FILTER DESIGN FOR GRID CONNECTED PV INVERTERS

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Abstract—This paper proposes filter design guideline for single-phase grid-connected PV inverters. By analyzing the instantaneous voltage applied on the filter inductor, the switching ripple current through the filter inductor is precisely calculated. Therefore, filter inductance can be designed accurately which guarantees the switching ripple current under the target value. Proposed filter design method is verified by experiment.

Keywords: Grid-connected PV inverters, Single-phase PWM inverters, Switching ripple current, Filter design

I. Introduction

Distributed power generation systems (DPGS) are widely exploited according to the development of renewable energy systems [1,2]. DPGSs cover wide power ranges from 1kW class residential applications to several hundred MW class generation parks. Medium and small scale DPGSs are normally connected to grid systems through utility interactive inverters that inject grid current by current control mode operation [3-7].

Since the power quality of the grid interface is influenced by the quality of the injection current, the current quality is generally regulated by utility companies [8,9]. For example, the total demand distortion (TDD) of 10-minute averaged value for the injection current on a DPGS should not goes over 5%, and the even harmonics should be limited under 25% to the neighbored harmonic limitation.

\[
TDD = \sqrt{\sum_{h=2}^{\infty} I^2(h) / I^2_{new}} \tag{1}
\]

Moreover, there exist higher order harmonics based on the switching frequency of the utility inverters which come from the circuit condition between the PWM switching pattern and the grid voltages. Thus to evaluate the influence of utility inverters to the power quality on a grid interface, not only the low order harmonics described by (1), but also the high order harmonics described by (2) should be considered [10,11].

\[
I^2_{new,\inf} = \sum_{h=1}^{\infty} I^2(h) / I^2_{new} \tag{2}
\]

The current ripples resulted from the high frequency switching of the utility inverters can be attenuated not by controllers, but by passive filters [12-16]. The influence of the ripple current on power quality can be evaluated by the ripple factor (RF) defined by (3).

\[
RF_{sw} = \frac{I_{b}}{I_{new}} \times 100 \% \tag{3}
\]

This paper analyzes the relation between the filter inductance and the ripple factor according to the PWM pattern of grid-connected single-phase inverters. Based on the analysis, this paper proposes design guideline to get precise filter inductance that satisfies given ripple factor limit for the grid injection current.

Proposed design guideline not only gets accurate filter inductance in L-filter configuration, but also estimates precise ripple factor for the inverter side L-filter of LCL-filter configuration which is necessary to get exact LCL filter parameters [11]. Proposed design guideline also gives correct RMS value of the ripple current which further can be used for the loss calculation of grid-connected PV inverters.

Experiment validates the proposed theory and design guideline.

II. Analysis on ripple current

A) Inverter topology

Fig.1 describes a single-phase grid-connected inverter using full-bridge topology. If the b-leg switch is not used and the node \( v_n \) is directly connected to the DC split O, then the power circuit changes to a half-bridge topology.

Grid voltage \( e_a \) is assumed ideal sinusoid. To simplify the analysis, the fundamental component of the grid current in Fig.1 is assumed to be zero. Thus, the fundamental component of the voltage applied on the filter inductor is also zero as (4)

\[
v_{v1} = v_{vn} - e_a = 0 \tag{4}
\]

As can be seen in Fig.2, single-phase full-bridge inverters normally use unipolar PWM, so that the inverter output voltage \( v_g \) has three step values; \( V_d, 0, \) and \(-V_d\).
However, single-phase half-bridge inverters have to use bipolar PWM as shown in Fig. 3, so that the inverter output voltage \( v_o \) has two step values; \( +V_{dc}/2 \) and \( -V_{dc}/2 \).

Thus, the characteristics of the ripple current are different between the two inverter topologies. This paper analyzes the switching ripple current on the filter inductor according to the two topologies.

When the switching frequency \( f_{sw} \) is much higher than the utility frequency \( f_0 \), the time average value of the inverter output voltage \( v_{AV} \) can be regarded to be constant during the switching period \( T_s \).

Thus, the filter inductor current of grid-connected single-phase full-bridge inverters during any switching period has typical waveform as shown by the lower curve in Fig. 2. In this case, the peak-to-peak value of the filter inductor current \( \Delta i_{pp} \) that results from the unipolar PWM switching can be calculated as (5).

\[
\Delta i_{pp} = 2\Delta i_{min} = \frac{(V_o - V_{dc})}{L} \frac{d_{i}}{2} T_s
\]

Moreover, when the condition described by (4) is applied to single-phase full-bridge inverters during the interval of \( 0 < \alpha < \pi \), equations (6) and (7) can be deduced.

\[
v_{av}(\alpha) = d_{i}(\alpha)V_{dc}, \quad e_{i}(\alpha) = m_{a}V_{dc} \sin(\alpha)
\]

(6)

\[
d_{i}(\alpha) = m_{a} \sin(\alpha)
\]

(7)

From (6) and (7), the peak-to-peak value of the filter inductor current during \( 0 < \alpha < \pi \) can be calculated by (8).

\[
\Delta i_{pp}(\alpha) = \frac{V_{dc} T_s}{2L} (1 - m_{a} \sin(\alpha)) \cdot m_{a} \sin(\alpha)
\]

(8)

here, \( 0 < \alpha < \pi \).

Fig. 4 shows magnitude distribution of \( \Delta i_{pp} \) of grid-connected single-phase full-bridge inverters according to the parameter of modulation index \( m_{a} \) during the angle \( 0 < \alpha < \pi \). \( \Delta i_{pp}(\theta) \) has minimum or maximum value when the utility angle \( \theta \) is \( \sin^{-1}(1/2 m_{a}) \), \( \pi/2 \), and \( \pi - \sin^{-1}(1/2 m_{a}) \).

B) Analysis of ripple current

When the switching frequency \( f_{sw} \) is much higher than the utility frequency \( f_0 \), the time average value of the inverter output voltage \( v_{av} \) can be regarded to be constant during the switching period \( T_s \).

Thus, the filter inductor current of grid-connected single-phase full-bridge inverters during any switching period has typical waveform as shown by the lower curve in Fig. 2. In this case, the peak-to-peak value of the filter inductor current \( \Delta i_{pp} \) that results from the unipolar PWM switching can be calculated as (5).

\[
\Delta i_{pp} = 2\Delta i_{min} = \frac{(V_o - V_{dc})}{L} \frac{d_{i}}{2} T_s
\]

Moreover, when the condition described by (4) is applied to single-phase full-bridge inverters during the interval of \( 0 < \alpha < \pi \), equations (6) and (7) can be deduced.

\[
v_{av}(\alpha) = d_{i}(\alpha)V_{dc}, \quad e_{i}(\alpha) = m_{a}V_{dc} \sin(\alpha)
\]

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here, \( 0 < \alpha < \pi \).

Fig. 4 shows magnitude distribution of \( \Delta i_{pp} \) of grid-connected single-phase full-bridge inverters according to the parameter of modulation index \( m_{a} \) during the angle \( 0 < \alpha < \pi \). \( \Delta i_{pp}(\theta) \) has minimum or maximum value when the utility angle \( \theta \) is \( \sin^{-1}(1/2 m_{a}) \), \( \pi/2 \), and \( \pi - \sin^{-1}(1/2 m_{a}) \).
As the same way, the peak-to-peak value of the filter inductor current $\Delta i_p$ that results from the bipolar PWM switching can be calculated as (9).

$$\Delta i_p(\omega) = \frac{V_s T}{4L} [1 - m_s^2 \sin^2(\omega t)]$$

(9)

here, $0 < \omega < \pi$.

Fig. 5 shows magnitude distribution of $\Delta i_p$ of grid-connected single-phase half-bridge inverters according to the parameter of modulation index $m_a$ during the angle $0 < \omega < \pi$. $\Delta i_p(\theta)$ has minimum or maximum value when the utility angle $\theta$ is; $0, \pi / 2$, and $\pi$.

Since the voltage and current waveforms are half-cycle symmetry, the situation during $\pi < \omega < 2\pi$ repeats same as that of during $0 < \omega < \pi$.

C) RMS value of ripple current

The ripple current of utility-interactive single-phase full-bridge inverters is consisted with tri-angle waves bounded by $\pm \Delta i_p/2$ as described by Fig. 6.

Since RMS value is related with only absolute value, the RMS value of Fig. 6 can be calculated equivalently by the RMS value as Fig. 7.

When the switching frequency $f_s$ is assumed to integer multiple of the utility frequency $f_0$, the number of triangle waves during the 1/4 period $T/4$ of the utility angle will be $n$. Fig. 8 describes the distribution of triangle waves, where the magnitude of any $k$-th triangle wave can be calculated as (10).

$$\Delta i_{\text{rms}}(T_k) = \frac{V_s T}{4L} [1 - m_s(\theta_k)][m_s \sin(\theta_k)]$$

(10)

here, $\theta_k = (2k - 1)\frac{\pi}{4n}, k = 1, 2, ..., n$.

The ripple current of utility-interactive single-phase full-bridge inverters is consisted with tri-angle waves bounded by $\Delta i_p/2$ as described by Fig. 9.
Thus, the RMS value of the switching ripple current in single-phase half-bridge inverters can be calculated by (15)

\[ I_s = \frac{V_T T_s}{8L} \left\{ \frac{2\pi}{3} \left( 1 - m_c^2 + \frac{3}{8} m_i^2 \right) \right\} \]

\[ = \frac{V_T T_s}{8L} \left[ \frac{1}{3} \left( 1 - m_c^2 + \frac{3}{8} m_i^2 \right) \right] \]

III. Filter design guideline

A) Filter design on full-bridge topology

The fundamental component for the filter inductor current of grid-connected single-phase full-bridge inverters can be calculated as (16).

\[ I_L = \frac{m V_o}{\sqrt{2} Z_{in}} = \frac{m T V_o}{2\sqrt{2}\pi L_o} \]

Thus, the switching ripple factor of grid-connected single-phase full-bridge inverters \( (RF_{sw}) \) is calculated by (17).

\[ RF_{sw} = \frac{I_L}{I_s} \left[ \frac{\pi}{3} \left( \frac{1 + 3 m_c^2}{4} - \frac{4}{5} m_i^2 \right) T_s \frac{L_o}{T} \right] \]

Reversely, when the ripple factor of the injection current is given by \( RF_{sw} \), the filter inductor must be designed by (18).

\[ L_o = \frac{1}{RF_{sw}} \left[ \frac{\pi}{3} \left( \frac{1 + 3 m_c^2}{4} - \frac{4}{5} m_i^2 \right) T_s \frac{L_o}{T} \right] \]

B) Filter design on half-bridge topology

The fundamental component for the filter inductor current of grid-connected single-phase half-bridge inverters can be calculated as (19).

\[ I_L = \frac{m V_o}{\sqrt{2} Z_{in}} = \frac{m T V_o}{2\sqrt{2}\pi L_o} \]

Thus, the switching ripple factor of grid-connected single-phase half-bridge inverters \( (RF_{sw}) \) is calculated by (20).

\[ RF_{sw} = \sqrt{\frac{\pi^2 (1 - m_c^2 + 3m_i^2 / 8)}{6m_c^2}} \frac{T_s}{T} \frac{L_o}{L} \]

When the ripple factor of the injection current is given by \( RF_{sw} \), the filter inductor must be designed by (21).

\[ \frac{L}{L_o} \geq 1 \left[ \frac{\pi^2 (1 - m_c^2 + 3m_i^2 / 8)}{6m_c^2} \right] \frac{T}{T} \]

C) Filter design example

Table 1 describes circuit conditions for an example grid-connected PV inverter.

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power ( P )</td>
<td>10kVA</td>
</tr>
<tr>
<td>Rated Voltage ( V )</td>
<td>220V</td>
</tr>
<tr>
<td>Utility frequency ( f_o )</td>
<td>60Hz</td>
</tr>
<tr>
<td>Switching frequency ( f_{sw} )</td>
<td>6kHz</td>
</tr>
</tbody>
</table>

The per-unit system for the circuit condition can be calculated as follows;

\[ I_s = \frac{P}{V} = 45.45 \] \[ Z_o = \frac{V^2}{P} = 4.84 \] \[ L_o = \frac{Z_o}{2\pi f_o} = 12.84 \]

Thus when the switching ripple factor limitation is set to 10%, filter inductance for single-phase PV inverter can be designed by Table 2 and Table 3. Table 2 is for full-bridge inverters, and Table 3 is for half-bridge inverters.

Per-unit filter inductance data in Table 2 and Table 3 can be applied to any power rating and any voltage rating. When the modulation index is \( m_a = 1.0 \), the filter inductance of single-phase half-bridge inverter is around 3.79 times to that of single-phase full-bridge inverter. While, when the modulation index is \( m_a = 0.8 \), the filter inductance of single-phase half-bridge inverter is around 3.63 times to that of single-phase full-bridge inverter.

<table>
<thead>
<tr>
<th>Modulation Index</th>
<th>Filter inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_a = 1.0 )</td>
<td>0.02075 0.266</td>
</tr>
<tr>
<td>( m_a = 0.8 )</td>
<td>0.03166 0.406</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modulation Index</th>
<th>Filter inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_a = 1.0 )</td>
<td>0.07854 1.008</td>
</tr>
<tr>
<td>( m_a = 0.8 )</td>
<td>0.11489 1.475</td>
</tr>
</tbody>
</table>
IV. Experiment

To verify presented theory between the switching ripple factor and the filter inductance of grid-connected single-phase inverters, experiment is proceed on 10kVA/220V grid-connected PV inverter as described by Fig. 10.

Fig. 10 Experimental system of grid-connected single-phase full-bridge inverter.

Fig. 11 Experimental waveform of grid-connected single-phase full-bridge inverters when $m_a=0.8$.

Fig. 12 Experimental waveform of grid-connected single-phase half-bridge inverters when $m_a=0.8$.

Experimental conditions are equal to Table 1. Here, modulation index is set to $m_a=0.8$ through the experiment. However, the experimental verification goes opposite way. Since precise implementation of filter inductor is not easy, this paper first selects available filter inductor in the laboratory, then measure the switching ripple factor $RF_{sw,mes}$ by the selected filter inductor. Next, estimates the switching ripple factor $RF_{sw,est}$ by (17) or (20) applying the same filter inductances used in the experiment. Then the measured ripple factor $RF_{sw,mes}$ and the estimated ripple factor $RF_{sw,est}$ are compared to verify proposed theory.

Table 4 Experimental results for proposed grid-connected single-phase inverters.

<table>
<thead>
<tr>
<th>PWM topology</th>
<th>Filter Inductor [mH]/[pu]</th>
<th>Ripple Factor $RF_{sw,est}$ [%]</th>
<th>$RF_{sw,mes}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unipolar</td>
<td>0.27/0.021</td>
<td>15.0766</td>
<td>14.5</td>
</tr>
<tr>
<td>Bipolar</td>
<td>0.505/0.039</td>
<td>29.2351</td>
<td>28.4</td>
</tr>
</tbody>
</table>

Table 4 demonstrates the experimental results by the proposed filter design guideline for grid-connected single-phase full-bridge inverter and half bridge inverter respectively. Half-bridge inverter is implemented by adopting bipolar PWM topology to the same experimental system.

Fig. 11 shows experimental waveform of the grid-connected single-phase full-bridge inverter with the filter inductance of 0.27 [mH] whose per-unit value is 0.021 [pu]. As expected by the theory, the magnitude of the ripple component varies quadruple during the utility cycle.

Applying the equivalent per-unit filter inductance, equation (17) estimates the switching ripple factor of the inductor current in the single-phase full-bridge inverter as $RF_{sw,est} = 15.0766$ [%]. From FFT analysis for the measured filter inductor current, the switching ripple factor $RF_{sw,mes}$ can be calculated to around 14.5 [%] to the rated RMS current. This is 96.17 [%] against the estimated switching ripple factor $RF_{sw,est}$. Thus the error is about -4 [%].

Fig. 12 shows experimental waveform of the grid-connected single-phase half-bridge inverter with the filter inductance of 0.505 [mH] whose per-unit value is 0.0393 [pu]. As expected by the theory, the magnitude of the ripple component varies twice during the utility cycle.

Applying the equivalent per-unit filter inductance, equation (20) estimates the switching ripple factor of the inductor current in the single-phase half-bridge inverter as $RF_{sw,est} = 29.2351$ [%]. From FFT analysis for the measured filter inductor current, the switching ripple factor $RF_{sw,mes}$ can be calculated to around 28.4 [%] to the rated RMS current. This is 96.17 [%] against the estimated switching ripple factor $RF_{sw,est}$. Thus the error is about -3 [%].

However, the error is expected to decrease further if the experimental system uses rated load resistor of 4.84 [Ω] instead of presently used load resistor of 4.80 [Ω] that is 99 [%] to the rated resistance.
V. Conclusion

This paper has proposed design guideline for the filter inductor of grid-connected single-phase PV inverters, which was verified by experiment. RMS value of fundamental component and ripple component for the filter inductor current of grid-connected single-phase PV inverters was analyzed qualitatively and quantitatively. Based on the ripple current analysis, design guideline for filter inductor against the limitation of ripple factor was presented. Experiment verified that the proposed filter design guideline is very precise with the error under 4\%. Proposed design guideline is useful not only to get accurate filter inductance in L filter design, but also to get necessary intermediate filter inductance in LCL filter design. Proposed RMS calculation of the switching ripple current can be used for loss calculation of grid-connected single-phase inverter systems.

References


