $J=0$, VSG control is equivalent to droop control, which reveals the internal relationship between the two control methods.

4. Small signal model analysis of parallel operation stability of inverter generator set

Through the above analysis, it can be found that the moment of inertia is the core part of the difference between VSG control and droop control [17-19]. Therefore, the simulation further analyzes the stability of two different control methods in the inverter generator parallel system by setting different values of virtual inertia. The parallel model of the inverter generator set is shown in Figure 4. $U_2 \angle \phi_2$ is the equivalent power supply of the generator set, the moment of inertia is always $J$. $U_2 \angle \phi_2$ is the equivalent power supply of the grid connected inverter, the moment of inertia changes from 0 to $J$. The inverter control is transformed into droop control to VSG control. Observe the stability change of the parallel system in this process.

$$
\begin{align*}
U_1 \angle \phi_1 & = \text{generator set output voltage} \\
E & = \text{grid connected inverter output voltage} \\
J & = \text{moment of inertia}
\end{align*}
$$

Figure 4. Parallel system model of microsource

In order to determine the parallel stability of the system, a small signal model is established, $E \angle 0$ is the AC bus voltage, and the phase angle is set as zero, $\delta_i$ is the phase angle difference between the inverter and the generator set, $U_i \angle \phi_i$ ($i=1,2$) is the output voltage value of each micro source inverter, $Z_i$ is the common load of the parallel system, and $Z_i$ ($i=1,2$) is the output impedance of the inverter and the generator set respectively.

When $J_1=J_2=J$, the system is equivalent to the operation state of double synchronous machine (or double VSG control), and the parallel system is linearized at the steady-state working point $(\omega_s, P_{es}, \delta_s)$ [20], which can be obtained from equation 3-2

$$
\begin{align*}
\frac{d(\omega_0 + \Delta \omega)}{dt} &= \frac{P_{ref} + K_{wi} \Delta \omega}{J_0 \omega_0} - \frac{D_0}{J_0} \Delta \omega - \frac{\Delta P_i}{J_0 \omega_0} \\
\frac{d(\delta_0 + \Delta \delta)}{dt} &= \Delta \omega
\end{align*}
$$

Direct flow is omitted and sorted into matrix form as follows:

$$
\begin{bmatrix}
\frac{d \Delta \delta_1}{dt} \\
\frac{d \Delta \omega}{dt} \\
\frac{d \Delta \omega_1}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & 1 & -1 \\
-S_1 & -\frac{K_{wi} J_1}{J_0 \omega_0} + \frac{D_1}{J_1} & 0 \\
-S_2 & 0 & -\frac{K_{wi} J_2}{J_2 \omega_0} + \frac{D_2}{J_2}
\end{bmatrix} \begin{bmatrix}
\Delta \delta_1 \\
\Delta \omega \\
\Delta \omega_1
\end{bmatrix}
$$

$$
(8)
$$

$J_i$ and $D_i$ are inertia and damping of inverter and generator set respectively (inverter is virtual inertia and virtual damping); $\Delta \omega$, $\Delta \delta$ and $\Delta P_{ei}$ are angular frequency, power angle and active power increment respectively. $S_{wi}$ is the whole step power factor, which meets the following equation.
\[
\begin{align*}
\Delta P_n &= S_n \Delta \delta_{12} \\
\delta_{12} &= \delta_1 - \delta_2 \\
S_{s1} &= U_1 U_2 (-G_{12} \sin \delta_{12} + B_{12} \cos \delta_{12}) \\
S_{s2} &= U_1 U_2 (-G_{12} \sin \delta_{12} - B_{12} \cos \delta_{12})
\end{align*}
\] 

(9)

The output and load impedances in parallel network are transformed by Y-Δ to obtain \(G_{12}\) and \(B_{12}\) (take \(jX_l = 10, r_1 = r_2 = jX_l = 0, r_l = 1\)), which are brought into matrix. The characteristic equation is as follows:

\[
s^3 + As^2 + Bs + C = 0
\]

(11)

\[
A = \frac{K_{s1}}{J_1 \omega_b} + \frac{D_1}{J_1} + \frac{K_{s2}}{J_2 \omega_b} + \frac{D_2}{J_2}
\]

\[
B = \frac{K_{s1} K_{s2}}{J_1 J_2 \omega_b^2} + \frac{D_1 K_{s2}}{J_1 J_2 \omega_b} + \frac{D_2 K_{s1}}{J_1 J_2 \omega_b} + \frac{S_{s1}}{J_1 \omega_b} - \frac{S_{s2}}{J_2 \omega_b}
\]

\[
C = \frac{K_{s2} S_{s1} - K_{s1} S_{s2} + \omega_0 (D_1 S_{s1} - D_2 S_{s2})}{J_1 J_2 \omega_b}
\]

(12)

In order to simplify the equation, if the work angle is assumed to be \(\delta_{12} = 0, \sin \delta_{12} \approx 0, \cos \delta_{12} \approx 1\), then:

\[
\begin{align*}
S_{s1} &= U_1 U_2 |B_{12}| \\
S_{s2} &= -U_1 U_2 |B_{12}|
\end{align*}
\]

(13)

In order to simplify the analysis, since the synchronous generator and VSG control function in the frequency modulation characteristics, \(D\) is similar to \(K_{s1}\) it will be set to 0 here (when the system is converted to droop control, \(D\) is realized by \(K_p\)). When \(D = D_1 = J_2 + \Delta J\), there are:

\[
\begin{align*}
A &= \frac{1}{J_1} + \frac{1}{J_2} \\
B &= \frac{D^2}{J_1 J_2} + \frac{S_{s1}}{J_1 \omega_b} - \frac{S_{s2}}{J_2 \omega_b} \\
C &= \frac{D (S_{s1} - S_{s2})}{J_1 J_2 \omega_b}
\end{align*}
\]

(14)

Taking \(D = 3\) and \(J = 1\), the small signal stability analysis results of the parallel system of inverter generator set shown in the figure can be obtained. When \(\Delta J = 0\), the pole is in the left half plane. With the increase of \(\Delta J\), the pole of the system moves to the virtual axis gradually, and the stability of the parallel system decreases. When \(\Delta J \to J\), the system changes from VSG control to droop control, and the stability of the parallel system decreases to the lowest, and the pole is still in the left half plane. It can be seen that the droop control and VSG control have certain stability when they operate in parallel with the generator set, but the VSG control is more stable when they operate in parallel, and when the moment of inertia of VSG control and the generator set are the same, the system stability is the best.
5. Parallel operation simulation

In order to verify the conclusion, the grid connection simulation model of generator and inverter is established, and the system parameters are set as follows [21-23]:

| Parameter type                          | Parameter value          |
|-----------------------------------------|--------------------------|
| Rated power                             | 10kW                     |
| Rated voltage                           | 380V                     |
| Rated frequency                         | 50Hz                     |
| Inertia coefficient                     | 0.6kg                    |
| Damping coefficient                     | 60                       |
| Stator internal resistance              | 0.3Ω(0.02pu)             |
| Synchronous reactance                   | 10mH(0.2pu)              |
| Prime mover frequency modulation coeff. | 0                        |
| Voltage regulation coeff. of exciter   | 2e-4                     |

| Parameter type                          | Parameter value          |
|-----------------------------------------|--------------------------|
| DC voltage                              | 700V                     |
| Rated voltage                           | 380V                     |
| Rated frequency                         | 50Hz                     |
| Switching frequency                     | 10kHz                    |
| Filter inductance                        | 2mH                      |
| Filter capacitor                        | 50μF                     |
| Virtual resistor                        | 0.3Ω(0.02pu)             |
| Virtual reactance                       | 10mH(0.2pu)              |
| Droop control active frequency droop coeff. | 5.5e-4                  |
| Droop control reactive voltage droop coeff. | 2e-4                    |
| Moment of inertia                       | 0.6kg                    |
| Damping coefficient                     | 60                       |
| VSG control active frequency droop coeff. | 0                       |
| VSG control reactive voltage droop factor | 2e-4                    |

The process of load switching in parallel operation of the system is simulated. The specific working conditions are as follows: in the initial stage, the output power of micro source and generator unit is 8kW, the pre synchronization switch is started at 0.2s, the pre synchronization switch is closed at 0.5s, the grid connection switch is opened, and after the parallel operation, the load is added with $P_{load}=10$kW at 0.8s, the load is cut off at 1.4s, the grid connection switch is closed at 2.2s, and the simulation time is 2.5s, respectively. The active and reactive power of the motor group and the inverter are sampled to observe the fluctuation.
Figure 6. Output waveform of droop control inverter and power change of generator set

Figure 7. Output waveform of VSG control inverter and power change of generator set

Table 3. Analysis results of power frequency fluctuation

| Parameter type               | Droop control | VSG control |
|------------------------------|---------------|-------------|
| Power fluctuation rate       | 34.0%         | 18.8%       |
| Power stabilization time     | ≥0.23s        | ≥0.11s      |
| Frequency volatility         | 0.4%          | 0.2%        |
| Frequency stabilization time | ≥0.22s        | ≥0.2s       |

Under the premise of stable parallel operation, it can be seen from the simulation waveforms in Fig. 6 and Fig. 7 that the output characteristics of VSG controlled inverter and generator set are more similar to that of droop control. Under the condition of load fluctuation, the VSG controlled parallel system can realize stable power distribution and frequency stability more quickly and stably. Table 3 analyzes the fluctuation of system power and frequency. VSG has a smaller fluctuation range and shorter stability time, which verifies the correctness of theoretical analysis results.

6. Conclusion
Based on the analysis of power frequency characteristics and small signal model, this paper verifies that VSG control can better deal with the load fluctuation, realize the stable distribution of power, reduce the risk of system disconnection, and improve the stability of the system when the inverter and the generator unit operate in parallel Qualitative. VSG control of inverter has a good application prospect in the independent microgrid system.

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