Enhanced Power Quality and Minimized Peak Current Control in An Inverter based Microgrid under Unbalanced Grid Faults

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Abstract—The microgrid inverter experiences the power oscillations and current harmonics in case of the unbalanced grid voltage faults. However, there is a trade-off between power oscillations and current harmonics should be considered in three phase three wire inverter systems during the conventional fault ride through control. In order to solve this problem, a novel control strategy is proposed to enhance the output current quality while mitigating the active and reactive output power oscillations. Moreover, a simple current-limited control strategy can be achieved without the necessity of the voltage/current positive/negative sequence extraction. Finally, the simulation tests of the conventional and proposed control solutions are carried out. The results verify the effectiveness of the proposed strategy.

Keywords—microgrid inverter; unbalanced; fault ride through; current-limited

I. INTRODUCTION

Microgrid integrated with renewable energy resources (RES) has attracted considerable attentions due to its economic aspects and flexible controllability [1-4]. In general, power electronic inverters which act as the interfaces between RESs and grid should have the ability to enhance power quality and ride through services of grid-connected inverters [12]. However, for three-phase three-wire grid-connected inverter system, the control freedoms seems not enough to eliminate instantaneous power oscillations and current harmonics at the same time from the viewpoint of the conventional Instantaneous Power Theory [13-15]. Another new series of control strategies which utilize the zero sequence components are proposed to enhance the power control ability under unbalanced grid conditions. But the current reference generator based on a six dimensional matrix which is greatly increasing computational burden [16].

Further, advanced control algorithms for FRT are mainly based on symmetric sequences to achieve particular control objectives related to the current harmonics, power oscillations, dc bus ripples, voltage support and complex peak current limitation during the unbalanced grid voltage faults have been proposed in [17-20]. In fact, the excessive and harmonic current in case of the unbalanced grid fault ride through significantly affects the system operation reliability [21]. The power oscillations will damages continuity of power supply for inverters based microgrid system [22]. However, few works have been developed for both power quality control and peak current-limited capacity for grid-connected inverter especially under unbalanced grid faults. On the one hand, in contrast to conventional Instantaneous Power Theory, the active and reactive power should be estimated accurately while the current harmonics are reduced [23]. On the other hand, it is more complex to control the amplitude of three phase currents during unbalanced grid faults, mainly because of the trend of simultaneously injecting both active and reactive powers coupling positive and negative sequence components. In such cases, the injection of positive and negative sequence power inherently induces different amplitudes in the injected phase current [24]. Therefore, the FRT solutions focuses on the enhanced power quality and minimized peak current control are attractive and needs further investigation.

In this paper, a novel control strategy based on delayed voltage is proposed to suppress the current harmonics while mitigating the active and reactive output power oscillations for three phase three wire systems. Moreover, it can achieve currents limitation in a simple control structure without any
necessity of voltage/current positive and negative sequence extraction.

II. THE SYSTEM WORKING PRINCIPLE AND CONTROL STRATEGY

The three-phase grid voltage can be expressed as follows to explain the working principle of the system. For the sake of analysis, only one inverter based microgrid is considered to explain the working principle of the system. This paper will focus on the latter case, especially for the FRT control under unbalanced grid voltage faults condition.

The system working principle and control strategy

A. Inherent reason for current distortion and power oscillation

For the sake of analysis, only one inverter based microgrid is considered to explain the working principle of the system. The three-phase grid voltage can be expressed as follows

\[
\begin{bmatrix}
u_a \\ u_b \\ u_c \\ \end{bmatrix} = \begin{bmatrix}
U^+ \sin(\alpha + \theta_p) + U^- \sin(\alpha + \theta_n) \\
U^+ \sin(\alpha + \theta_p - 120^\circ) + U^- \sin(\alpha + \theta_n + 120^\circ) \\
U^+ \sin(\alpha + \theta_p + 120^\circ) + U^- \sin(\alpha + \theta_n - 120^\circ)
\end{bmatrix}
\]

(1)

where \( U^+, U^-, \theta_p, \theta_n \) and \( \omega \) represent the positive and negative sequence voltage amplitude, phase angle and angular frequency, respectively.

With the Clarke transformation, equation (1) can be expressed in stationary frame as follows

\[
\begin{bmatrix}
u_a^* \\ u_b^* \\ u_c^* \\ \end{bmatrix} = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
u_a \\ u_b \\ u_c \\ \end{bmatrix} = \begin{bmatrix}
u_a^* \\ u_b^* \\ u_c^* \\ \end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
u_a^* \\ u_b^* \\ u_c^* \\ \end{bmatrix} = \begin{bmatrix}
U^+ \sin(\alpha + \theta_p) \\
U^+ \cos(\alpha + \theta_p) \\
U^- \sin(\alpha + \theta_n) \\
U^- \cos(\alpha + \theta_n)
\end{bmatrix}
\]

According to the conventional Instantaneous Power Theory, active and reactive power can be expressed as [13-15]

\[
\begin{bmatrix}
p \\ q \\ \end{bmatrix} = \frac{3}{2} \begin{bmatrix}
u_a^* & u_b^* & -u_c^* \\ u_a^* & u_b^* & -u_c^* \\ \end{bmatrix} \begin{bmatrix}
i_a^* \\ i_b^* \\ i_c^* \\ \end{bmatrix}
\]

(3)

Substituting (2) into (3) the current components can be obtained as follows

\[
\begin{bmatrix}
i_a^* \\ i_b^* \\ i_c^* \\ \end{bmatrix} = \frac{3}{2} \begin{bmatrix}
u_a^* & u_b^* & -u_c^* \\ u_a^* & u_b^* & -u_c^* \\ \end{bmatrix} \begin{bmatrix}
p^* \\ q^* \\ \end{bmatrix} = \begin{bmatrix}
i_{a(p)} + i_{a(q)} \\ i_{b(p)} + i_{b(q)} \\ i_{c(p)} + i_{c(q)} \\ \end{bmatrix}
\]

(4)

where \( i_{a(p)}, i_{b(p)}, i_{c(p)}, i_{a(q)}, i_{b(q)}, i_{c(q)} \) represent the active and reactive power current components in stationary frame respectively. \( P^* \) and \( Q^* \) are the inverter output active and reactive power reference and determined by the inverter rated capacity.

It should be noted that the inverter current will not be easily achieved with a notch filter of \( \frac{2P^*U^+U^-}{(U^+)^2+(U^-)^2} \cos(2\alpha+\theta_p+\theta_n) \) in (5).

On the other hand, reference [11] suggests that the inverter current harmonics can be eliminated on condition that \( 2U^+U^-\cos(2\alpha+\theta_p+\theta_n) \) in (5) is cancelled, which can be easily achieved with a notch filter of \( F(s) \). Thus, the sinusoidal inverter current harmonics can be obtained as follows

\[
\begin{bmatrix}
i_{a(p)} \\ i_{a(q)} \\ i_{b(p)} \\ i_{b(q)} \\ i_{c(p)} \\ i_{c(q)} \\ \end{bmatrix} = \frac{2}{3} \begin{bmatrix}
(u_a)^2+(u_b)^2 \\ (u_a)^2+(u_b)^2 \\ (u_a)^2+(u_b)^2 \\ (u_a)^2+(u_b)^2 \\ (u_a)^2+(u_b)^2 \\ (u_a)^2+(u_b)^2 \\ \end{bmatrix} F(s) = \frac{2}{3} \begin{bmatrix}
P^*u_a \\ Q^*u_a \\ P^*u_b \\ Q^*u_b \\ P^*u_c \\ Q^*u_c \\ \end{bmatrix}
\]

(6)

Substituting (6) into (3), the active and reactive power can be expressed as follows

\[
p = \frac{P^*}{2} (u_a^2+u_b^2)
\]

\[
q = \frac{2P^*U^+U^-}{(U^+)^2+(U^-)^2} \cos(2\alpha+\theta_p+\theta_n)
\]

(7)
It can be seen from the equation (7) and (8), the sinusoidal current references can be derived from (9) as follows:

\[
\begin{align*}
\hat{p}_a &= \frac{1}{2}\hat{u}_a - \hat{u}_\beta \\
\hat{q}_a &= \frac{1}{2}\hat{u}_a + \hat{u}_\beta \\
\hat{p}_\beta &= \left(\hat{u}_a + \hat{u}_\beta\right) - \left(U^+ + U^-ight) \cos(\alpha) \\
\hat{q}_\beta &= \left(\hat{u}_a + \hat{u}_\beta\right) + \left(U^+ - U^-ight) \sin(\alpha)
\end{align*}
\]

where \(\hat{u}_a\) and \(\hat{u}_\beta\) represent the delayed grid voltage components, which can be achieved by \(\frac{T}{4}\) delay signal processor [26-28]. Assuming that \(\theta_p = 0\) and \(\theta_a = 0\), the delayed voltage can be expressed as:

\[
\begin{align*}
\hat{u}_a &= u_{a\_delay(T/4)} = -\left(U^+ + U^-\right) \cos(\alpha) \\
\hat{u}_\beta &= u_{\beta\_delay(T/4)} = \left(U^+ - U^-\right) \sin(\alpha)
\end{align*}
\]

With the same control target, active and reactive power references are \(P^*\) and \(Q^*\) without fluctuation. The microgrid inverter output current references can be derived from (9) as follows:

\[
\begin{align*}
\hat{i}_{a\_ref} &= \frac{2}{3}u_a - \frac{1}{3}u_\beta \\
\hat{i}_{\beta\_ref} &= \frac{2}{3}u_a + \frac{1}{3}u_\beta \\
\hat{i}_{a\_ref} &= 2P^*\hat{u}_\beta - \frac{2}{3}P^*\hat{u}_a \\
\hat{i}_{\beta\_ref} &= 2Q^*u_\beta - \frac{2}{3}Q^*u_a
\end{align*}
\]

Diagrams and illustrations are not included in the text. The analysis involves control strategies for microgrid inverters, including delayed voltage control and the use of proportional resonant controllers. The equations illustrate the methods for deriving current references and the implications for system stability and power management. The diagrams would typically show the system configurations and control block diagrams, but these are not transcribed here.
As can be seen from (13), it is clear that the unbalanced and excessive output currents phenomenon is caused by the negative sequence voltage component $U^-$ ≠ 0, which means the system is under unbalanced grid voltage faults.

On the other hand, in order to limit the output current within a rated operating range during the FRT process of the inverter and three phase output currents should be measured and calculated in real time. The current references based on (12) can be modified into equation (14) as follows

$$
\begin{bmatrix}
I_{r}^+ \\
I_{b}^+ \\
I_{c}^+
\end{bmatrix} = \begin{bmatrix}
I_{r}^+ \\
I_{b}^+ \\
I_{c}^+
\end{bmatrix} = I_{\text{rated}} \cdot \frac{I_{\text{max}}}{I_{\text{max}}} \left[ \frac{I_{\text{ref}(p)} + I_{\text{ref}(q)}}{2} \sqrt{\frac{3}{2}} \right] \left[ \frac{I_{\text{ref}(p)} + I_{\text{ref}(q)}}{2} \right] - \frac{I_{\text{ref}(p)} + I_{\text{ref}(q)}}{2}
$$

(14)

where $I_{\text{rated}}$ represents the rated current value of the inverter, $I_{\text{max}}$ represents the maximum current value in three phase output currents.

It is clear that the current reference peak value in equation (14) will not beyond $I_{\text{rated}}$ under the unbalanced grid voltage conditions. As for balance grid conditions, the inverter output current can be also controlled as balanced and sinusoidal waveforms with the peak value $I_{\text{rated}}$.

On the other hand, it would be an interesting doubt about that whether P-Q regulator could be used to this proposed control. In this case, another power loop with PI control should be integrated with the existing current loop, which may be beneficial to the power regulation but at the expense of the control complicity due to two-loop (power-loop and current-loop) structure with two PI coefficients tuning to avoid interaction between outer power loop and inner current loop. That’s why the single-current-loop structure is used for most existing solutions. But for the high penetration of multi-inverters based microgrid systems under unbalanced grid faults, P-Q regulator with droop control integrated with current control might be an interesting solution but it is beyond the scope of this paper.

### III. Simulation Results

In order to verify the effectiveness of the proposed control strategy, the MATLAB/Simulink simulation test are carried on the conventional control method and proposed strategy. Assuming that the rated current of inverter is 5A, the unbalanced voltage grid fault occurs at 0.2s and the unbalanced factor is 0.3 with a common phase shift as shown in Fig.3. The detailed system parameters can be found in Table I. The simulation results can be found in Fig.4 and Fig.5.

**Table I: System Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$u_{dc}/V$</td>
<td>400</td>
<td>$u_a/V_{rms}$</td>
<td>120$^\circ$ 0$^\circ$</td>
</tr>
<tr>
<td>$u_b/V_{rms}$</td>
<td>120$^\circ$ -137$^\circ$</td>
<td>$u_c/V_{rms}$</td>
<td>120$^\circ$ 137$^\circ$</td>
</tr>
<tr>
<td>$U^+/V_{rms}$</td>
<td>92.5</td>
<td>$U^-/V_{rms}$</td>
<td>27.5</td>
</tr>
<tr>
<td>$P^*/W$</td>
<td>1000</td>
<td>$Q^*/var$</td>
<td>800</td>
</tr>
<tr>
<td>$L_1/mH$</td>
<td>1.8</td>
<td>$L_2/mH$</td>
<td>1.8</td>
</tr>
<tr>
<td>$C/\mu F$</td>
<td>27</td>
<td>$I_{\text{rated}}/A$</td>
<td>5</td>
</tr>
</tbody>
</table>
Theory and the above analysis. Furthermore, the system also experiences the excessive current stress in case of the unbalanced FRT progress.

Fig.6 shows the simulation results of delayed voltage control solution. It can be observed that the current harmonics can be greatly reduced and the active/reactive power can be estimated accurately at the same time due to the $T/4$ delayed voltage are used to eliminate the fluctuant item in the denominator of current reference which is different from the traditional FRT control schemes. For the transient impact of delayed voltage control system, there will be more complex characteristics to be analyzed, which would be the subject of our future research. However, it is should be noted that the system still experiences excessive current phenomenon which may lead to the failure of FRT control under unbalanced grid faults.

IV. CONCLUSION

In this paper, a novel FRT control strategy has been presented for grid-connected inverters under unbalanced grid voltage conditions. Compared with the conventional control schemes, the simulation test results reveal that the proposed strategy can enhance the inverter output current quality while mitigating the active and reactive power oscillations. Moreover, the inverter equipped with current-limited capacity...
will also improve the reliability of the process of FRT control under unbalanced grid faults.

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