Research on full-bridge LCL resonant converter as constant current source in the ZVS condition

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Abstract. A LCL-based resonant converter is shown to behave as a constant-current source when operated at resonant frequency in this paper. This paper focuses on the realization of zero voltage switching (ZVS) in the case of constant-current in LCL resonant converter and how to reduce the influence of high harmonics on the output current. First, the principle of LCL resonant converter as a constant-current source is described. Second, when the switching frequency of the converter deviates from the resonant frequency point, the current gain curves corresponding to different quality factor Q and the boundary curves realizing ZVS turn-on are analyzed. Third, the influence of the ratio (m) of resonant inductors on the output current of the converter and ZVS turn-on is analyzed, and the value of m is determined. Finally, Pexpert software was used to design the magnetic component model, and combined with Simplorer software for combined-simulation. A simulation circuit model with output 80W/0.32A was designed and experimental results are presented. The correctness of the theoretical analysis has been verified.

1. Introduction
Resonant converter can realize zero voltage switching (ZVS) or zero current switching (ZCS) with the design of resonant component, which has higher power transfer efficiency. The converter operating at high frequency point, which allows it to have a small volume. At present, resonant converter has been widely used in DC/DC converter, and is still developing. Based on the research of series and parallel resonant converter, the resonant converter with multiple components such as LLC and LCC that have also been applied [1-5]. However, most scholars at home and abroad have studied the characteristic of resonant converter as voltage source, but few have studied the characteristic of resonant converter as a constant current source. Constant current source has a wide range of applications in industry, medical, commercial and other aspects, such as LED power supply, capacitor charging, inductive power transmission (IPT) and so on.

In [6-11], the constant current characteristic and short circuit protection capability of LCL resonant converter have been studied, and corresponding control methods have been proposed. However, most of their research on LCL resonant circuit is based on fundamental wave analysis, and the influence of higher harmonics on resonant converter is ignored.
This paper is mainly from the following aspects. The first is to study the boundary constraints of zero voltage switching in LCL resonant converter. Second, the influence of high harmonics on the output performance of the converter can be reduced by the reasonable design of component parameters. Finally, the theoretical analysis is verified by theoretical calculation and joint simulation of Ansoft’s Pexprt and Simplorer software.

2. Structure and theoretical analysis

Figure 1 shows the circuit topology of LCL-based full-bridge resonant converter. The circuit mainly consists of full-bridge inverter circuit, LCL resonant circuit and load circuit. First, the input dc voltage through the full-bridge inverter circuit to obtain the alternating square-wave voltage with constant amplitude. Then, the constant current characteristics of LCL resonant circuit operating at resonant frequency point are used to obtain high-frequency alternating constant current source. Finally, the dc current source is obtained after full-bridge rectifier and filtering.

2.1. Theoretical analysis of LCL resonant circuit as constant current source

In the ac analysis, the load impedance is converted to the output port of LCL resonant circuit, and its total equivalent impedance $R_{ac}$ and quality factor $Q$ are defined as [6]

$$R_{ac} = \frac{8n^2}{\pi^2} R_{Load}, \quad Q = \frac{Z_0}{n^2 R_{Load}}$$

Where, $n$ is the ratio of primary winding and secondary winding of high-frequency transformer $T_S$, and $Z_0 = \sqrt{L_1/C_1}$ is the characteristic impedance.

Figure 2 shows the equivalent circuit of LCL resonant converter. $u_{in}$ is the square-wave voltage output by the full-bridge inverter, and the amplitude is $U_{in}$. The square-wave voltage is composed of infinite odd harmonics, then the RMS value of each odd harmonic is defined as

$$U_k = \frac{2\sqrt{2}U_{in}}{k\pi}, \quad k=1, 3, 5,$$

Then, the current generated by each odd harmonics at the output terminal of the LCL converter can be expressed as

$$I_k = \frac{U_k}{j\omega_0 L_1 - k^2 \omega_0^2 C_1 L_2 R_{ac} + R_{ac} - jk^3 \omega_0^3 C_1 L_1 L_2 + jk\omega_0 L_2}$$

Where, $\omega_0$ is the fundamental-wave resonant frequency. At $\omega_0 = \sqrt{1/C_1}$, the output current of the resonant converter can be obtained

$$I_1 = \frac{U_1}{j\omega_0 L_1}$$
According to Equation (4), when the values of fundamental-wave voltage and inductor \( L_1 \) are determined, the constant current source can be obtained through LCL resonant circuit, and the output current is independent of inductor \( L_2 \) and equivalent load \( R_{ac} \). The phase of the output current is 90° behind the fundamental voltage.

![Equivalent circuit of resonant converter.](image)

**Figure 2.** Equivalent circuit of resonant converter.

**Figure 3.** Voltage and current at the resonant circuit input terminal.

### 2.2. Analysis of ZVS constraints

In order to realize ZVS of full-bridge inverter, when the LCL resonant converter at the resonant frequency point is inductive impedance, the output voltage phase of the full-bridge inverter is prior to the current phase, as shown in Figure 3. The body diodes conduct prior to switches in each cycle, therefore, the ZVS can be realized to reduce switching loss.

Dead-time control and switching frequency are two key points to realize zero voltage switching. When inductor \( L_1 \) and \( L_2 \) are equal at the fundamental-wave resonant frequency point, a small dead-time is the basic condition for the full-bridge inverter to realize zero voltage switching under most loads. After setting the parameters of the resonant circuit component, the LCL resonant circuit will present different impedance properties with different switching frequency. Simultaneously, the phase relationship between the output voltage and current of the full-bridge inverter can be determined.

Define the ratio of inductor \( L_1 \) to inductor \( L_2 \) as

\[
m = \frac{L_2}{L_1}
\]  

(5)

The current gain of the converter can be expressed as [12]

\[
H = \frac{1}{(1/Q)(1-\omega_n^2) + j(\pi^2/8)(1+m)\omega_n - m\omega_n^3}
\]  

(6)

Where, \( Q \) is the quality factor, \( \omega_n \) is the normalized resonant frequency \( (\omega_n = \omega/\omega_0) \), and \( \omega \) is the switching frequency.

When the LCL resonant circuit is resistive, that is the imaginary part of the impedance is 0, the following formula can be obtained

\[
\text{Im}\left[ j\omega L_1 + \frac{1}{j\omega C_1} \right] = 0
\]  

(7)

\[
\rightarrow Q = f(\omega_n, m)
\]

By substituting (7) into (6), the boundary function \( G_b(\omega_n, m, Q) \) of zero voltage switching can be obtained. At \( m=1 \), the curves of normalized frequency \( \omega_n \) and current gain \( H \) are shown in Figure 4.
Figure 4 shows that the zero voltage switching cannot be realized with the switching frequency changes greatly. However, the switching frequency bound to deviate from the resonant frequency point ($\omega_n=1$) of the resonant converter in the actual circuit. Therefore, it is necessary to design the parameters of resonant circuit, so that the converter can still achieve ZVS and maintain good constant current characteristic when the switching frequency is deviated from the resonant frequency point.

By assuming that the initial phase of $u$ in is 0, the voltage and current phase angle relationship at the output terminal of the full-bridge inverter can be obtained as

$\delta|_{\alpha_b=1} = \delta_v - \delta_i = \arctan \frac{\pi^2 (m-1) Q}{8}$  \hspace{1cm} (8)

\[
\begin{cases}
  \delta|_{\alpha_b=1} = 0 & m = 1 \\
  \delta|_{\alpha_b=1} < 0 & 0 < m < 1 \\
  \delta|_{\alpha_b=1} > 0 & m > 1
\end{cases}
\]

(9)

According to Equations (8), (9) and Figure 5, at $m=1$, the phase difference between the voltage and current is 0. At $m<1$, when the value of inductor $L_2$ is less than $L_1$, the current phase lags behind voltage phase, and zero voltage switching (ZVS) can be realized to reduce the switching loss. However, the value of inductor $L_2$ cannot be less than inductor $L_1$ without limit. If the value of $m$ is small, the third harmonic current output by resonant circuit will be large, which will affect the power supply performance.

### 2.3. Parameter characteristics of resonant circuit

When the LCL resonant circuit is acted only by the fundamental sinusoidal voltage, the output current is independent of the impedance ($L_1$ and $R_{ac}$) in the circuit. But, the resonant circuit is also affected by odd harmonics in fact. The influence of third harmonics on resonant circuit is analyzed.

The LCL resonant circuit parameters: $U_{in}=84V$, $L_1=394uH$, $C_1=160nF$, $f=20kHz$. The RMS value of $I_1$ is 1.5A. The ratio (RMS value of $I_3$ to $I_1$) is calculated when change $Q$ and $m$, the result is shown in Figure 6.

Figure 6 shows the third harmonic reaches the maximum when $m$ is around 0.06. And, after reaching the maximum, it shows a monotonously decreasing trend. Noteworthy, this extreme point is the third harmonic resonant point, which will generate a great third resonant current when the load is light, which will seriously endanger the component and the load in the resonant circuit. In the design of the prototype circuit, it is necessary to actively avoid the third resonant point, so that $m$ approaches 1 in the LCL resonant circuit, and the third harmonic $I_3$ is very small when the load changes. It can be
explained that the current generated by higher harmonics is smaller and negligible. The analysis in the previous section shows that ZVS can be achieved by setting $m<1$. Therefore, when $m$ is slightly less than 1 in the design. At this parameter point, not only can the LCL resonant circuit maintain good constant current characteristic, but also ZVS can be realized to reduce switching loss.

![Figure 6. The ratio of third harmonic to fundamental.](image)

### Table 1. Parameters of the system.

| Parameter                  | Value   |
|----------------------------|---------|
| Input voltage $U_{in}$/V    | 100     |
| Switching frequency $f$/kHz | 20      |
| Inductor $L_1$/μH          | 394     |
| Inductor $L_2$/μH          | 390     |
| Capacitor $C_1$/nF         | 160     |
| Transformer turn ratio $n$ | 1/5     |
| Filter capacitor $C_o$/μF  | 10      |
| Output current $I_{out}$/A  | 0.32    |

3. **Simulation analysis**

Based on the analysis in the previous section, the experimental circuit was designed with $Q=16/\pi^2$. A constant current source simulation model based on LCL full-bridge resonant converter with 80W output is designed. The LCL converter has the following specifications: input voltage is 100 VDC, output current is 0.32 A, and switching frequency is 20 kHz. The main parameters are shown in Table 1. The Pexpert software of was used to design magnetic component, and Simplorer software was combined to carry out the combined-simulation, the simulation circuit is shown in Figure 7.

![Figure 7. LCL resonant simulation circuit.](image)
Figure 8 and Figure 9 show the output current of the full-bridge inverter varies proportionally with the load. Moreover, the output current of the full-bridge inverter lags behind the voltage waveform slightly, it shows that the ZVS turn-on is implemented, as predicted in Section 2.2. Thus reducing the switching loss and improving the efficiency of the LCL resonant converter.

Figure 8. The voltage and current waveform at the output of the inverter at half load.

Figure 9. The voltage and current waveform at the output of the inverter at full load.

Figure 10. Full-bridge inverter output voltage and LCL resonant converter output current.

Figure 11. Constant current source characteristic under different loads.

Figure 10 shows the distortion of output current waveform of resonant converter is small. It is shown that the LCL resonant converter with reasonable design parameters has good filtering characteristic.

Figure 11 shows the output current of the LCL converter under different loads ($Q=16/\pi^2$, $24/\pi^2$, $32/\pi^2$, and $64/\pi^2$, respectively). The output current changes small as the changes load greatly. The output current decreases slightly as the load increases that are due to the increase in losses in the LCL resonant converter and full-bridge inverter.

4. Conclusions

This paper focuses on the research of full-bridge LCL resonant converter as constant-current Source in the ZVS condition. By theoretical analysis, the ratio $m$ and quality factor $Q$ are determined. When $m$ is slightly less than 1 and $Q=16/\pi^2$, the LCL resonant converter has good output performance, effectively reducing the impact of higher harmonics on the output current. The model of magnetic component designed by Pexprt software and the circuit simulation with Simplorer software is used to verify the correctness of theoretical analysis. The research in this paper can provide a good theoretical reference for the practical manufacture of LCL resonant converter.
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