Small Signal Stability Analysis of Microgrid with Multiple Parallel Inverters

Yi Han¹, Zhongmin Qian¹, Danlu Shao¹, Qiujia Lin¹, Shuangrui Yin², Minyu Chen², Qian Ai²*

¹ ZheJiang Huayun Information Technology Co., Ltd., Hangzhou, Zhejiang, 310008, China
² Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

Abstract. Microgrids are introduced into power grid for managing the high penetration of renewable energy sources (RESs). Based on the resistive characteristics of the microgrid line, this paper proposes an inverter control mode combining the outer power loop controller with anti-droop control and the inner voltage-current dual-loop controller. Meanwhile, a complete small signal model of single inverter including anti-droop control, dual-loop control, filter and branch is established. Then considering the coupling relationship of the output voltage phase angles of each inverter, the small-signal model of the microgrid with multiple parallel inverters is established under the global coordinate system. The static stability analysis of the complete microgrid is carried out by the root locus method. Results show that the anti-droop control is more conducive to the accurate distribution and fast response of the active power output by inverter units than the traditional droop control.

1. Introduction

Considering the adverse effects caused by high penetration of RESs and low-inertia power electronic devices, the islanded microgrid is more prone to oscillation than the traditional power grid [1]. Therefore, the coordinated control of each inverter connecting general distributed generation (GDG) in the microgrid is particularly important. The droop control strategy can realize the "plug and play" of power units while adapting to both grid-connected and islanded modes of microgrids, and has been widely used [2-3]. Reference [4] introduces virtual complex impedance and proposes an improved droop control strategy on the basis of analysis of multiple inverters parallel in low voltage microgrid. Besides, a generalized droop control method is proposed for a grid-supporting inverter based on a comparison between traditional droop control and virtual synchronous generator control in [5]. However, due to the resistive characteristics of the microgrid line, the decoupling conditions of traditional P-f and Q-V droop control are not satisfied. Hence the P-V and Q-f anti-droop control method can be adopted [6]. Reference [7] comprehensively considers the impact of load changes on the basis of anti-sag control. Meanwhile, the concept of resistive virtual impedance is introduced as well as an improved robust droop multi-loop control strategy is proposed in [7]. In order to analyze the influence of the control strategy on the static stability of the system, the method of small signal modeling is often used [8-9]. In [10], the whole small signal models for the current mode constant reference current and current mode dynamic reference current controlled tri-state boost converter were established respectively. Similarly, a detailed small-signal model of the MMC with consideration of the internal dynamics of the converter is developed in [11], together with the small signal model of a simplified terminal model. Results show that the
simplified model cannot evaluate some instability phenomena accurately and hence the establishment of a detailed MMC model is necessary. Besides, A complete small-signal model of grid-connected inverter is developed for the conventional droop control and an improved one with additional power differential term for the proposed droop control in [12]. Based on the above works, in this paper, we first give the anti-droop control mode in the microgrid and briefly analyze the influence of droop coefficients on the operating characteristics of the system. Then, the single inverter mathematical model is derived based on voltage and current dual-loop control. Furthermore, the complete small signal model of microgrid with multiple parallel inverters is established in the global coordinate system. Finally, the stabilities of microgrid under anti-droop control and traditional droop control mode are compared and analyzed.

2. The Microgrid Under Anti-droop Control

The basic structure of microgrid with multiple parallel inverters is shown in figure 1. DC-GDG is connected to the microgrid bus through the transmission branch after inverse and filter processing. And then the power is supplied to the load through the distribution branch.

![Figure 1. Structure diagram of microgrid with multiple parallel inverters](image)

Where $R_{e,i}$, $L_{e,i}$, $C_{e,i}$ are the filter parameters of Inverter I, $R_{c,i}$, $L_{c,i}$ are the transmission branch parameter. $R_{load,j}$, $L_{load,j}$ are the resistance and inductance of load j.

Comparing with traditional droop control, anti-droop control strategies are obtained as:

$$
\begin{align*}
\omega_i &= \omega_{IN} + m_{p,i}(Q_{o,i} - Q_{IN}) \\
U_{o,i} &= U_{IN} - m_{q,i}(P_{o,i} - P_{IN})
\end{align*}
$$

Where $\omega_i$ is the output angular frequency of Inverter i; $\omega_{IN}$, $U_{IN}$ are the no-load output frequency and voltage amplitude, respectively; $m_{p,i}$, $m_{q,i}$ are the active and reactive droop coefficients, respectively; $P_{IN}$, $Q_{IN}$ are the rated output power; $P_{o,i}$, $Q_{o,i}$ are the direct output power of Inverter i. Since the frequencies in the stable system will eventually converge, the reactive power in steady state can be accurately distributed. In order to realize the accurate distribution of active power, it is necessary that

$$
\frac{m_{p,i}}{m_{q,i}} = \frac{R_{c,j}}{R_{v,j}}
$$

Obviously, the above equation is difficult to be realized in the microgrid with multiple inverters, so the larger the value of P-droop coefficient is, the less the impact of branch resistance on active power distribution, and the response speed of inverters can be improved.
3. Small Signal Model of Single Inverter
To simplify the problem of electromagnetic coupling between three phases of the inverter, the output voltage and current of the inverter can be converted to d-q coordinate system through the outer power loop controller to calculate the instantaneous output power \( \dot{p}, \dot{q} \). The average values \( \bar{P}, \bar{Q} \) are obtained after filtering by a low pass filter. Compared with the single-loop control, the inner loop control using voltage-current dual-loop control can provide more system damping and has faster response speed.

Select the first inverter as a reference, then the phase angle difference between the d-q axis and the global D-Q axis of other inverters \((i \neq 1)\) can be expressed as:

\[
\Delta \delta = \Delta \omega - \Delta \omega_i \tag{3}
\]

In this way, except for the first inverter, the state variables of other inverters are all 13, namely:

\[
[\Delta x_{\text{inv},i}] = [\Delta \delta_i, \Delta P_{\text{ao}}, \Delta Q_{\text{ao}}, \Delta \phi_{d,i}, \Delta \phi_{q,i}, \Delta \gamma_{d,i}, \Delta \gamma_{q,i}, \Delta i_{d,i}, \Delta i_{q,i}, \Delta u_{o,d,i}, \Delta u_{o,q,i}, \Delta i_{o,d,i}, \Delta i_{o,q,i}]^T
\]

The reference inverter has no phase angle difference, so the total number of state variables is 12. A complete small signal model of a single inverter can be obtained by combining the filter and transmission branch link model:

\[
[\Delta x_{\text{inv},i}] = A_{\text{inv},i}[\Delta x_{\text{inv},i}] + B_{\text{inv},i}[\Delta u_{\text{bdQ},i}] + B_{\text{conv},i}[\Delta \omega_{\text{com}}]
\]

\[
[\Delta \omega_i, \Delta \omega_{\text{bdQ},i}] = [C_{\text{invw},i}, C_{\text{invc},i}][\Delta x_{\text{inv},i}] \tag{5}
\]

4. Small Signal Modeling for Complete Microgrid
The microgrid bus voltages \([\Delta u_{\text{bdQ}}]\) are common input variables included in both the parallel model of multiple inverters and load model. To effectively represent the node current conservation relationship between inverter cell state variables and load state variables, a large enough virtual resistance \(r_M\) can be introduced. Then we can get:

\[
[\Delta u_{\text{bdQ}}] = R_M [D_{\text{INV}}[\Delta i_{\text{bdQ}}] + D_{\text{LOAD}}[\Delta i_{\text{loadDQ}}]) \tag{6}
\]

where \(R_M = \text{diag}(r_M, r_M)\); \(D_{\text{INV}}, D_{\text{LOAD}}\) are the current flow matrices. Thus, the \((13s + 2n - 1)\)-order small signal model of the complete microgrid is represented as follows

\[
[\Delta x_{\text{INV}} \atop \Delta i_{\text{loadDQ}}] = A_{\text{MG}}[\Delta x_{\text{INV}} \atop \Delta i_{\text{loadDQ}}] = [A_1 \ A_2 \ A_3 \ A_4][\Delta x_{\text{INV}} \atop \Delta i_{\text{loadDQ}}] \tag{7}
\]

where \(A_1 = A_{\text{INV}} + B_{\text{INV}} R_M D_{\text{INV}} C_{\text{INVc}}; A_2 = B_{\text{INV}} R_M D_{\text{LOAD}}; A_3 = A_{\text{LOAD}} + B_{\text{LOAD}} R_M D_{\text{LOAD}}; A_4 = B_{\text{LOAD}} R_M D_{\text{INV}} C_{\text{INVc}} + B_{\text{LOAD}} C_{\text{INVw}}

5. Case Study
The microgrid model shown in Figure 1 is selected for analysis, in which the numbers of inverter cells and loads are \(s=2\) and \(n=3\), respectively. The inverter and load parameters are shown in Table 1. The initial frequency of the microgrid is set as \(\omega_0 = 314\text{Hz}\) and the remaining steady-state operating values are shown in Table 2.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \(R_f / \Omega\) | [0.15, 0.12] | \(\omega_c\) | 31.4 |

Table 1. Parameters of inverters and loads
\[ L_f / \text{mH} \quad [1.5, 2] \]
\[ C_f / \text{mF} \quad [0.15, 0.15] \quad k_{pv} \quad 10 \]
\[ R_f / \Omega \quad [0.5, 0.8] \quad k_{iv} \quad 100 \]
\[ L_c / \text{mH} \quad [0.127, 0.159] \quad k_{pc} \quad 10 \]
\[ R_{\text{load}} / \Omega \quad [25, 21, 24] \quad k_{ic} \quad 0 \]
\[ L_{\text{load}} / \text{mH} \quad [5, 7, 6]/314 \quad G \quad 0.7 \]

**Table 2. Static operating values**

| Parameter | Value          | Parameter | Value          |
|-----------|----------------|-----------|----------------|
| \(i_D\)  | 25.2, 19.71   | \(i_Q\)  | 18.37, 5.86    |
| \(u_D\)  | 381.6, 385.02 | \(u_{oQ}\) | 0, -10.06      |
| \(i_0\)  | 25.2, 19.24   | \(i_Q\)  | 0.4, -12.27    |
| \(i_{\text{loadD}}\)  | 14.18, 15.8, 14.46 | \(i_{\text{loadQ}}\)  | -2.88, -3.32, -3.66 |
| \(u_{ibD}\)  | 369.02        | \(u_{bQ}\)  | -1.21          |

Hence, the dominant root loci of MG when the P-coefficient and the Q-coefficient are multiplied under anti-droop control are shown in Figure 2 and Figure 3 respectively.

**Figure 2. Dominant root loci as droop coefficient increasing under anti-droop control (\(m_p\) increasing)**

**Figure 3. Dominant root loci as droop coefficient increasing under anti-droop control (\(m_q\) increasing)**

Under the same parameter settings, the dominant root loci of traditional droop control are shown in Figure 4 and Figure 5 respectively.

**Figure 4. Dominant root loci as droop coefficient increasing under traditional droop control (\(n_p\) increasing)**

**Figure 5. Dominant root loci as droop coefficient increasing under traditional droop control (\(n_q\) increasing)**
As can be seen from the figures, the maximum value of $P$-coefficient is three orders of magnitude higher when anti-droop control is adopted than that of the traditional droop control, which is conducive to accurate distribution and rapid adjustment of active power. On the other hand, considering that the parallel impedance of the inverter has little influence on the distribution of reactive power, even if the upper limit of the $Q$-coefficient is lower when anti-droop control is adopted, the adjustment ability can still be guaranteed, and other reactive power compensation devices can also be used to realize the rapid adjustment of reactive power.

6. Conclusions and Future Work
The small signal model of an inverter cell is established based on anti-droop control, and the control method with outer power loop and inner voltage-current dual-loop is adopted. Then the small signal model of the complete microgrid is established in the global coordinate system. And the static stabilities of the system are compared when anti-droop control and traditional droop control are adopted. Results show that the $P$-coefficient of inverters under anti-droop control has more adjustment space, and a larger value can be selected to improve the active power distribution accuracy and response speed.

References
[1] Z. Li and M. Shahidehpour, “Small signal modeling and stability analysis of hybrid AC/DC Microgrids,” IEEE Transactions on Smart Grid, vol. 10, no. 2, pp. 2080-2095, Mar. 2019.
[2] V. N. KUMAR and S. K. PARIDA, “Parameter optimization of universal droop and internal model controller for multi inverter-fed DGs based on accurate small-signal model,” IEEE Access, vol. 7, pp. 101928-101940, Jul. 2019.
[3] K. Yu, Q. Ai, S. Wang, J. Ni, and T. Lv, “Analysis and optimization of droop controller for microgrid system based on small-signal dynamic model,” IEEE Transactions on Smart Grid, vol. 7, no. 2, pp. 695-705, Mar. 2016.
[4] LI Haoran, YANG Xuhong, FENG Chengchen. Control strategy research of output impedance analysis and improved droop control based on multiple-inverters parallel[J]. Power System Protection and Control. 2015, 43(20): 29-35.
[5] X. Meng, J. Liu and Z. Liu, "A Generalized Droop Control for Grid-Supporting Inverter Based on Comparison Between Traditional Droop Control and Virtual Synchronous Generator Control," in IEEE Transactions on Power Electronics, vol. 34, no. 6, pp. 5416-5438, June 2019, doi: 10.1109/TPEL.2018.2868722.
[6] Z. Zhao, P. Yang, Y. Wang, Z. Xu, and J. M. Guerrero, “Dynamic characteristics analysis and stabilization of PV-based multiple microgrid clusters,” IEEE Transactions on Smart Grid, vol. 10, no. 1, pp. 805-818, Jan. 2019.
[7] WANG Yichao, LUO An, JIN Guobin. Improved robust droop multiple loop control for parallel inverters in microgrid[J]. Transactions on China Electrotechnical Society, 2015, 30(22): 116-123.
[8] J. Chen, and J. Chen, “Stability analysis and parameters optimization of islanded microgrid with both ideal and dynamic constant power loads,” IEEE Transactions on Industrial Electronics, vol. 65, no. 4, pp. 3263-3274, Apr. 2018.
[9] S. Wang, Z. Liu, J. Liu, D. Boroyevich, and R. Burgos, “Small-signal modeling and stability prediction of parallel droop-controlled inverters based on terminal characteristics of individual inverters,” IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 1045-1063, Jan. 2020.
[10] ZENG Shaohuan, ZHOU Gouhua, ZHOU Shuhan. Small-signal modeling and load transient characteristic analysis of current mode controlled tri-state boost converter[J]. Transactions on China Electrotechnical Society, 2018.
[11] LI Tan, GOLE A M, ZHAO Chengyong. Small-Signal model of the modular multilevel converter considering the internal dynamics [J]. Proceedings of the CSEE, 2016, 36(11): 2890-2899.
[12] CHEN Xin, ZHANG Changhua. HUANG Qi. Small-signal modeling with power differential term for droop control inverter and analysis[J]. Electric Power Automation Equipment, 2017, 37(2): 151-156.