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A Modified LLCL Filter With the Reduced Conducted EMI Noise

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Abstract—For a transformerless grid-tied converter using pulse width modulation, the harmonics of grid-injected current, the leakage current, and the electromagnetic interference (EMI) noise are three important issues during designing of the output filter. In this paper, the common mode and the differential mode EMI noises are investigated for the LCL- and LLCL-filter-based single-phase full-bridge grid-tied inverters. Based on this, a modified LLCL-filter topology is proposed to provide enough attenuation on the conducted EMI noise as well as to reduce the dc-side leakage current. The parameter design method of the filter is also developed. The comparative analysis and discussion on four filter cases (the conventional LCL filter, the conventional LLCL filter, the modified LCL filter, and the modified LLCL filter) are carried out and verified through simulations and experiments on a 0.5-kW, 110 V/50 Hz single-phase full-bridge grid-tied inverter prototype.

Index Terms—DC-side leakage current, differential mode (DM), EMI, LCL filter, LLCL filter, single-phase grid-tied inverter.

I. INTRODUCTION

THE photovoltaic power generation has increasingly grown due to the shortage of fossil fuels. In order to connect the PV generation panels to the single-phase utility grid, the full-bridge inverter using the pulse width modulation (PWM) has been widely adopted [1]–[3]. With the merits of more efficient, less bulky, and less cost than the isolated topology, the transformerless type system catches more attentions [4], [5]. Thus, the harmonics of grid-injected current, the leakage current, and the EMI noise are three important issues when designing the PV-inverter system, especially for the output filter. For example, the harmonic currents injected into the grid are suggested to satisfy the standards of IEEE 1547.2-2008 and 519-1992 [6], [7] and the leakage current and the EMI noise should be below special requirements based on the safety considerations [8]–[14].

In industrial applications, the cost is an important factor to select the power filter of the grid-tied inverter. In contrast to the conventional LCL filter, the LLCL filter can save the total material as well as the cost since the grid-side inductance can be reduced a lot [15], [16]. However, the EMI noise attenuation of the LLCL filter seems to decline due to its small grid inductor and the additional inductor in the loop of a capacitor.

In this paper, the conducted EMI noise of the LCL filter and the LLCL filter is first investigated. Then, a modified LLCL filter structure is proposed and analyzed to suppress the EMI noise as well as to reduce the leakage current in the photovoltaic application, when the discontinuous unipolar modulation [17] is adopted. Third, a design procedure of the modified LLCL filter is introduced. Finally, comparative analysis and discussion on the EMI issues are carried out between the conventional LCL filter, the conventional LLCL filter, the modified LCL filter, and the modified LLCL-filter-based inverter systems.

II. CONDUCTED EMI NOISE OF HIGH-ORDER POWER-FILTER-BASED GRID-TIED INVERTER

Fig. 1 shows the configuration of the single-phase full-bridge grid-tied inverter with the conventional LLCL filter, where the stray capacitor $C_P$ in the photovoltaic applications is considered and a simplified line impedance stabilization network (LISN) module is used as an interface between the inverter and the grid to measure the EMI noise. For analyzing the common mode (CM) and the differential mode (DM) EMI noises, the ideal equivalent of the conventional LLCL-filter-based inverter system are illustrated in Fig. 2.
The components of the CM voltage noise $V_{CM}(t)$ and DM voltage noise $V_{DM}(t)$ can be calculated as

$$V_{CM}(t) = \frac{V_{AN}(t) + V_{BN}(t)}{2}, \quad V_{DM}(t) = V_{AN}(t) - V_{BN}(t)$$

where, $V_{AN}(t)$ and $V_{BN}(t)$ are the terminal voltages of the two phase legs with respect to the midpoint of the split dc capacitors $N$, as labeled in Fig. 1.

Within the frequency range of 150 kHz–1 MHz, the attenuation gains on the CM and DM voltage noises through the ideal conventional $LLCL$ filter can be approximately derived with (2) and (3), respectively

$$\text{Att}_{CM, LLCL}(\omega) \left[ \text{dB} \right] \approx -20 \log_{10} \left[ 0.25 j\omega (L_1 + L_2) \right]$$

$$+ \frac{1}{2j\omega C_p} + Z_{LISN,1} + 20 \log_{10} \left[ \frac{j\omega L_{LISN}}{2} \right]$$

$$- 20 \log_{10} \left[ \frac{R_{LISN}}{2} + 2j\omega C_{LISN} + j\omega L_{LISN} \right]$$

$$+ 20 \log_{10} \left[ \frac{R_{LISN}}{2} \right]$$

$$+ Z_{LISN,2} / / Z_f + j\omega L_1$$

$$+ 20 \log_{10} \left( 2R_{LISN} \right)$$

$$+ 20 \log_{10} \left( \frac{Z_f}{j\omega L_2 + Z_f + Z_{LISN,2}} \right)$$

$$+ 20 \log_{10} \left( \frac{j\omega L_{LISN}}{R_{LISN} + 1 / j\omega C_{LISN} + j\omega L_{LISN}} \right)$$

where $Z_{LISN,1} = 0.5 j\omega L_{LISN} / \left( 0.5 R_{LISN} + 1 / 2 j\omega C_{LISN} \right)$,

$Z_{LISN,2} = 2 j\omega L_{LISN} / \left( 2 R_{LISN} + 2 / j\omega C_{LISN} \right)$, and $Z_f = j\omega L_f + 1 / j\omega C_f$.

As shown in Fig. 1, if the resonant inductor $L_f$ is shortened, then the conventional $LCL$-filter-based system is obtained. For analyzing the CM voltage noise, the ideal equivalent circuit of the conventional $LCL$-filter-based system is the same as that of the conventional $LLCL$ filter, which is also shown in Fig. 2(a).

The related attenuation gain on the CM voltage noise can also be obtained. Then, the attenuation gain on conducted DM voltage noise through the ideal conventional $LCL$ filter can be calculated as

$$\text{Att}_{DM, LCL}(\omega) \left[ \text{dB} \right] \approx -20 \log_{10} \left( j\omega L_2 \right)$$

$$+ Z_{LISN,2} / / j\omega C_f + j\omega L_1$$

$$+ 20 \log_{10} \left( 2R_{LISN} \right)$$

$$+ 20 \log_{10} \left( \frac{1 / j\omega C_f + Z_{LISN,2}}{j\omega L_2 + 1 / j\omega C_{LISN} + j\omega L_{LISN}} \right)$$

For the single-phase full-bridge inverter application, the unipolar PWM method is popular as it causes less switching power losses. When the asymmetrical regular sampled discontinuous unipolar PWM method [17] is adopted, the spectrum of the DM and CM voltage noise generated by an ideal full-bridge single-phase inverter can be depicted as

$$v_{DM}(t) = \alpha U_{dc} \cos (\omega_0 t) + \frac{2 U_{dc}}{\pi} \sum_{m=1}^{\infty} \frac{1}{m} \sum_{n=-\infty}^{\infty} \sum_{k=1}^{\infty} J_{2k-1} (m \pi \alpha) \cos \left( m \omega_s t + n \omega_0 t \right)$$

$$\times J_n \left( m \pi \alpha \right) \sin \left( \frac{n \pi}{2} \right) \cos \left( m \omega_s t + n \omega_0 t \right)$$

$$+ 4U_{dc} / \pi^2 \sum_{m=1}^{\infty} \frac{1}{m} \sum_{k=1}^{\infty} \frac{1}{2k-1} J_{2k-1} (m \pi \alpha) \cos (m \omega_s t)$$

$$- 4U_{dc} / \pi^2 \sum_{m=1}^{\infty} \frac{1}{m} \sum_{n=-\infty}^{\infty} \sum_{k=1}^{\infty} J_{2k-1} (m \pi \alpha) \cos \left( m \omega_s t + n \omega_0 t \right)$$

$$\cdot \cos \left( m \omega_s t + n \omega_0 t \right)$$

$$\times (m \pi \alpha \beta) \left[ \frac{2k-1}{(n+2k-1)(n+2k-1)} \right]_{n \neq 2k-1}$$

where $\alpha$ is the modulation index, $U_{dc}$ is the dc-link voltage, $J_n$ are Bessel functions [17], and $\omega_0$ and $\omega_s$ are the fundamental and the switching frequencies in radians per second, respectively.
TABLE I
PARAMETERS OF THE INVERTER FOR SIMULATION AND EXPERIMENT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conventional LCL-filter</th>
<th>Conventional LLCL-filter</th>
<th>Modified LCL-filter</th>
<th>Modified LLCL-filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₁</td>
<td>1.2mH</td>
<td>1.2mH</td>
<td>1.2mH</td>
<td>1.2mH</td>
</tr>
<tr>
<td>L₂</td>
<td>0.22mH</td>
<td>0.22mH</td>
<td>0.6mH</td>
<td>0.18mH</td>
</tr>
<tr>
<td>Cₐ</td>
<td>2µF</td>
<td>2µF</td>
<td>2µF</td>
<td>2µF</td>
</tr>
<tr>
<td>Lₐ</td>
<td>—</td>
<td>32µH</td>
<td>—</td>
<td>32µH</td>
</tr>
<tr>
<td>Cₘᵣ</td>
<td>44mF</td>
<td>44mF</td>
<td>44mF</td>
<td>44mF</td>
</tr>
</tbody>
</table>

During the EMI noise analysis, note that the total EMI noise should not only be related to the background EMI noise caused by the auxiliary power supply of the controller, but also depend much on the parasitic parameters, which are closely related to the circuit layout and the character of the switches [18]–[20]. However, according to [21] and [22], within the frequency range of 150 kHz ~ 1 MHz, the EMI effect caused by parasitic parameters of the output filter is not so serious. So in order to further illustrate the EMI noise for a high-order power-filter-based system, in order to ensure the EMI noise to meet the requirement of standards of CISPR, further measures should be taken.

III. PROPOSED MODIFIED LLCL FILTER

Recently, Dong et al. [23] proposed an interesting method to suppress the leakage current of the LCL-filter-based single-phase grid-tied inverter system. In this paper, a similar structure is proposed for the LLCL-filter-based inverter as shown in Fig. 4. Compared with the conventional LLCL-filter, two extra split CM capacitors of $C_{CM}$ are inserted in parallel with the $L_f$–$C_f$ resonance circuit. The mid-point of the extra split CM capacitors is linked with the midpoint of the split dc capacitors $C_{dc_S}$. Then, most of the high-frequency CM voltage noise passes through the split capacitor branch. At the same time, the series noninductive split CM capacitors also do suppress the DM voltage noise.

For the modified LLCL-filter-based system, the ideal equivalent circuits for analyzing the CM and DM voltage noises are illustrated in Fig. 5. The attenuation gains on suppressing the CM and DM voltage noise can approximately be calculated as

$$\text{Att}_{\text{CM,LLCL}}(\omega) \approx 20 \log_{10} \frac{0.25 j \omega L_2}{\omega \geq 2 \pi \cdot 150 \text{kHz}}$$

$$+ Z_{\text{LISN,L}} + \frac{1}{2 j \omega C_p} / (1/j \omega C_S + 0.25 j \omega L_1)$$

$$- 20 \log_{10} \left| 0.25 j \omega L_2 + Z_{\text{LISN,L}} + \frac{1}{2 j \omega C_p} + j \omega C_S \right|$$

$$- 20 \log_{10} \left| j \omega C_S \right|$$

$$- 20 \log_{10} \left| 0.5 j \omega L_{\text{LISN}} + \frac{1}{2 j \omega C_{\text{LISN}}} + 0.5 R_{\text{LISN}} \right|$$

$$+ 20 \log_{10} \frac{R_{\text{LISN}}}{2} + 20 \log_{10} \left| \frac{j \omega L_{\text{LISN}}}{2} \right|$$

(7)
Fig. 5. Equivalent circuit of the modified LLCL-filter for analyzing (a) CM voltage noise (b) DM voltage noise.

\[
\text{Att}_{\text{DM,LLCL}}' (\omega) \left[ \text{dB} \right] \left|_{\omega \geq 2\pi \cdot 150\text{kHz}} \right. \\
\approx -20 \log_{10} \left| j\omega L_2 + Z_{\text{LISN,2}} \right| \\
+ 20 \log_{10} \left( 2R_{\text{LISN}} \right) \\
+ 20 \log_{10} \left( j\omega L_2 + Z_{f,1} + Z_{\text{LISN,2}} \right) \\
+ 20 \log_{10} \left( j\omega L_{\text{LISN}} + R_{\text{LISN}} + \frac{1}{j\omega C_{\text{LISN}}} + j\omega L_{\text{LISN}} \right) \\
\] (8)

where \( C_s = \frac{2C_{\text{CM}} C_{\text{dc}}}{C_{\text{CM}} + C_{\text{dc}}}, Z_{f,1} = (j\omega L_f + \frac{1}{j\omega C_f}) / \frac{1}{j\omega C_{\text{CM}}} \).

Similarly, as shown in Fig. 4, if the \( L_f \) is shortened, then the modified LCL-filter-based system, which is the same as the filter structure proposed by Dong \textit{et al.} [23], is obtained. The ideal equivalent circuit of the modified LCL-filter-based system for analyzing the CM voltage noise is also shown in Fig. 5(a) and the attenuation gain of the CM voltage noise can be calculated with (7). The equivalent circuit for analyzing DM voltage noise can be obtained when \( L_f \) is shortened in Fig. 5(b) and the related attenuation gain can be depicted as

\[
\text{Att}_{\text{DM,LCL}}' (\omega) \left[ \text{dB} \right] \left|_{\omega \geq 2\pi \cdot 150\text{kHz}} \right. \\
\approx -20 \log_{10} \left| j\omega L_2 \\
+ Z_{\text{LISN,2}} \right| \\
+ 20 \log_{10} \left( 2R_{\text{LISN}} \right) \\
+ 20 \log_{10} \left( j\omega L_2 + Z_{f,1} + Z_{\text{LISN,2}} \right) \\
+ 20 \log_{10} \left( j\omega L_{\text{LISN}} + R_{\text{LISN}} + \frac{1}{j\omega C_{\text{LISN}}} + j\omega L_{\text{LISN}} \right) \\
\] (9)

Based on the parameters of Table I, the simulated maximum amplitudes of the attenuations on the CM and DM voltage noises for the modified LLCL and LCL filter are shown in Fig. 6. Compared with Fig. 3, it can be seen that the attenuation on the EMI noise within the frequency range of 150 kHz~1 MHz has been improved a lot.

IV. DESIGN OF THE MODIFIED LLCL FILTER

A. Constraints on Harmonics of the Grid-Injected Current and EMI Noise Within 150 kHz~1 MHz

In [15], the design of the conventional LLCL filter has been introduced step by step based on the requirements of five limits, which were also discussed in [24] and [25]. For the modified LLCL filter, the parameters of the inverter-side inductor and the \( L_f - C_f \) resonant circuit are similar to those of the conventional LLCL filter. This paper will focus on designing the grid-side inductor and the additional split CM capacitor. Certainly, the trial and error method is still used for the design. The additional split CM capacitor depends on the rule of

\[
0.5 C_{\text{CM}} + C_f \leq \frac{5\% P_{\text{rated}}}{V_g \cdot V_g},
\]

where \( P_{\text{rated}} \) is the rated output power of inverter and \( V_g \) is the RMS value of the grid voltage. In this paper, the additional split CM capacitor is first selected as

\[
0.5 C_{\text{CM}} = C_f = \frac{1.5\% P_{\text{rated}}}{\omega_o V_g V_g}.
\]

The transfer function of the grid-injected current versus the output voltage for the modified LCL-filter-based inverter can
be derived as

\[
G_{u_i \rightarrow i_g} (s) = \frac{Z_U (s)}{Z_{\text{ref}} (s)} = \left| \frac{Z_C (s)}{Z_1 (s) Z_2 (s) + Z_1 (s) Z_C (s) + Z_2 (s) Z_C (s)} \right|_{s=j\omega}
\]

(10)

where \( Z_1 (s) = sL_1 \), \( Z_2 (s) = sL_2 \), \( Z_C (s) = (\frac{1}{0.5sC_{CM}}) / (sL_f + \frac{1}{sC_f}) \).

Fig. 7 shows the Bode diagrams of the grid-injected current versus the ac output voltage for the LLCL-filter-based grid-tied inverter system. It can be seen that owing to the \( L_f = C_f \) resonant circuit, the current harmonics around the switching frequency have been attenuated to over 80 dB both for the conventional LLCL filter and the modified LLCL-filter-based system. If harmonics around the double of the switching frequency are small enough, then the harmonic current requirements of the IEEE 519-1992 can be met. Therefore, the criteria to choose the grid-side \( L_2 \) of the modified LLCL filter is expressed as

\[
\frac{\frac{1}{\pi} \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} |J_1 (2m\pi) | |J_2 (2n\pi) | |J_3 (2\pi) |}{I_{\text{ref}}} \leq 0.3\%
\]

(11)

where \( I_{\text{ref}} \) is the rated reference peak current.

**B. Constraints on Leakage Current**

In many applications, such as in photovoltaic generation, if it is done without galvanic isolation, the inverter will generate a variable CM voltage and the leakage current (CM current) appears in the stray capacitor between the PV array and the protection earth [26]. So for safety considerations, the leakage current should be limited to a required level [27].

For the modified LLCL-filter-based system, the equivalent circuit for analyzing the leakage current is given in Fig. 8. The split CM capacitors provide a high-frequency attenuation loop on the CM voltage noise as well as the dc leakage current. The negative dc-rail voltage with respect to the earth \( v_{dc-N} \) and the leakage current can be approximately estimated as

\[
v_{dc-N} \approx -\frac{v_{CM} (\omega)}{1 - \left( \frac{\omega}{\omega_r} \right)^2} - 0.5V_{dc} + 0.5V_g
\]

(12)

\[
I_{\text{leakage}} \approx \sqrt{\sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \left( 2 \left( m\omega_s + n\omega_0 \right) \cdot C_p \cdot v_{dc-N} (m\omega_s + n\omega_0) \right)^2}
\]

(13)

where \( \omega_r = \sqrt{\frac{2(C_{CM}+C_p)}{L_2 L_{CM}}}, V_g \) is the grid voltage, \( V_{dc} \) is the dc-link voltage of the inverter, and \( I_{\text{leakage}} \) is the RMS value of the leakage current.

When \( C_{CM} \) and \( L_2 \) are selected, the EMI requirement within the frequency of 150 kHz–1 MHz should be verified with (7) and (8), where the total EMI noise requirement should be met. If it is necessary, a coupled CM inductor \( L_{CM} \) needs to be connected with the inverter-side inductor to further reduce the CM EMI noise and the leakage current.

**V. EXPERIMENTAL RESULTS**

In order to confirm the effectiveness of the proposed modified LLCL filter on suppressing the conducted EMI noise, a 500-W prototype of the single-phase full-bridge grid-tied inverter with the DSP (TMS320LF2812A) controller is constructed. The experiments are evaluated and investigated under the given conditions of \( f_s = 20 \text{ kHz}, U_{dc} = 175 \text{ V}, U_g = 110 \text{ V/50 Hz}, P_{\text{rated}} = 500 \text{ W}, \) and the discontinuous unipolar PWM
TABLE II
ATTENUATIONS ON THE MAXIMUM HARMONIC CURRENT FOR FOUR DIFFERENT FILTER BASED SYSTEMS AROUND THE SWITCHING FREQUENCY AND THE DOUBLE OF THE SWITCHING FREQUENCY

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Conventional LCL-filter</th>
<th>Conventional LLCL-filter</th>
<th>Modified LCL-filter</th>
<th>Modified LLCL-filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_s</td>
<td>49 dB</td>
<td>53 dB</td>
<td>49 dB</td>
<td>53 dB</td>
</tr>
<tr>
<td>2f_s</td>
<td>62 dB</td>
<td>54 dB</td>
<td>62 dB</td>
<td>57 dB</td>
</tr>
</tbody>
</table>

Fig. 10. Measured power spectrum results of the grid-injected current with four type power-filter-based system (a) conventional LCL filter (b) conventional LLCL filter (c) modified LCL filter (d) modified LLCL filter.

modulation method is adopted. The experimental parameters of the filter are the same as those for simulations listed in Table I.

The photo of the modified LLCL-filter-based inverter system is shown in Fig. 9. Note that the size of the L2 is much smaller than L1. Certainly, the further optimization on the design of total filter need be carried out to minimize the total size and the footprint.

The experimental results on the power spectrum of the grid-injected current, the conducted EMI noise in the grid-side, the negative dc-rail voltage with respect to the earth \( v_{dc-N} \) and the leakage current of four filter cases are given in Figs. 10–14, respectively.

A. Power Spectrum of the Grid-Injected Current

Fig. 10 shows measured power spectrum of the grid-injected current for four different types of the power-filter-based system.

Table II shows the measured attenuations on the maximum harmonic current for four different filter-based systems around the switching frequency and the double of the switching frequency. It can be seen that compared with the conventional LCL filter and the modified LCL filter, the conventional LLCL filter and the modified LLCL filter have better attenuating effects on the harmonics of the grid-side current around the switching frequency, but the opposite around the double of the switching frequency. The modified LLCL filter has a better attenuation on the harmonic than the conventional LLCL filter around the double of the switching frequency due to the extra series split CM capacitors.

B. Measured Conducted EMI Noise

A spectrum analyzer (Agilent E4402) and LISN (EMCO 4825) are used to measure the EMI noise. In the spectrum analyzer, the peak value of the conducted EMI voltage is tracked. Fig. 11 shows the measured background EMI noise when the auxiliary power supply of the controller is ON and output PWM signals are all blocked for four different types of system. It can be seen that the background EMI noise is close to the standards of CSIPR 11 class B around the frequency of 150 kHz. It should be pointed out that no extra ac EMI filter is inserted during the test.

Fig. 12 shows the measured grid-side conducted EMI voltages of four type power-filter-based systems. It can be seen that for the conventional LLCL filter or LCL-filter-based system, the total conducted EMI noise cannot meet the standards of CSIPR 11 class A. But for the modified LLCL filter or LCL-filter-based system, the total conducted EMI noise can meet the standards of CSIPR 11 class A. Comparing the parameters of the modified
Fig. 11. Measured background conducted EMI noise for different filter-based system (a) conventional $LCL$ filter, (b) conventional $LLCL$ filter, (c) modified $LCL$ filter, (d) modified $LLCL$ filter.

Fig. 12. Experimental results of conducted EMI noise for different filter-based system (a) conventional $LCL$ filter (b) conventional $LLCL$ filter (c) modified $LCL$ filter (d) modified $LLCL$ filter.
LLCL filter with the modified LCL filter as listed in Table I, it can be seen that the total inductance of the LLCL filter is smaller about 20% than that of the LCL filter.

C. Negative DC-Rail Voltage With Respect to the Earth $v_{dc-N}$ and the Leakage Current

In the photovoltaic inverter application, the stray capacitance between the PV array and the protection earth is generally proportional to the power rating of the inverter system. In the experimental prototype, two capacitors of 44 nF are used to emulate the stray capacitors of $C_P$ as shown in Figs. 1 and 4. For the conventional LLCL filter and the modified LLCL-filter-based systems, the measured waveforms of the negative dc-rail voltage with respect to the protection earth $v_{dc-N}$ and the leakage current are shown in Figs. 13 and 14, respectively. It can be seen that with the modified LLCL-filter structure, the negative dc-rail voltage of the system is much smooth and the RMS value of the leakage current can be attenuated from 664 to 10.3 mA, which can also meet the standards given in DIN V VDE V 0126-1-1 [27].

Note that the leakage current waveform of the modified LCL-filter-based system is similar to the modified LLCL-filter and the measured RMS value of the leakage current is 9.4 mA, which can also meet the standards given in DIN V VDE V 0126-1-1 well.

VI. CONCLUSION

This paper analyzes and addresses the conducted EMI issues for the high-order power-filter-based single-phase full-bridge grid-tied inverter using the discontinuous unipolar modulation. The following can be concluded.

1) If the extra ac EMI filter is not inserted, both the CM and the DM EMI noises cannot meet the requirements of CISPR 11 for the conventional LLCL-filter-based system, while the CM EMI noises cannot meet the requirements of CISPR 11 for the conventional LCL-filter-based system.

2) Compared with the conventional LCL and LLCL filter, the attenuation on EMI noise of the modified LCL- and LLCL-filter-based inverter systems has been improved a lot.

3) Compared with the conventional LCL filter, the RMS value of the leakage current of the modified LLCL-filter-based system decreases from 664 to 10.3 mA for a 500-W prototype with two stray capacitors of 44 nF, which fully meets the leakage current requirement of DIN V VDE V 0126-1-1 [27].

4) Compared with the LCL filter, the modified LLCL filter can save about 20% of the total inductance. Note that currently, our work focuses on the principle of this new topology, more work needs to be carried out on the integration of the filter to minimize the size and the footprint.
A design method of the proposed modified LLCL filter has also been introduced. The theoretical analysis has been fully verified through simulations and experiments on a 500-W, 110 V/50 Hz prototype with four different type of power-filter structure. The experimental results are greatly in agreement with the theoretical analysis.

REFERENCES


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