Comparison of fault transient characteristics of inverter-based distributed generators using different control strategies

Xiao Chang¹, Ying Xiao¹, Yunlei Yang¹, Jun Zhao¹, Yonghai Xu² and Chengjiang Deng³

¹ State Grid Shanxi Electric Power Research Institute, China
² State Key Laboratory of Alternate Electrical Power System with Renewable Energy Source (North China Electric Power University), Beijing 102206, China
³ South China University of Technology, Guangzhou, Guangdong, China

*Corresponding author: 337172056@qq.com

Abstract. The inverter-based distributed generators (IBDG) using different control strategies have different fault transient characteristics, which are the key issue of fault analysis for the distribution networks with IBDGs. To this end, this study analyzes and compares the fault transient characteristics of IBDGs using PQ control, droop control and virtual synchronous generators (VSG) control by PSCAD/EMTDC simulation, and considering the requirements of low-voltage ride through (LVRT) during grid-connected operation. The simulation results demonstrate that under the asymmetric fault condition of distribution networks, the IBDGs using different control strategies can maintain symmetric output. And when fault occurs in the distribution networks, the IBDGs using different control strategies have different transient response rate and overshoot of the output current.

1. Introduction
With the continuous development of DG technology, grid-connected inverters have received extensive attention as their interface with the power grid [1-5]. There have been many control strategies for IBDGs, common grid-connected inverter control strategies include: constant power control (also known as PQ control), droop control (also known as Droop control) and VSG control [5-7]. As the coupling between IBDGs and the grid continues to increase, many countries have proposed that IBDGs connecting with the grid should have LVRT capabilities [8-10]. There are many literatures that have studied the IBDG’s control strategies considering LVRT. The literatures [11, 12] used the double synchronous rotating coordinate system to independently control the positive-sequence and negative-sequence current, which can effectively suppress the negative-sequence component and improve the power quality. In [13], a PQ control strategy using the positive-sequence voltage at point of common coupling (PCC) was proposed to improve the output performance of IBDG under asymmetric conditions. Reference [14] proposed a VSG control strategy that when the voltage sag is small, keeps the VSG mode, and when the voltage depth drops, switches the VSG mode to the phase tracking and the reactive power control mode.

The fault characteristics of the IBDGs are quite different from those of conventional generators. At present, many literatures have studied the fault characteristics of IBDGs. For example, references [15-18] put forward different fault analysis methods of distribution network with IBDGs; the literature [19]...
proposed an iterative solution method for fault analysis of the distribution network with IIDG and DFIG; reference [20], firstly, studied the fault characteristics of IBDG using PQ strategy during grid-connected operation, and then discussed the fault characteristics of IBDG using Droop strategy under isolated island; but all of them only studied the fault steady-state characteristics of IBDGs, and didn’t analyze the fault transient characteristics of IBDGs using different control strategies considering LVRT. Reference [21] discussed the fault transient characteristics of IBDG with PQ control considering LVRT, however, there was no analysis for the fault transient characteristics of IBDGs using other control strategies. The document [22] compared the different damper control modes of the active output part between droop control and VSG control, but there was no comparison with the transient characteristics during grid-connected operation. This paper builds a simulation model of distribution network with IBDG using different control strategies, and analyzes the IBDG’s fault transient characteristics during grid-connected operation.

2. Low-voltage ride through

2.1. LVRT requirement

According to latest grid-connected standard, the dynamic reactive current injected into the grid by DG is

\[
I'_{qf} = \begin{cases} 
0, & U_{pcc,f} > 0.9 \text{ p.u.} \\
K_1(0.9 - U_{pcc,f})I_N, & 0.2 \leq U_{pcc,f} \leq 0.9 \text{ p.u.} \\
K_2I_N, & U_{pcc,f} < 0.2 \text{ p.u.}
\end{cases}
\]  

(1)

where \(I'_{qf}\) is the reference reactive current of IBDG under the fault condition; \(I_N\) is the rated current of IBDG; \(U_{pcc,f}\) is the voltage at PCC under the fault condition; \(K_1\) is the voltage support coefficient, reflecting the dynamic support capability of the reactive power; \(K_2\) determines the maximum reactive current allowed by IBDG.

In order to avoid damaging the inverter’s power electronic switch caused by overload, it is also necessary to limit the IBDG’s output current. Foreign countries usually require the overload capacity of IBDG to be within 1 to 3 times the rated current. Domestically, China’s latest national standard GB 50797-2012 requires the photovoltaic plant’s overload capacity to be 1.2 times the rated current [24].

2.2. Current control during unbalanced faults

Under asymmetric conditions, the grid voltage and current not only have positive-sequence components, but also have negative-sequence components. The output power of IBDG is

\[
\begin{bmatrix}
P_0 \\
P_1 \\
P_2 \\
Q_0 \\
Q_1 \\
Q_2 \\
\end{bmatrix} = 
\begin{bmatrix}
U_d^P & U_q^P & U_d^N & U_q^N & U_d^N & U_q^N \\
U_d^P & U_q^P & -U_d^N & -U_q^N & U_d^N & U_q^N \\
U_d^P & U_q^P & -U_d^N & -U_q^N & -U_d^N & -U_q^N \\
U_d^P & U_q^P & -U_d^N & -U_q^N & U_d^N & U_q^N \\
U_d^P & U_q^P & -U_d^N & -U_q^N & -U_d^N & -U_q^N \\
-U_d^P & -U_q^P & U_d^N & U_q^N & U_d^N & U_q^N \\
\end{bmatrix}
\begin{bmatrix}
I_d^P \\
I_q^P \\
I_d^P \\
I_q^P \\
I_d^P \\
I_q^P \\
\end{bmatrix}
\]  

(2)

where subscript d, q denotes d-axis component and q-axis component; superscript P, N denotes positive-sequence component and negative-sequence component, respectively; \(P_0\) is the DC component of active power, \(Q_0\) is the DC component of reactive power, \(P_1, Q_1\) represent the peak values of cosine harmonics of quadratic active and reactive power respectively; \(P_2, Q_2\) represent the secondary active and reactive power sinusoidal harmonic peaks, respectively. In order to eliminate the negative-sequence current under asymmetric conditions, this study set the negative-sequence reference current.
to zero. To eliminate the influence of the negative-sequence voltage at PCC, this study adopt a control method using the positive-sequence voltage at PCC. The DC component of power in equation (2) is

\[
\begin{align*}
P_0 &= \left( \begin{array}{c} U_p^d \\ U_q^p - U_d^p \end{array} \right) I_d^p \\
Q_0 &= \left( \begin{array}{c} U_d^p \\ U_p^q - U_q^d \end{array} \right) I_d^p
\end{align*}
\]

(3)

3. The control strategies considering LVRT

3.1. PQ control
The purpose of PQ control is to make the output active power and reactive power of IBDG equal to its reference power. That is, when the voltage and frequency of the system vary within the allowable range, the IBDG’s output power remains unchanged. Therefore, the IBDGs using PQ control do not have the ability to maintain system voltage and frequency constant and can only operate by connecting to the grid.

3.2. Droop control
The droop control is a control method that simulates the "power frequency static characteristics" of the generators. When the impedance between the inverter and the AC network is inductive, its output power is

\[
\begin{align*}
P &= \frac{U V \sin \phi}{X} \\
Q &= \frac{U V \cos \phi - U^2}{X}
\end{align*}
\]

(4)

where \( U \) is the voltage at PCC and \( V \) is the output voltage of the inverter bridge arm. \( \phi \) is the phase angle difference between \( U \) and \( V \). \( X \) is the impedance between the inverter and the AC network. Therefore, when \( \phi \) is small, it can make: \( \sin \phi = \phi \), \( \cos \phi = 1 \), its inverter output active power has a linear relationship with \( \phi \), and the reactive power has a linear relationship with the voltage amplitude at PCC.

3.3. VSG control
The VSG control strategy makes IBDGs have inertial and damping by simulating the synchronous generators, which can improve the stability of the system. The control strategy is similar to the droop control, except that the inertia link and the damping link are added to the active control, as can be seen in Fig.1. Where \( P_0 \) is the reference active power, \( P_e \) is the electromagnetic active power; \( J \) is the virtual inertia coefficient, \( D \) is the virtual damping coefficient. The inertia link and the damping link contribute to the stability of the system, but also slow down the rate of regulation of IBDGs when fault occurs in the grid.

4. Comparison of fault transient characteristics of different control strategies
For PQ control, when the LVRT condition is met, the IBDGs immediately switch to LVRT control, and the output current of IBDGs can follow the reference quickly.
In Droop control, while switching to LVRT control, the sudden change of reference power will cause the output frequency of IBDGs to deviate from the system rated frequency for a short time, resulting in
a short deviation of the output of IBDGs. After stabilization, the output current of IBDGs can accurately follow the reference. For the VSG control, the same thing happens with the droop control when switching to the LVRT control. And the existence of inertia link and damping link further slows down its dynamic response rate.

5. Case studies
The simulation model shown in Fig.2 is built by PSCAD/EMTDC. The system simulation parameters are shown in Table 1.

![Figure 2. 10kV distribution network model with IBDG.](image)

**Table 1.** The system simulation parameters.

| Parameter                        | Value                     |
|----------------------------------|---------------------------|
| System equivalent potential      | 10kV                      |
| System equivalent impedance Zs   | j0.233 Ω                 |
| Line impedance Z1                | 0.26+j0.712 Ω            |
| Line impedance Z2                | 0.845+j2.314 Ω           |
| Total maximum load               | 9+j0.5MVA                |
| IBDG rated capacity             | 4MW                      |

**Case 1:** A two-phase ground fault occurs in the system at 2 seconds, and the voltage at PCC drops to 65%. The output currents of IBDGs using PQ control, Droop control and VSG control are shown in Fig.3, Fig.4 and Fig.5.
(b) three-phase current

Figure 3. The output waveform diagram of IBDG using PQ control.

(a) d-axis, q-axis negative-sequence current component

(b) three-phase current

Figure 4. The output waveform diagram of IBDG using Droop control.

(a) d-axis, q-axis negative-sequence current component

(b) three-phase current

Figure 5. The output waveform diagram of IBDG using VSG control.

It can be seen from Fig. 3 that when an asymmetrical fault occurs in the system, the IBDG using PQ can quickly eliminate the negative-sequence component of the output current, so as to maintain the symmetry of the output current. Fig. 4 show that the IBDG using Droop control can effectively eliminate the negative-sequence component of the output current and keep the symmetry of the output.
current. From Fig.5, the IBDG using VSG control can maintain the current symmetric output in the case of asymmetric fault.

**Case 2:** A three-phase ground fault occurs in the system at 2 seconds, and the voltage at PCC drops to 45%. The output of IBDGs using PQ control, Droop control and VSG control are shown in Fig.6, Fig.7 and Fig.8, respectively.

**Figure 6.** The output waveform diagram of IBDG using PQ control.
As can be seen from Fig. 6 that when a three-phase fault occurs in the system, the transient response time of the IBDG using PQ control is about 0.06 seconds, the overshoot of output active current and reactive current are 0.36 and 0.18 respectively. Fig. 7 show that when a three-phase fault occurs in the system, the transient response time of the IBDG using Droop control is about 0.3 seconds, the overshoot of output active current and reactive current are 0.87 and 0.45 respectively. It can be seen from Fig. 8 that when a three-phase fault occurs in the system, the transient response time of the IBDG using VSG control is about 0.5 second, the overshoot of output active current and reactive current are

![Diagram](image_url)
0.89 and 0.45 respectively. So it’s easy to know that the overshoot of output current of IBDG using PQ control is smaller than that of the IBDG using Droop control which is similar to that of the IBDG using VSG.

6. Conclusions
This paper analyses the fault transient process of IBDGs using PQ control, Droop control and VSG control, and draws the following conclusions:
1) Under the asymmetric fault condition of distribution networks, the IBDGs using PQ control, Droop control and VSG control can keep the output current symmetrical.
2) When fault occur in the distribution networks, the IBDGs using PQ control have the fastest transient response rate and the overshoot of output current is small. The transient response rate of IBDGs using Droop control is slower than that of IBDGs using PQ control, and the overshoot of output current is larger than that of IBDGs using PQ control. The transient response rate of IBDGs using VSG control is the slowest, and the overshoot of output current is similar to that of IBDGs using Droop control.

7. References
[1] Xiaoming Zou, Xiong Du, Guoning Wang, Yougeng Yang, Yongliang Ji. Analysis of frequency coupling mechanism and stability determination of three-phase grid-connected inverter. Automation of Electric Power Systems, 2018, 42(18): 57-70
[2] Manyi Dai, Hua Chen, Fen Zheng. Improving the hysteresis current control strategy of grid-connected inverter in microgrid. Power Electronics, 2018, 52(04): 24-26
[3] Xiaotong Wang, Qingshou Yang, Zhizhong Qi, Lin Wang. Research on the mechanism of islanding detection for sag control grid-connected inverter. Advanced Technology of Electrical Engineering and Energy, 2018, 37(04):15-23
[4] Panpan Gu, Jianyong Zheng, Huiyu Yan, Jie Yang, Wei Yang. A review of research on grid-connected inverters for photovoltaic distributed generators systems. Electrical Engineering, 2017(11):1-5+29.
[5] Chengshan Wang, Wei Li, Ke Peng. Overview of typical control methods for the grid-connected inverters of distributed generators. Electric Power System and Automation, 2012, 24(02): 12-20
[6] Tianjiao Li, Chang Yong Yin. Overview of virtual synchronous generators technology. Journal of Shenyang Institute of Engineering(Natural Science Edition),2018,14(04):344-348
[7] Qing Kang, Wei Luo, Xinjia Lu, Peng Gao Simulation of Microgrid Fault Characteristics Based on Converter Control Strategy. Power System Protection and Control, 2019, 47(02): 147-153
[8] M. García-Gracia, N. E. Halabi, H. Ajami, and M. P. Comech. Integrated control technique for compliance of solar photovoltaic installation grid codes. IEEE Transactions on Energy Conversion, vol. 27, no. 3, pp. 792–798, Sep. 2012
[9] X. Liu, Z. Xu, and K. P. Wong. Recent advancement on technical requirements for grid integration of wind power. Journal of Modern Power Systems Clean Energy, vol. 1, no. 3, pp. 216–222, Dec. 2013
[10] Y. Bae, T. K. Yu, and R. Y. Kim. Implemental control strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low-to-medium voltage network. IEEE Transactions on Energy Conversion, vol. 28, no. 3, pp. 619–631, Sep. 2013
[11] Xianbin Huang, Da Lin, Huifang Wang, Tao Wu. Overview of low voltage ride through strategy for grid-connected photovoltaic systems. Mechanical & Electrical Engineering,2016,33(05):589-594+601
[12] Zhiqiang Zhai, Situ Qin. Control method of photovoltaic grid-connected inverter with three-phase voltage asymmetric drop. Power System Protection and Control, 2015, 43(14): 126-130
[13] Bowen Han. Research on novel protection principles for distribution networks with inverter-interfaced distributed generators. South China University of Technology, 2018.

[14] Xu Li, Panyu Wu, Xing Zhang, Weiqun Liu. Low voltage ride through control method of virtual synchronous generators. Power Electronics, 2018, 52(11): 8-10

[15] Quan Liu, Fei Wang, Xing Yan, Suiyang Liu, Fangfan Liao, Yi Peng. Fault analysis and research of distribution network with distributed Photovoltaic generators. Smart Power, 2018, 46 (08):79-83.

[16] Xiangping Kong, Zhe Zhang, Xianggen Yin, et al. Study on fault current characteristics and fault analysis methods of power grid with inverter based distributed generators. Chinese journal of electrical engineering, 2013, 33 (34): 65-74.

[17] Guoqing Pan, Dehui Zeng, Gang Wang, et al. A fault analysis method of distribution network with inverter based distributed generators based on PQ controll. Chinese Journal of Electrical Engineering, 2014, 34(4): 555-561.

[18] Weitao Yang, Longjun Wang. A method for fault analysis of distribution network with two distributed generators. Electrical Automation, 2017, 39 (06):51-54.

[19] Zhengrong Wu, Gang Wang, Haifeng Li, et al. A fault analysis method of distribution network considering the control characteristics of inverter based distributed generators. Automation of Power Systems, 2012, 36(18): 92-96.

[20] Huaidong Qi, Qing Zhang, Jingyuan Du, Ping Lu, Ming Xu, Xiong Xiong, Tianjun Jing. Analysis of fault characteristics under different control modes of inverter interfaced distributed generators in regional distribution network. Renewable Energy, 2016, 34 (12): 1786-1791.

[21] Guoqing Pan. Fault Analysis on Distribution network with Inverter Interfaced Distributed Generations based on PQ control strategy. South China University of Technology, 2014

[22] Hongyu Chen, Yuyu Zhang, Yu Qiu, Wei Yang, Jianyong Zheng. Comparison of drop control strategy and virtual synchronous generators control strategy. Electrical and Energy Efficiency Management Technology, 2018(15):25-31+44

[23] GB/T 19964-2012 Technical regulations for accessing power systems for photovoltaic power station. Beijing: China Standard Press, 2012.

[24] GB 50797-2012 Photovoltaic power station design specification. Beijing: China Planning Press, 2012