Design of LLCL Filter for Single Phase Inverters with Confined Band Variable Switching Frequency (CB-VSF) PWM

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Abstract

Recently, the use of LLCL filters for grid inverters has been suggested to give better harmonic attenuation than the commonly used L and LCL filters, particularly around the switching frequency. Nevertheless, this filter is mainly designed for constant switching frequency pulse width modulation (CSF PWM) methods. In variable switching frequency PWM (VSF PWM), the harmonic components are distributed across a wide frequency band which complicates the use of a high order filter, including LCL and LLCL filters. Recently, a confined band variable switching frequency (CB-VSF) PWM method has been proposed and demonstrated to be superior to the conventional constant switching frequency (CSF) PWM in terms of switching losses. However, the applicability of LLCL filters for this type of CB-VSF PWM has not been discussed. In this paper, the authors study the suitability of an LLCL filter for CB-VSF PWM and propose design guidelines for the filter parameters. Using simulation and experimental results, it is demonstrated that the effectiveness of an LLCL filter with CB-VSF PWM depends on the parameters of the filters as well as the designed variable frequency band of the PWM. Simulation results confirm the performance of the suggested LLCL design, which is further validated using a lab scale prototype.

Key words: Confined band variable switching frequency CB-VSF PWM, Constant switching frequency PWM (CSF PWM), LCL filter, LLCL filter

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>Inverter side inductor</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Grid side inductor</td>
</tr>
<tr>
<td>$C_f$</td>
<td>Filter capacitor (tuning branch)</td>
</tr>
<tr>
<td>$X_C$</td>
<td>Capacitive impedance of $C_f$</td>
</tr>
<tr>
<td>$C_{f_{\text{min}}}$</td>
<td>Minimum value of the filter capacitor</td>
</tr>
<tr>
<td>$C_{f_{\text{max}}}$</td>
<td>Maximum value of the filter capacitor</td>
</tr>
<tr>
<td>$L_f$</td>
<td>Filter inductor (tuning branch)</td>
</tr>
<tr>
<td>$X_{L_f}$</td>
<td>Inductive impedance of $L_f$</td>
</tr>
<tr>
<td>$Z_{LC_f}$</td>
<td>Impedance of the tuning branch ($L_C$)</td>
</tr>
</tbody>
</table>

$G(s)$  
$I_{\text{in}}(s)$  
$V_{\text{in}}(s)$  
$f_s$  
$f_{\text{tune}}$  
$n_{\text{f}}$  
$C_f$  
$f_{\text{r}}$  
$f_{\text{CB-VSF}}$  
$f_{\text{VSF}_{\text{min}}}$  
$\omega_s$  
$\omega_{\text{r}}$  
$\omega_{\text{tune}}$  
$\omega_{\text{CB-VSF}}$  
$\omega_{\text{VSF}_{\text{min}}}$  
\(k\)  

Transfer Function:

- Inverter side current
- Inverter side voltage
- Switching frequency
- Tuned frequency
- Multiples of the switching frequency
- Resonance switching frequency
- Grid frequency
- Variable switching frequency
- Resonant angular frequency
- Tuned angular frequency
- Switching angular frequency
- Variable switching angular frequency
- Minimum variable switching frequency
- Grid angular frequency
- Constant value equal to ($L_1 \cdot L_2 / L_1 + L_2$)

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Design of LLCL Filter for Single Phase Inverters with ...
CSF PWM [6] is well known as shown in Fig. 2(a), with switching harmonics appearing around \(nf_s\), where \(f_s\) is the switching frequency and \(n = \{1, 2, 3 \ldots\}\). In terms of magnitude, the harmonics around \(n=1\) have the highest magnitude and are quickly reduced as \(n\) increases.

B. CB-VSF PWM Harmonic Spectrum

The CB-VSF PWM scheme is proposed in [18] such that the switching frequency is varied within a predefined frequency band. The variable switching frequency range of CB-VSF PWM is confined between minimum and maximum switching frequencies with the highest amplitude at the minimum switching frequency \(f_{\text{VSFmin}}\) as presented in Fig. 2(b). The confined frequency band ensures that CB-VSF PWM does not create harmonics that coincide with the resonance frequency of the filter.

C. Harmonic Spectrum Similarities and Differences Between CSF PWM and CB-VSF PWM

For both of the PWM schemes, the highest harmonic component appears approximately around multiples of the effective switching frequency, whereas the dominant harmonics appear at the first effective switching frequency. On the other hand, the distributions of harmonic components are quite different. The harmonic components for CSF PWM concentrate around multiples of the switching frequency, while harmonics for CB-VSF PWM spread out over a frequency band depending on the design of the CB-VSF PWM [18]. Nevertheless, the highest harmonic component of CB-VSF PWM is always lower than that of CSF PWM as shown in Fig. 2(a) and Fig. 2(b), which were obtained at the same parameters and serial filter value (5 mH) for the two PWM schemes. Since the harmonic spectra of CBVSF-PWM is different from that of CSF-PWM, the filter must be designed so that the harmonic components in the frequency band are effectively attenuated.

D. LLCL Filter Response

Passive power filters are commonly used in full-bridge inverters as shown in Fig. 3. The transfer functions of the LLCL filter can be derived as [6], [10]:

\[
G_{V_{\text{inv}} \rightarrow I_{\text{inv}}}(s) = \left. \frac{I_{\text{inv}}(s)}{V_{\text{inv}}(s)} \right|_{V_{g}(s)=0} = \frac{(l_2 + L_f) c_f s^2 + 1}{(l_1 + l_2) c_f + (l_1 + l_2) L_f c_f s^2 + (l_1 + l_2) s} \quad (1)
\]

\[
G_{V_{\text{inv}} \rightarrow V_g}(s) = \left. \frac{I_g(s)}{V_{\text{inv}}(s)} \right|_{V_{g}(s)=0} = \frac{L_f c_f s^2 + 1}{(l_1 + l_2) c_f + (l_1 + l_2) L_f c_f s^2 + (l_1 + l_2) s} \quad (2)
\]

\[
f_r = \frac{1}{2\pi \sqrt{(l_1 + l_2 + L_f)c_f}} \quad (3)
\]

\[
f_{\text{tune}} = \frac{1}{2\pi \sqrt{L_f c_f}} \quad (4)
\]

Fig. 2. Harmonic current spectrum of an inverter through a serial 5 mH filter: (a) With CSF PWM of \(f_s = 10\) kHz; (b) With CB-VSF PWM, \(f_{\text{VSF}} = 10\) kHz-20 kHz.

The resonance frequency \(f_r\) represents the frequency at which the harmonics are amplified as shown in Fig. 4. This must be avoided in the design of the PWM and the filter. The use of a “confined band” in CBVSF-PWM ensures that this can be achieved easily for VSF-PWM. On the other hand, the harmonics that appear at \(f_{\text{tune}}\) are significantly attenuated. It is worth highlighting that the LLCL filter provides better
attenuation than the LCL filter for frequencies around \( f_{\text{tune}} \). However, this advantage diminishes for frequencies further above \( f_{\text{tune}} \).

For CSF-PWM, the design is focused on selecting \( f_{\text{tune}} \) to be equal to the effective switching frequency, and adjusting the rest of the parameters to minimize \( L \) and \( C \), while maintaining the losses and THD. Since CBVSF-PWM has different harmonics spectra, it is necessary to reexamine the design guidelines, with the following points taken into consideration:

i) Knowing that the highest harmonic component is still around the effective switching frequency, \( f_{\text{tune}} \) should be selected around this frequency.

ii) The resonance frequency should be higher than 10 times the fundamental frequency (grid frequency) \( f_g \) but lower than half the effective switching frequency \( f_s \).

iii) The output current ripple and reactive power from the capacitor should be within acceptable ranges.

iv) The \( L \) and \( C \) values should be selected to maximize the attenuation effect while satisfying conditions (i) – (iii).

In this study, a fixed serial inductance \((L_1 + L_2)\) is considered to limit the voltage drop of these inductors and to focus on analyzing the effect of \( C_f \) & \( L_f \) variations on the attenuation effectiveness of the LLCL filter.

III. LLCL FILTER DESIGN CONSIDERATIONS FOR CB-VSF PWM BASED SINGLE PHASE INVERTERS

In this section, an analysis is done by looking at the design requirement for each of the components in an LLCL filter.

A. Inverter Side Inductor \( L_1 \)

The value of the inverter side filter inductor \((L_1)\) should agree with the constrain of the maximum ripple of the switching frequency on the inverter side current, which is commonly accepted to be in the range of 15% to 40% as shown in (5) \[6\]:

\[
15\% \leq \frac{V_{dc}}{4 \ L_1 f_i I_{\text{p}} \omega_s} \leq 40\%
\]  (5)

Where \( V_{dc} \) is the DC link voltage, \( f_i \) is the switching frequency, and \( I_{\text{p}} \) is the peak value of the rated current.

This parameter will be considered as a fixed value in subsequent discussions.

B. Allowable Component Ranges of the \( L_f \) & \( C_f \) Tuning Branch

Similar to the case of CSF PWM, the maximum allowable limit of absorbed reactive power should be restricted to 5% of the rated system power \[6\]. This gives the maximum limit of \( C_f \) as (6):

\[
C_{f_{\text{max}}} = \frac{5\% \ P_{\text{rated}}}{V_g^2 \ \omega_g} \quad (6)
\]

Where \( P_{\text{rated}} \) is the system rated power, \( V_g \) is the root mean square value of the grid voltage, \( \omega_g \) is \( 2 \pi f_g \) and \( f_g \) is the grid frequency.

To ensure the suppression of the dominant switching harmonics, the values of \( L_f C_f \) should be chosen so that the tuning frequency is equal to the effective switching frequency, i.e.:

\[
\frac{1}{L_f C_f} = \omega_{\text{VSPFmin}}^2 = \omega_s^2 = \omega_{\text{tune}}^2 \quad (7)
\]

However, the choice of \( C_f \) affects the resonance frequency, as dictated by (3). This means that while satisfying the maximum condition at (6), the high filter capacitor negatively affects the stability of the grid current \[10\], and the acceptable values of \( C_f \) should take the allowable range of the resonance frequency into consideration (10 \( f_g < f_r < 0.5 f_s \)), such that:

\[
10 \omega_g < \frac{1}{(L_1 L_2 + L_f) C_f} < 0.5 \omega_g \quad (8)
\]

The value of \( L_1 \) is determined by (5) and \( L_f \) is evaluated from (7). Based on (8), it is clear that \( L_1 \) and \( C_f \) are two factors that need to be optimized together. The selection of \( L_2 \) is discussed subsequently.

Reducing \( C_f \) degrades the attenuation effectiveness, the minimum allowable value of \( C_f \) is limited by the maximum allowable value of the resonance frequency \( f_r \), which is equal to half of the switching frequency. Therefore, the case of \( C_f \) (0.5 \( \mu \)F) is selected to explain the effect of exceeding the minimum limit of \( C_f \).

The minimum allowable \( C_f \) can be determined for each of the \( L_f \) and \( L_2 \) values by starting from the resonance frequency \( f_r \) relationship shown in (9) \[13\] for the LLCL filter components:

\[
(2 \pi f_r)^2 \left( \frac{1}{L_1 L_2 + L_f} \right) C_f^2 = \frac{1}{(k+L_f)C_f} \quad (9)
\]

At fixed \( L_1 \) and \( L_2 \) values, the minimum value of the filter capacitor can be obtained by considering the maximum allowable value of the resonance frequency \( f_r = 0.5 f_s \). Hence, the resonance relationship of (9) can be written as follows:

\[
(2 \pi \times 0.5 f_s)^2 = \frac{1}{(k+L_f)C_f} \quad (10)
\]

Where the constant \( k \) is \( \frac{L_1 L_2}{L_1 + L_2} \).

From (7), \( L_f \) can be written as function of \( C_f \):

\[
L_f = \frac{1}{4 \pi^2 f_s^2 \ k + \frac{1}{C_f}} \quad (11)
\]

Substituting (11) into (10) yields (12):

\[
C_f = \frac{1}{\pi^2 f_s^2 k + \frac{1}{C_f}} = \frac{4C_f}{4 \pi^2 f_s^2 k C_f + 1} \quad (12)
\]

The value of \( C_f \) in (12) represents the minimum value of
the filter capacitor $C_{f\text{min}}$ because it is derived at the condition of the maximum resonance frequency $f_r$. The minimum value of $C_{f\text{min}}$ can be found from (13) after re-arranging (12):

$$C_{f\text{min}} = \frac{3}{4\pi^2 f_r^2 R}$$  \hspace{1cm} (13)

There are multiple combinations of $C_f$ and $L_f$ values that can satisfy conditions (6), (7) and (13). To understand the effect of changing $C_f$ on the LLCL filter response, four values $0.5 \, \mu F$, $1 \, \mu F$, $2 \, \mu F$ and $3 \, \mu F$ are selected for demonstration purposes. By keeping $f_{\text{tune}}$ at 10 kHz, the corresponding calculated $L_f$ values are 0.507 mH, 0.253 mH, 0.127 mH and 0.084 mH, respectively. The ability to attenuate harmonics using the $C_fL_f$ branch is determined by the value of the equivalent impedance of $Z_{eq} = X_{L_f} + X_{C_f}$. Since a lower impedance $Z_{eq}$ gives better attenuation, the combination of $L_f=0.084$ mH and $C_f=3 \, \mu F$ is expected to be better than the case with $L_f=0.507$ mH and $C_f=0.5 \, \mu F$.

Variations of $X_L$ and $X_C$ for the selected $L_f$ and $C_f$ values are shown in Fig. 5. From Fig. 5(b), it can be observed that the differences among the impedance magnitudes reduce with the value of $C_f$ rising. It can also be noticed that the impedance of $L_f$ (0.084 mH) and $C_f$ (3 \, \mu F) at 20 kHz is equal to 7.958 $\Omega$, which is markedly less than the impedance 47.75 $\Omega$ of $L_f$ (0.507 mH) and $C_f$ (0.5 \, \mu F). At the same time, the difference of 11.94 $\Omega$ - 7.958 $\Omega$ is equal to 3.982 $\Omega$, which is less than the difference of 47.75 $\Omega$ - 23.87, which is equal to 23.88 $\Omega$.

![Fig. 5. Four inductive and capacitive impedances variations with respect to the range of the frequency: (a) $XL$ and $XC$ impedances; (b) Equivalent impedance.](image)

Fig. 6 shows four Bode plots of an LLCL filter at four different $C_f$ and $L_f$ values of the same tuning (10 kHz), whereas the inverter side inductor $L_1$ and the grid side inductor $L_2$ are fixed. Fig. 6 shows the effect of changing $C_f$ and $L_f$ on the LLC filter attenuation above the switching frequency.

From Fig. 6, it can be seen that increasing $C_f$ reduces the resonance frequency $f_r$ and vice versa. Furthermore, increasing the $C_f$ value increases the attenuation of harmonics above $f_r$. In particular, the attenuation for frequencies above $f_s$, i.e. where the switching harmonics of the CBVSF-PWM are located, increases with a higher $C_f$. Nevertheless, the improvement in attenuation is reduced with an increasing $C_f$. For example, from the zoomed in graph of Fig. 6(b), increasing $C_f$ from 1 $\mu F$ to 2 $\mu F$ improves the attenuation by -5.5 dB. However, increasing $C_f$ from 2 $\mu F$ to 3 $\mu F$ only improves the attenuation by -3.5 dB. It is clear that even though $C_f$ should be maximized to improve harmonics attenuation. However, increasing $C_f$ too much results in the absorbed reactive power increasing with a marginal gain in attenuation.

As a tradeoff between attenuation and losses, it is proposed here that the value of $C_f$ is selected by averaging its maximum and minimum limits as shown in (14):

$$C_f = \frac{C_{f\text{max}} + C_{f\text{min}}}{2}$$  \hspace{1cm} (14)

C. Allowable Range of the Grid Side Inductance $L_2$

In order to determine the values of $C_f$ based on (14), it is necessary to decide the value of $L_2$. For CSF PWM, $L_2$ is selected to ensure that the harmonic components at the effective switching frequency are lower than 0.3% [6] in accordance with IEEE519-1992. For VSF PWM, the harmonic components are always lower than those of CSF PWM. Hence, the same (14) used in [6] for $L_2$ selection in CSF PWM is sufficient to ensure compliance with IEEE519-1992.

In addition, the choice of $L_2$ should take into consideration...
the effect of the resonance frequency as in (8). $L_2$ can be expressed as a function of the resonance frequency as follows:

$$L_2 = \frac{(1 - \omega_f^2 L_f C_f) L_1}{\omega_f^2 L_1 C_f + \omega_f^2 L_f C_f - 1}$$ (15)

Substituting (7) into (15) yields (16):

$$L_2 = \frac{1 - \left(\frac{\alpha}{\omega_{tune}}\right)^2 L_1}{\left(\frac{\alpha}{\omega_{tune}}\right)^2 + \left(\frac{\alpha}{\omega_{tune}}\right)^2 - 1}$$ (16)

Assume:

$$\left(\frac{\omega_f}{\omega_{tune}}\right)^2 = \alpha$$ (17)

Substituting (17) into (16) yields (18):

$$L_2 = \frac{(1 - \alpha) L_1}{\left(1 + \frac{\alpha}{\omega_{tune}} L_1 C_f\right) \alpha - 1}$$ (18)

From (18), the value of $L_2$ can be expressed in terms of $C_f$:

$$L_2 = \frac{(1 - \alpha) L_1}{\left(1 + \frac{\alpha}{\omega_{tune}} L_1 C_f\right) \alpha - 1}$$ (19)

Since, the values of $L_1$ and $\omega_{tune}$ can be directly selected, the value of $\alpha$ is bounded by the resonance frequency limits $10 f_s < f_i < 0.5 f_s$, while the maximum value of $C_f$ is bounded by (6). In addition, the feasible values of $L_2$ can be calculated for different combinations of $C_f$ and $\alpha$. By crosschecking the obtained $L_2$ values with the IEEE519-1992 harmonic requirement [6], final values of $L_2$ and $C_f$ can be decided.

IV. IMPLEMENTATION OF LLCL FILTER DESIGN CONSIDERATION FOR A CB-VSF PWM BASED SINGLE PHASE INVERTER

To conceptualize the design procedure discussed above, an example of its implementation is discussed here. A single-phase inverter with a CB-VSF PWM and an LLCL filter is considered here with the parameters given in Table I.

Based on the system parameters shown in Table I, the calculated $L_1$ is 3.55 mH and the selected value is 3.6 mH. For the minimum variable switching frequency $f_{VSF_{min}}$ of 10 kHz with a fixed $L_1$ of 3.6 mH, the reasonable range of $\alpha$ for $0.5 \text{ kHz} < f_i < 5 \text{ kHz}$, is $0.0025 < \alpha < 0.25$. Based on (17), the range of the allowable $L_2$ value can be determined using (18) or (19) for each of the tuned values of $C_f$ and $L_2$. Using the Table I parameters, the maximum value of the tuning branch capacitor $C_{f_{max}} = 3.09 \mu F$ is obtained using (6). Hence, the allowable values of $L_2$ can be calculated for $0.0025 < \alpha < 0.25$ and $0.5 \mu F < C_f < 3.0 \mu F$ as shown in Fig. 7. As demonstrated in Fig. 6(b), the required value of $L_2$ is reduced with an increase in $C_f$ as well as an increase in $\alpha$.

To guarantee that the attenuations for each of the harmonic components around and above the double switching frequency are equal to or less than 0.3%, the attenuation of harmonics order >35 can be calculated using the method in [6] for different combinations of $L_2$, $C_f$ and $L_f$, as shown in Fig. 8.

Note that $L_f$ and $C_f$ maintain the same tuning frequency at 10 kHz. From Fig. 8, as the value of $C_f$ increases, the value of $L_2$ needs to be reduced. Based on the plots in Fig. 7 and Fig. 8, the lower the values of $L_2$ in the allowable ranges are inversely proportional to $C_f$. In other words, the lower $L_2$ is equal to 0.3 mH when $C_f$ is equal to 3 $\mu F$, and it is 1.5 mH when $C_f$ is equal to 0.5 $\mu F$. The selected value of $L_2$ is 1.2 mH to avoid the necessity of selecting the highest $C_f$ value. The $L_2$ value is fixed in this study to focus on the effect of $L_f$ and $C_f$ variations on the LLCL filter attenuation along the different bands of CB-VSF PWM.

With selected values of $L_1$ (3.6 mH) and $L_f$ (1.2 mH), the calculated minimum capacitor is $C_{f_{min}} = 0.844 \mu F$. According to (14), the suitable designed value of $C_f$ is 1.967 $\mu F$. Therefore, $C_f = 2 \mu F$ is selected. Cross-checking with Fig. 8, it is clear that the selected value of 1.2 mH is well above the minimum 0.48 mH required to meet grid harmonics requirements.

In order to confirm the validity of the proposed LLCL filter design guidelines, simulation and experimental studies have
TABLE I
INVERTER SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Input dc link voltage, $V_{dc}$</td>
<td>350 V</td>
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<td>Rated power</td>
<td>1 kW</td>
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<td>$f_{\text{VSFmax}}$ for different band of CB- VSF PWM and R- VSF PWM</td>
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<td>Adopted Strategy</td>
<td>Unipolar PWM</td>
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<td>Dead time, $T_d$</td>
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<td>IGBT with ultrafast soft recovery</td>
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<td>Load resistor</td>
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<td>Modulation Index, $m$</td>
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<tr>
<td>Current Ripple Factor, $\Delta I_{\text{ref}}$</td>
<td>40% of $I_{\text{ref}}$</td>
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TABLE II
SIMULATED AND EXPERIMENTAL FILTER COMPONENTS (10 kHz TUNING)

<table>
<thead>
<tr>
<th>Component</th>
<th>LLCL Filter:1</th>
<th>LLCL Filter:2</th>
<th>LLCL Filter:3</th>
<th>LLCL Filter:4</th>
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<tr>
<td>$L_1$</td>
<td>3.6 mH</td>
<td>3.6 mH</td>
<td>3.6 mH</td>
<td>3.6 mH</td>
</tr>
<tr>
<td>$L_2$</td>
<td>1.2 mH</td>
<td>1.2 mH</td>
<td>1.2 mH</td>
<td>1.2 mH</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.5 $\mu$F</td>
<td>1 $\mu$F</td>
<td>2 $\mu$F</td>
<td>3 $\mu$F</td>
</tr>
<tr>
<td>$L_f$</td>
<td>507 $\mu$H</td>
<td>253 $\mu$H</td>
<td>127 $\mu$H</td>
<td>84 $\mu$H</td>
</tr>
</tbody>
</table>

been conducted. Different variable switching frequency bands were investigated through a unipolar PWM strategy [20] for a single-phase inverter. Table II shows the LLCL filter components with four different combinations of $L_f$ and $C_f$. The first three cases use L and C values within the allowable ranges presented in the guidelines. Meanwhile, in the fourth case, $C_f$ (0.5 $\mu$F) was selected to be lower than the minimum limit of $C_f$. This is to show the effect of a low capacitance on the production of high impedance $Z_{L_fC_f}$ which consequently leads to high THD levels in the load current spectrum.

V. SIMULATION RESULTS

MATLAB/Simulink is adopted to simulate a single-phase full-bridge inverter with an LLCL filter. Simulations results are recorded based on the parameters listed in Table I and Table II. The LLCL filter performance is investigated using four different values of $L_f$ with four different $C_f$ under the condition of the same tuning (10 kHz).

The filter performance is evaluated in terms of the harmonic reduction effectiveness starting from 10 kHz and the zero-switching-band total harmonic distortion (THD) i.e. CSF PWM. Then the filter performance is evaluated at different frequency bands. Analyses and comparisons are carried out for a 5 kHz CSF PWM along with 5-6 kHz, 5-7.5 kHz, 5-10 kHz and 5-15 kHz CB- VSF PWM based on the unipolar PWM strategy, which leads to harmonics appearing at twice the above mentioned switching frequencies. In other words, the effective switching frequency for CSF PWM is 10 kHz. Meanwhile, for CB- VSF PWM, the switching frequency bands are (10-12 kHz), (10-15 kHz), (10-20 kHz) and (10-30 kHz) respectively.

Fig. 9 shows the harmonic spectrums of load currents for 10 kHz PWM using four LLCL filters. It is clear that the LLCL filter is able to provide good attenuation around the tuning frequency. However, it is slightly less effective in suppressing higher frequency harmonics. In addition, $C_f$ increasing has a positive effect on the overall harmonic suppression capability of the LLCL filter. However, even the current THD improves with $C_f$ increasing this improvement become marginal as $C_f$ continues to increase, which agrees with previous theoretical discussion.
Fig. 10. Simulated harmonic spectrums of load current based on 10-12 kHz CB-VSF PWM using LLCL filters of the same tuning at $f_{VSF_{\text{min}}}$: (a) $C_f = 0.5 \ \mu F$, $L_f = 0.507 \ \text{mH}$; (b) $C_f = 1 \ \mu F$, $L_f = 0.253 \ \text{mH}$; (c) $C_f = 2 \ \mu F$, $L_f = 0.127 \ \text{mH}$; (d) $C_f = 3 \ \mu F$, $L_f = 0.084 \ \text{mH}$.

The LLCL filter behavior for CB-VSF PWM with a wider band of 10-30 kHz (20 kHz band) is shown in Fig. 11 via the reflected harmonic spectrums of the load currents. For the same LLCL filter, the THDs in Fig. 11 are higher than those in Fig. 10. This is due to the fact that as the CBVSF band increases, the switching harmonics begin spreading out above the switching frequency. Since the attenuation capability of the LLCL filter is mainly around the switching frequency, it becomes less effective as the harmonic spectrum spreads out over a wider frequency range. A higher $C_f$ value is needed to obtain a better THD. To illustrate the performance of the LLCL filter under different VSF bands and filter parameters, simulations were carried out for different VSF bands with the results being summarized in Table III and illustrated in Fig. 12.

It is clear that the harmonic suppression capability of the LLCL filter is reduced with increases of the VSF band, due to the fact that the LLCL filter is better at attenuating harmonics around the tuning frequency. As discussed earlier, increasing $C_f$ improves the overall harmonic suppression capability, and the enhancement becomes marginal with further increases in $C_f$. Fig. 13 shows the THD enhancement based on (20) with respect to the filter capacitor range; (0.5-1 $\mu F$), (1-2 $\mu F$), and (2-3 $\mu F$). From Fig. 13, it is noticeable that there is enhancement in the THD percentage levels for all of the filter capacitor ranges. Meanwhile, the enhancement percentage is small for the filter capacitor (2-3 $\mu F$).

Therefore, there is no need to select the highest value of the filter capacitor to simultaneously avoid absorbing the maximum part of the system reactive power and avoid the negative effect on system stability [10].

In addition, the THD level enhancement is small at the wide 20 kHz band due to higher harmonic spectrums along the high frequency locations starting from $f_{VSF_{\text{min}}}$ (10 kHz).

\[
\text{THD Enhancement} \ % = \frac{[\text{THD}_{f} - \text{THD}_{s}] \ %}{\text{THD}_{s} \ %} \times 100 \ \% \quad (20)
\]

The simulation results in Section 5 confirmed the theoretical
Fig. 11. Simulated harmonic spectrums of load current based on 10-30 kHz CB-VSF PWM using LLCL filters of the same tuning at $f_{\text{VSFmin}}$: (a) $C_f = 0.5 \mu F$, $L_f = 0.507 \text{ mH}$; (b) $C_f = 1 \mu F$, $L_f = 0.253 \text{ mH}$; (c) $C_f = 2 \mu F$, $L_f = 0.127 \text{ mH}$; (d) $C_f = 3 \mu F$, $L_f = 0.084 \text{ mH}$.

Fig. 12. Simulated THD% levels of load currents for different switching frequency bands through LLCL filters of the same tuning at 10 kHz.

Fig. 13. Simulation results of the THD enhancement percentages using (20) with respect to the filter capacitor changing.

discussion on the selection of the LLCL filter parameters, particularly on the tuning branch capacitance $C_f$.

While a larger $C_f$ is preferred in terms of THD performance, the selection of $C_f$ using (14) was proven to be effective since it allows for the use of a smaller $C_f$ (less reactive power absorbed), while providing comparable THD performance with a larger $C_f$ value.

VI. EXPERIMENT RESULTS

To validate the simulation results, an experimental rig including a full bridge single phase inverter and an LLCL filter has been implemented based on the parameters listed in Table I and Table II using a Texas Instruments TMS 320F28335 digital signal processor (DSP) board. The 10 kHz CSF PWM and CB-VSF PWM schemes were then implemented using different VSF bands (2 kHz, 5 kHz, 10 kHz and 20 kHz) and four LLCL filters with different $L_f$ and $C_f$ components (all of them were selected with the same 10 kHz tuning frequency).

The method in [18] was adopted to implement the CB-VSF PWM technique based on the unipolar strategy. The experimental work was carried out in an open-loop manner without a current controller. Since the main focus of this paper is to propose the design guidelines of an LLCL filter for variable switching frequency PWM, a current controller was not included in this paper. Due to page limitations, the design of the current controller and its performance will be included in a future work.

Fig. 14 shows PWM pulses generated by the DSP unit based on the CB-VSF PWM technique with a 5-10 kHz frequency (5 kHz band).

Due to the unipolar switching strategy, the actual switching harmonics appear from 10-20 kHz i.e. with a 10 kHz band. From Fig. 14, it is noticeable that CB-VSF PWM has a regular frequency variation. Figs 15 and 16 show the experimental harmonic spectrum and THD levels of the load side currents (after the LLCL filter) using 10 kHz CSF PWM.
Fig. 14. PWM pulses of CB-VSF PWM for band (5-10 kHz), pulses of S1, S2' (CH3) and S3, S4' (CH4).

(a)  

(b)  

(c)  

(d)  

Fig. 15. Experimental load current (blue) with its spectrum (red) at 10 kHz CSF PWM using LLCL filters of the same $f_s$ tuning: (a) $C_f = 0.5 \mu F, L_f = 0.507 \text{ mH}$; (b) $C_f = 1 \mu F, L_f = 0.253 \text{ mH}$; (c) $C_f = 2 \mu F, L_f = 0.127 \text{ mH}$; (d) $C_f = 3 \mu F, L_f = 0.084 \text{ mH}$.

Fig. 16. Experimental harmonic spectrums of load current based on 10 kHz CSF PWM using LLCL filters of the same $f_s$ tuning: (a) $C_f = 0.5 \mu F, L_f = 0.507 \text{ mH}$; (b) $C_f = 1 \mu F, L_f = 0.253 \text{ mH}$; (c) $C_f = 2 \mu F, L_f = 0.127 \text{ mH}$; (d) $C_f = 3 \mu F, L_f = 0.084 \text{ mH}$.

The effect of increasing the filter capacitor on reducing the harmonic spectrum is markedly noticeable. As seen in the simulation, while increasing $C_f$ helps to reduce the THD, further increasing of $C_f$ from 2 $\mu F$ to 3 $\mu F$ does not provide a significant improvement in the THD. Similar observations can be made for 10-20 kHz CB-VSF PWM (10 kHz band), as seen in Fig. 17 and Fig. 18.

Table IV shows the THD percentage levels of the load
currents for CSF PWM and CB-VSF PWM with different VSF bands, which are illustrated in Fig. 19.

The percentages of the THD improvements are calculated using (20) for all of the PWM methods in this study. These percentages are shown in Fig. 20, which confirms that increasing the filter capacitance is necessary to have better THD levels due to the lower equivalent impedance of the serial $C_fL_f$ branch along the variable switching frequency band.

Due to the nonlinearity behavior of the filter capacitor
TABLE IV
EXPERIMENTAL THD PERCENTAGE LEVELS OF LOAD CURRENTS USING 10 KHz TUNING AT DIFFERENT SWITCHING FREQUENCY BANDS

<table>
<thead>
<tr>
<th>Switching Frequency</th>
<th>LLCL: 1</th>
<th>LLCL: 2</th>
<th>LLCL: 3</th>
<th>LLCL: 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_f$ = 0.507 mH</td>
<td>$L_f$ = 0.253 mH</td>
<td>$L_f$ = 0.127 mH</td>
<td>$L_f$ = 0.084 mH</td>
</tr>
<tr>
<td>CSF PWM $f_s$ = 10 kHz</td>
<td>2.6879</td>
<td>2.3542</td>
<td>2.2345</td>
<td>2.2155</td>
</tr>
<tr>
<td>CB-VSF PWM $f_{sW}$ = 10-12 kHz</td>
<td>2.8561</td>
<td>2.6722</td>
<td>2.5637</td>
<td>2.5673</td>
</tr>
<tr>
<td>CB-VSF PWM $f_{sW}$ = 10-15 kHz</td>
<td>3.0646</td>
<td>2.9179</td>
<td>2.8232</td>
<td>2.8432</td>
</tr>
<tr>
<td>CB-VSF PWM $f_{sW}$ = 10-20 kHz</td>
<td>3.4162</td>
<td>3.3143</td>
<td>3.2855</td>
<td>3.2566</td>
</tr>
<tr>
<td>CB-VSF PWM $f_{sW}$ = 10-30 kHz</td>
<td>3.9707</td>
<td>3.8548</td>
<td>3.8059</td>
<td>3.7885</td>
</tr>
</tbody>
</table>

Fig. 19. Experimental load current THD% for different switching frequency bands.

Fig. 20. Experimental THD enhancement percentages using (20) with respect to the filter capacitor changing.

The experimental results confirm the superiority of the 2 μF $C_f$ over the 3 μF $C_f$ for avoiding the 5% maximum limit of the absorbed reactive power.

impedance as explained in Section 3 (B), it is not necessary to select the maximum filter capacitor by which the system will absorb the maximum power limit.

The experimental results confirm the superiority of the 2 μF $C_f$ over the 3 μF $C_f$ for avoiding the 5% maximum limit of the absorbed reactive power.

VII. LLCL FILTER PARAMETERS SELECTION PROCEDURE FOR CB-VSF PWM

Throughout the theoretical analysis as well as the simulation and experimental results, it is found that choosing LLCL filter parameters for CB-VSF PWM can be facilitated using the steps of the flowchart in Fig. 21. The general selection procedure is provided based on the discussion presented in Section 3, with an additional step for ensuring system stability.

It is known that LCL and LLCL filters have stability issues, which can be mitigated using a damping resistor in the tuning branch. However, this causes the filter performance to degrade. In addition, the optimal sizing of the damping resistor has been a topic of previous studies.

Recently, the authors of [10] found that the stability of an LLCL filter can be guaranteed without the use of a damping resistor if stability criteria (21) is satisfied:

$$\frac{1}{f_s} \leq f_{rc} < f_r$$

$$f_{rc} = \frac{1}{2\pi \sqrt{(L_f + L_r) C_f}}$$

This method is adopted here to ensure the robustness of the LLCL filter with grid operation.

The selection procedure starts with the initialization of the system parameters, i.e. the DC link voltage, grid voltage, system rated power, desired current ripple and minimum switching frequency. The inverter side inductor $L_1$ can be decided based on the desired value of the current ripple using (5). The maximum allowable value of the filter capacitor...
$C_{\text{fmax}}$ can be determined by considering 5% of the absorbed rated power using (6).

The grid side inductor $L_2$ can be selected in the range of (18), while considering that the selected $L_2$ value should be bigger than the minimum limit of the (18) or (19) range and agree with a grid condition 0.3% of the harmonics order > 35 [6]. After deciding and selecting $L_2$, the minimum limit of the filter capacitor $C_{\text{fmin}}$ can be calculated using (13) by substituting the tuning frequency value at $f_t$ and the value of the constant $k$ from $L_1$ and $L_2$. Based on these facts, a lower LLCL filter attenuation is observed for high order harmonics at a low value of filter capacitor. Secondly, there is low enhancement in the filter attenuation and consequently in the THD of the load current based using between the maximum filter capacitor $C_{\text{fmax}}$ or a little lower $C_{\text{fmax}}$. This is done to avoid absorbing the maximum allowable 5% of the rated power and to avoid effecting the system stability. This paper proposes an average of the maximum and minimum filter capacitor limits ($(C_{\text{fmax}} + C_{\text{fmin}})/2$) that is more reasonable in LLCL filter design for CBVSF PWM. The process of designing the components of the LLCL filter is shown in the flowchart of Fig. 21. The filter tuning branch inductor $L_f$ can be determined using (7). After determining all of the LLCL filter parameters, the system stability status is checked based on the stability criterion in (21). If the criterion is not satisfied, the filter capacitor value should be reduced and a new value for the tuning inductor $L_f$ should be determined. This process is repeated until the stability criterion is met.

VIII. CONCLUSIONS

A study of the design of an LLCL filter for the CB-VSF PWM technique is presented in this paper. The effects of the parameter selections for LLCL filters are discussed and compared in terms of harmonic spectrum and load current THDs. It can be concluded that the LLCL filter can be useful for CB-VSF PWM as long as different design considerations are taken. In addition, when placing the tuning frequency around the highest switching frequency harmonic, the filter needs to be designed to maximize the attenuation for the whole switching frequency band. By analyzing the effect of each parameter selection on the filter performance, it is found that increasing $C_f$ improves the THD levels and the harmonics spectrum attenuation. However, this also increases the level of system reactive power absorption and effects negatively on the system stability, which makes it important to select a certain moderate capacitor value. Therefore, a general LLCL filter selection guideline is presented to allow for its use with the CB-VSF PWM method.

When compared to previous studies for LLCL filter parameter design, this study has the advantages of facilitating the LLCL filter parameter design for CBVSF PWM. Meanwhile, previous studies are only proposed for CSF PWM based inverter applications. In addition, the study analyzes the $C_f$ and $L_f$ changing effect on the harmonic attenuation effectiveness of the filter for the band of frequencies. Finally, this study provides guidelines for filter parameter design. The disadvantage of this proposal is the need for increasing $C_f$ more than $C_{\text{fmin}}$, which increases the system reactive power absorption. This disadvantage was tackled by Eq. (14), which aims to select a moderate level of $C_f$ to guarantee an acceptable level of reactive power absorption.

Simulation results and laboratorial investigations of a 1 kW single-phase inverter validated the theoretical discussion.

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