Active power improvement of three-phase grid-connected inverter under unbalanced grid faults

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Abstract. Unbalanced grid voltage causes fault-phase over-current, affects the life span of devices and even leads to control system instability. The conventional current limiting strategy reduces the output power of grid-connected inverter. In order to increase the active power injected by the grid-connected inverter into the grid, this paper proposes a new current limiting strategy. On the premise of ensuring that the DC side voltage fluctuation and grid-connected current harmonics meet the grid standards, the fault-phase current and the normal phase current are respectively limited. The simulation results verify the proposed strategy can effectively improves the active power output of the grid-connected inverter.

1. Introduction

Renewable power generation systems (RPGS) have attracted more and more attention for its environmentally friendly and flexible controllability [1]. For RPGS, the grid-connected inverter is widely used as its energy conversion and transmission interface with the grid. When the grid voltage is unbalanced, the output power of grid-connected inverter will produce double-frequency fluctuation [2], which leads to DC bus voltage fluctuation, resulting in overvoltage even control system instability. Moreover, the voltage sag causes the rapid increase of the grid-side currents, endangering the safe operation of grid-connected inverter. Therefore, the grid-connected inverter is required to output high-quality power and operate in the safe area under unbalanced grid voltage faults.

A dynamic power decoupling strategy is proposed in [2], which can suppress the dc-link oscillation caused by the unbalanced grid fault without increasing the dc-link capacitance. A parameter is introduced in [3] to control the positive and negative sequence current, thus enhance the grid voltage and suppress the double frequency fluctuation of active power. The power compensation method is adopted to suppress the power fluctuation caused by the unbalanced fault of the power grid, which can ensure that the DC side voltage and output power of the grid connected inverter have no ripple, and the grid-connected current is an ideal sine wave [4, 5]. A small amount of unbalanced current in response to the level of unbalanced that exists in the grid voltage is injected into the grid to suppress the dc-link oscillation and grid-side current harmonics [6], which can improve the power quality and the robustness of the grid-connected inverter.

The above methods can suppress oscillations of the dc side voltage, power fluctuations and current harmonics of the ac side caused by grid imbalance, but the overcurrent of the faulty-phase is not considered.
A flexible positive and negative sequence control is adopted in [7] to evaluate the current peak value through the phasor diagram of grid-connected currents. The calculation of this method is complex. Moreover, there is no measure to limit the peak current. To limit the over-current caused by unbalanced grid voltage, a control strategy that maximizes the inverter power capability by injecting maximum rated current during voltage sags is proposed in [8]. However, the current peak value calculated by this method is inaccurate. When the power grid imbalance is large, the current peak value obtained by this method is still high. Then, a current-limited control strategy is proposed in [9], where the grid-connected current is limited by a current limiting coefficient calculated by the fault-phase current. This method can improve the stability of the system under grid voltage sag faults. The peak value of grid-connected current is limited by controlling active power and reactive power [10]. The method in [9, 10] can limit the peak value of the grid-side current within the allowable range of the inverter and suppress the active power fluctuation near to zero, but reduce the output power of the inverter. A control method based on recursive least squares with variable forgetting factor is proposed in [11], which can reduce the active power fluctuation and improve the active power output of the inverter when the grid voltage is distorted. However, this method does not solve the problem of overcurrent when the grid voltage is unbalanced and the grid-connected inverter may work under unsafe area.

Based on this, the over-current of the grid-connected inverter is controlled in this paper during unbalanced grid voltage. The current of each phase during single-phase voltage sag is analyzed through the established mathematical model. Then, a current limiting strategy is proposed, which can increase the active power output of grid-connected inverter under the condition of meeting the grid standard.

2. Peak currents during the voltage sag

Figure 1 shows the topology of the three-phase LCL type grid-connected inverter comprising a VSC (a two-level six-pulse inverter), an LCL filter (L1, L2, and C), the DC bus capacitor Cdc, a dc bus resistance representing the VSC loss (R), and the grid (uabc).

In case of single-phase fault, the three-phase voltage can be expressed as

\[
\begin{align*}
    u_a &= kU_m \cos(w_0 t) = kU_m e^{j\omega_0 t} \\
    u_b &= U_m \cos \left( w_0 t - \frac{2\pi}{3} \right) = e^{-j\frac{2\pi}{3}} U_m e^{j\omega_0 t} \\
    u_c &= U_m \cos \left( w_0 t + \frac{2\pi}{3} \right) = e^{j\frac{2\pi}{3}} U_m e^{j\omega_0 t}
\end{align*}
\]  

(1)

where \( k \) is the degree of close to balanced voltage, \( 0 \leq k \leq 1 \).

The positive and negative sequence components of the grid voltage can be obtained from (1):

\[
\begin{align*}
    V^+ &= \frac{2 + k}{3} U_m \\
    V^- &= \frac{1 - k}{3} U_m
\end{align*}
\]  

(2)
When the control target is that active power remains constant and the grid-connected inverter runs with unit power factor, the current reference value is

$$
\begin{align*}
    [ &i_a^*] = \frac{2P}{3} \left[ u_a^*- u_a^* \right] \\
    [ &i_b^*] = \left[ u_b^*- u_b^* \right]
\end{align*}
$$

(3)

where \( (V^+)^2 = (u_a^*)^2 + (u_b^*)^2, (V^-)^2 = (u_a^*)^2 + (u_b^*)^2 \).

The positive and negative sequence voltage in static coordinate system can be obtained by symmetrical component method [11]:

$$
\begin{align*}
    u_a^* &= \frac{1}{2} (u_a + ju_b) = \frac{1}{3} (-k-2) e^{j50^\circ} U_n e^{j\theta_d} \\
    u_b^* &= \frac{1}{2} (-ju_a + u_b) = \frac{1}{3} (k+2) e^{j50^\circ} U_n e^{j\theta_d} \\
    u_c^* &= \frac{1}{2} (u_a - ju_b) = \frac{1}{3} (1-k) e^{-j50^\circ} U_n e^{j\theta_d} \\
    u_d^* &= \frac{1}{3} (1-k) e^{j30^\circ} U_n e^{j\theta_d}
\end{align*}
$$

(4)

where

$$
\begin{align*}
    [ &u_a] = C_{2x3} \begin{bmatrix} u_a \\ u_b \\ u_c \\ u_d \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \\ \frac{1}{2} \\ 0 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} \sqrt{3} \\ \sqrt{3} \\ \sqrt{3} \end{bmatrix} \begin{bmatrix} \frac{1}{2} u_a - \frac{1}{2} u_c \\ \frac{1}{2} u_a - \frac{1}{2} u_c \\ \frac{1}{2} u_a - \frac{1}{2} u_c \end{bmatrix}
\end{align*}
$$

(5)

And

$$
\begin{align*}
    [ &i_a] = C_{2x3} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 \\ -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}
\end{align*}
$$

(6)

From (3)-(6), the expression of the grid-connected current under unbalanced grid voltage can be obtained:

$$
\begin{align*}
    [ &i_a] = \frac{2Pe^{j\theta_d}}{3U_n} \begin{bmatrix} 1 \\ \frac{1}{2} - j\sqrt{3}/6 (1+2k) \\ \frac{1}{2} + j\sqrt{3}/6 (1+2k) \end{bmatrix} \\
    [ &i_b] = \frac{1}{2} \pm j\sqrt{3}/6 (1+2k) \leq 1, \frac{1}{2} \pm j\sqrt{3}/6 (1+2k) \geq 1, k \leq 1
\end{align*}
$$

(7)

As can be seen from (6) (7), when the grid voltage is unbalanced, the fault-phase current is greater than the normal phase current, and the non-fault phase current will also be higher than the rated current, so it is necessary to limit the current to ensure the grid-connected inverter can operate in safe area.
3. Peak currents during the voltage sag

3.1. Derivation of current limiting coefficient

The current limiting methods mentioned can limit the grid-side current to the allowable range of the inverter, but reduce its power output capacity. Therefore, this paper limits the fault-phase current and the normal phase current separately on the premise of meeting the power grid standards, so as to improve the active power output of the grid-connected inverter. When the three-phase currents are all limited to the rated current, there are serious double-frequency fluctuations in both active and reactive power, which leads to the third harmonic of the grid-connected current and fluctuations in the DC link voltage [13]. Therefore, it is necessary to consider the third harmonic of grid-connected current and DC link voltage oscillation when limiting the active power fluctuation.

According to the national standard GB / T20046-2006, the third harmonic current \( I_{3rd} \) should be less than 4% of the fundamental current. Therefore, the relationship between the double-frequency fluctuation of active power \( \Delta p \) and \( I_{3rd} \) should satisfy [14]:

\[
\Delta p_{lim1} = \frac{12 I_{1m} w^2 L C_d U_d^2}{V_g} \tag{9}
\]

The DC bus voltage oscillation \( \Delta U_{dc} \) should be limited to less than 1% of the DC bus voltage \( U_{dc} \). The relationship between \( \Delta p \) and \( U_{dc} \) is shown in (11):

\[
\Delta p_{lim2} = \frac{2U_d \Delta U_{dc}}{X_c} \tag{10}
\]

where \( X_c \) is the DC side capacitance impedance.

From (9) and (10), the expression of active power fluctuations satisfying grid standards can be obtained:

\[
\Delta p_{lim} = \min(\Delta p_{lim1}, \Delta p_{lim2}) \tag{11}
\]

When the control target is that there is no fluctuation in active power, to prevent the three-phase current from overcurrent when the grid voltage is unbalanced, the grid-side current is required to be limited. The limited three-phase grid-connected currents can be expressed as:

\[
\begin{align*}
I_a &= I_n \cos(w_n t) \\
I_b &= m I_n \cos\left(w_n t - \frac{2\pi}{3}\right) \\
I_c &= m I_n \cos\left(w_n t + \frac{2\pi}{3}\right)
\end{align*} \tag{12}
\]

where \( m \) is the degree of close to the rated current, and \( 0 \leq m \leq 1 \).

Then, the positive and negative sequence expressions of current are as follows:

\[
\begin{align*}
I^+ &= \frac{1+2m}{3} I_n \\
I^- &= \frac{1-m}{3} I_n
\end{align*} \tag{13}
\]

The expression of active power fluctuation \( \Delta p \) can be obtained:

\[
\Delta p = \frac{3}{2} \left(V^+ I^+ + V^- I^-\right)
= \frac{3}{2} \left(2 + \frac{k}{3} U_a \frac{1+2m}{3} I_n + \frac{1-k}{3} U_a \frac{1-m}{3} I_n\right)
= \frac{1}{2} U_a I_n \left[(2 + k)(1+2m)+(1-k)(1-m)\right] \tag{14}
\]

The active power fluctuation after the current limitation is required to meet:

\[
\Delta p_{lim} \geq \frac{1}{2} U_a I_n \left[(2 + k)(1+2m)+(1-k)(1-m)\right] \tag{15}
\]
The maximum value of the current limiting coefficient $m_{\text{max}}$ can be obtained by (16):

$$m_{\text{max}} = \frac{2\Delta p_{\text{lim}} - 3U_m I_m}{3U_m I^n (1+k)} \quad \text{(16)}$$

So, the current limiting coefficients of the normal phase and the fault phase are:

$$m_i = \frac{2k+1}{3},$$

$$m_{\text{fault}} = \frac{\frac{1}{2} - j\frac{\sqrt{3}}{6} (1+2k)}{\left(\frac{2k+2}{3}\right)} \quad \text{(17)}$$

The control block diagram of the proposed strategy is shown in Figure 2.

![Figure 2. The control block diagram of the proposed strategy.](image)

where PCI is proportional complex integral, the current controller.

3.2. Improvement of active power output capacity

When $\Delta p=0$, $\Delta p_{\text{lim}}$, the active power output of the grid-connected inverter and the increased percentage in active power can be expressed as:

$$p_{\Delta p=0} = V^+ I^+ + V^- I^-$$

$$p_{\Delta p=\Delta p_{\text{lim}}} = V^+ I^+_{\text{lim}} + V^- I^-_{\text{lim}} + \Delta p_{\text{lim}}$$

$$\Delta p\% = \frac{p_{\Delta p=\Delta p_{\text{lim}}} - p_{\Delta p=0}}{p_{\Delta p=0}} \quad \text{(19)}$$

Substituting (12) and (19) into (20), the curve of $\Delta p\%$ can be obtained, as shown in Figure 3. It can be seen from Figure 3 that the proposed method can effectively improve the active power output under the premise of meeting the grid standards and the percentage of active power improvement can reach up to 38.4%.

![Figure 3. The increase of active power under single-phase ground fault with different $k$.](image)

4. Simulation results

To verify the effectiveness of the proposed strategy, the control system shown in Figure 1 is built in MATLAB/Simulink, and the system parameters are shown in Table 1.
Table 1. Parameters of LCL grid-connected inverter.

| Parameter                  | Symbol | Value  |
|----------------------------|--------|--------|
| Active power               | \( P \) | 800W   |
| Reactive power             | \( Q \) | 0 var  |
| DC source                  | \( U_{dc} \) | 140 V  |
| Grid line-line voltage     | \( v_g \) | 100 V  |
| DC-link capacitance        | \( C_{dc} \) | 1000 \( \mu \)F |
| Inverter-side inductor     | \( L_1 \) | 3.0 mH |
| Grid-side inductor         | \( L_2 \) | 1.5 mH |
| Filter capacitor           | \( C \) | 10 \( \mu \)F |

Figure 4 shows the DC bus voltage when \( a \)-phase voltage drops with \( k=0.4 \). As depicted in Figure 4, \( U_{dc} \) exhibits double-frequency fluctuation, which is consistent with the analysis in [2]. Figure 5 shows the dynamic process of the grid-connected currents when \( a \)-phase voltage drops with \( k=0.4 \). It can be seen that when the \( a \)-phase voltage is lower than the grid rated voltage, both the fault-phase current and the normal-phase current are greater than the allowable rated current of the grid-connected inverter, and the \( a \)-phase current is the largest, which is consistent with the theoretical analysis in (8).

![Figure 4](image1.png)

**Figure 4.** The waveform of \( U_{dc} \) under single-phase voltage sag (\( k=0.4 \)).

![Figure 5](image2.png)

**Figure 5.** The grid-side currents under single-phase voltage sag (\( k=0.4 \)).

![Figure 6](image3.png)

**Figure 6.** Waveforms of active power \( P \) and grid current with conventional strategy (\( k=0.4 \)).

![Figure 7](image4.png)

**Figure 7.** Waveforms of active power \( P \) and grid current with proposed strategy (\( k=0.4 \)).

Figure 6 shows the dynamic waveforms of active power \( P \) and the grid current \( i_{abc} \) with the current limiting strategy in [9, 10] adopted at \( t=0.3 \) s when \( k=0.4 \). As can be seen, when grid imbalance is large, this current limiting strategy reduces the active power fluctuation and limits the maximum grid-side current to the rated current, but it reduces the active power output. In contrast, Figure 7 shows the dynamic waveforms of active power \( P \) and the grid-side current \( i_{abc} \) from the conventional current limiting strategy in [9, 10] to the proposed strategy. Obviously, the proposed strategy can limit the
fault-phase current, and effectively increase the average active power output of the grid-connected inverter.

Table 2 shows $\Delta U_{dc}\%$, $I_{3rd}\%$ and $P$ with conventional current limiting strategy and the proposed strategy when $k=0.4$. It can be seen that while the proposed strategy improves the active power of the grid-connected inverter, it also increases the DC side voltage fluctuation and the THD of the grid-side current, but the DC side voltage fluctuation and the THD can meet the requirements of the grid standards.

Table 2. Comparison of the conventional strategy and the proposed strategy with $k=0.4$.

| $k$=0.4          | conventional strategy | proposed strategy |
|------------------|-----------------------|-------------------|
| $\Delta U_{dc}\%$ | 0.35                  | 0.57              |
| $I_{3rd}\%$      | 0.26                  | 0.16              |
| $P$/W            | 500                   | 570               |

Figure 8 shows the dynamic waveforms of active power $P$ and the grid current $i_{abc}$ with the conventional current limiting strategy in [9, 10] adopted at $t=0.35$ s when $k=0.8$. As can be seen that active power decreases with conventional strategy. Figure 9 shows the dynamic waveform of active power $P$ and grid current $i_{abc}$ from conventional strategy to the proposed strategy. The average active power has been increased, and grid-side current is nearly balanced when $k=0.8$.

Table 3 shows $\Delta U_{dc}$, $I_{3rd}$ and the average active power output $P$ of the grid-connected inverter with conventional current limiting strategy and the proposed strategy. As shown in Tables 2 and 3, the lower the voltage drops of the fault-phase, the more obvious the current-limiting strategy proposed in this paper will improve active power, which is consistent with Figure 3.

Table 3. Comparison of the conventional method and the proposed method with $k=0.8$.

| $k$=0.8          | conventional strategy | proposed strategy |
|------------------|-----------------------|-------------------|
| $\Delta U_{dc}\%$ | 0.21                  | 0.36              |
| $I_{3rd}\%$      | 0.11                  | 0.06              |
| $P$/W            | 700                   | 765               |

5. Conclusions
Unbalanced grid voltage causes fault-phase over-current, which deteriorates the service life of devices and affects the stable operation of energy conversion system. The conventional current limiting strategy reduces the output power of the grid-connected inverter. To increase the active power of the grid-connected inverter, this paper proposes a new current limiting strategy. On the premise of ensuring that the DC side voltage fluctuation and grid-side current harmonics meet the grid standards, the fault-phase current and the normal phase current are respectively limited. Simulation results show the proposed method can effectively improve the active power output of the grid-connected inverter.
The next step of this paper is to design control strategy to improve the stability of the grid-connected inverter under distorted grid.

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