A Novel Design Method for Resonance Network Parameters of Bi-directional CLLLC Resonance Converter

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Abstract: In order to solve the problem that there are many resonant elements and it is difficult to design the full bridge CLLLC resonant converter, an improved resonant network parameter design method combined with simulation analysis is proposed in this paper. Accurate DC voltage gain curves are obtained under different resonant parameters. A 3.5 kW simulation circuit is constructed based on the parameters of the proposed method. The simulation results confirm the correctness and feasibility of the proposed improved design method.

1. Introduction

In recent years, the isolated bi-directional DC/DC converter with input and output side electrical isolation function and energy bi-directional flow has been well applied in various charging and discharging systems\textsuperscript{[1-5]}. Among them, the bi-directional full-bridge CLLLC resonant converter that maintains the natural soft switch characteristics of the LLC resonant converter during the two-way flow of energy has been widely studied by scholars\textsuperscript{[6-8]}. With the traditional bi-directional DC/DC converter changing the energy flow direction through the change of the bridge phase of the bilateral inverter, the entire bridge CLLLC resonant converter only needs to add the normal complementary drive signal to the inverter bridge at the energy input. The rectifier side can change the direction of energy flow without driving the signal to achieve full bridge rectification.

In this paper, the design idea of combining the base-wave analysis method and the time-domain simulation method is proposed. First, the approximate curve of the influence of resonant network parameters on the gain of the converter is obtained by the base-wave analysis method. Then according to the actual requirements, the parameter changes are limited to a certain range. Then the parameter combination in this range is compared by time domain simulation method, and the optimized parameters are obtained.

2. Main circuit topology

Figure 1 shows the topology of the main circuit of the bi-directional full-bridge CLLLC resonant converter. During the operation of the bi-directional full-bridge CLLLC resonant converter, the secondary resonant elements $L_2$ and $C_2$ also participate in the resonant process of the converter, which is more complex than the LLC resonant converter resonant network. The following will focus on analyzing the influence of the resonant element parameters on the converter characteristics in the resonant network.
3. Base wave analysis

The forward working time of the bi-directional CLLLC resonant converter is analyzed by the base-wave analysis method. The equivalent circuit of the base-wave converter is shown in Figure 2. Let the ratio of transformer T primary to secondary be \( n \).

\[
\omega_n = \frac{1}{\sqrt{C_1(L_1 + L_m)}}.
\]

Among them, \( R_L \) is the load resistance of the converter.

\[
H_1(j\omega_s) = \frac{u_{\text{CDI}}}{u_{\text{ABI}}} = \frac{n^2R_0}{u_{\text{ABI}}} = \frac{n^2R_0 + Z_{12}}{n^2R_0 + Z_{12} + (n^2R_0 + Z_{12})/Z_{l_m}}
\]

Make \( \omega_s = \omega_a \), type (1) can be organized

\[
H_1(j\omega_a) = \frac{1}{(1 - \frac{1}{\omega_a^2}) + jQ_1[\omega_a(\frac{1}{\omega_a^2} + 1) - \frac{1}{\omega_a(\frac{2}{\omega_a^2} + 1)} + \frac{1}{\omega_a k_2} + 1]}
\]

Where \( \omega_s \) is the frequency of the switch angle, \( \omega_a = \frac{\omega_s}{\omega_0} \), \( Q_1 = \frac{\sqrt{L_1/C_1}}{R_{eq}} \).

The DC gain of the converter can be obtained according to formula (2):

\[
M_1(\omega_a) = \|H_1(j\omega_a)\| = \sqrt{\left(\frac{1}{\omega_a^2} + 1\right)^2 + Q_1^2[\omega_a\left(\frac{1}{\omega_a^2} + 1\right) - \frac{1}{\omega_a\left(\frac{2}{\omega_a^2} + 1\right)} + \frac{1}{\omega_a k_2} + 1]^2}
\]

Similarly, DC gains can be obtained when the two-way CLLLC resonant converter works in reverse:

\[
M_2(\omega_a) = \|H_2(j\omega_a)\| = \sqrt{\left(\frac{1}{\omega_s^2} + 1\right)^2 + Q_2^2[\omega_s\left(\frac{1}{\omega_s^2} + 1\right) - \frac{1}{\omega_s\left(\frac{2}{\omega_s^2} + 1\right)} + \frac{1}{\omega_s k_2} + 1]^2}
\]
From formula (3) and formula (4), it can be seen that the DC gain $M$ of the converter has nothing to do with the ramp ratio of the transformer when the quality factor $Q$ is certain.

When $k_1 = 1, \ k_2 = 3$, the variation curve for the normalized frequency $\omega_n$ of the forward DC gain $M_1$ of the converter can be drawn in the case of different quality factors $Q_1$:

![Figure 3. Normalized gain curve at different values](image)

From Figure 3, it can be seen that the DC gain of a low switching frequency converter increases within a specific range. And the lighter the load of the converter, the smaller the quality factor, the greater the maximum DC gain that the converter can obtain.

Figure 4 is the variation curve of the normalized frequency $\omega_n$ of the forward DC gain $M_1$ of the converter with different coefficients $k_1$ when $Q_1 = 0.5, \ k_2 = 3$. When $k_1$ is changed from small to large, the maximum DC gain obtained by DC converter is wavy. Although when $k_1$ is greater than 10, in the vicinity of certain specific $k_1$ values, reducing the switching frequency DC converter can also give a relatively large gain, but the frequency change range is very narrow, and when the switching frequency is too low, the efficiency of the converter will also be reduced.

![Figure 4. Normalized gain curve under different $k_1$ values](image)
When \( Q = 0.5 \), \( k_1 = 3 \), the variation curve of the normalized frequency \( \omega_n \) of the forward DC gain \( M_1 \) of the converter under different coefficients \( k_2 \) can be drawn:

![Graph showing the variation curve of the normalized frequency \( \omega_n \) of the forward DC gain \( M_1 \) of the converter under different coefficients \( k_2 \).](image)

Figure 5. \( k_1 = 3 \), normalized gain curve at different \( k_2 \)

From figure 5, it can be seen that when \( Q \) and \( k_1 \) are constant, the maximum DC gain obtained by increasing \( k_2 \) converter gradually decreases and tends to be constant.

### 4. Simulation Analysis

The base wave analysis method ignores the high harmonics in the resonant network to facilitate the analysis and derivation in the frequency domain. In the frequency domain analysis, the dead zone time and the coupling coefficient of the transformer are not considered. The approximation will inevitably lead to deviations from the actual situation, especially in the voltage gain characteristics, because the high harmonics of the input voltage of the resonant network will also provide energy for the load. The coupling coefficient of the transformer will affect the efficiency of energy transmission from the original edge to the secondary edge.

A simulation circuit is built in Matlab / Simulink to analyze the gain of the converter. The parameters of the simulation circuit are as follows:

| Simulation circuit parameters | Input Voltage | Load resistance \( R_L \) | series resonance frequency | Transformer ratio | Forward serial resonant inductor \( L_1 \) | Forward serial resonator capacitance \( C_1 \) | Switching pipe conduction resistance |
|-----------------------------|--------------|----------------|--------------------------|------------------|----------------|--------------------------|------------------|
|                            | 500V         | 0.5 \( \Omega \)  | 150KHz               | 2     | 17.2\( \mu \)H | 6.6e-8F    | 0.1\( \Omega \) |

Through simulation, we can draw the normalized DC voltage gain curve of the bi-directional full-bridge CLLLC resonant converter when the \( k_1 \) value is taken by 1, 2, and 3, as shown in Figure 6-8, and the corresponding converter inverter bridge to achieve ZVS.

By simulation, the normalized DC voltage gain curve of the bi-directional CLLLC resonant converter can be drawn when \( k_1 \) takes 1, 2, and 3:
Figure 6. \( k_1 = 1 \), Comparison of normalized DC voltage gain obtained from simulation analysis and base-wave analysis

Figure 7. \( k_1 = 2 \), Comparison of normalized DC voltage gain obtained from simulation analysis and base-wave analysis

Figure 8. \( k_1 = 3 \), Comparison of normalized DC voltage gain obtained from simulation analysis and base-wave analysis
Figure 6-8 can be analyzed. When the switching angle frequency meets $\omega_m < \omega_s < \omega_1$, the normalized gain of the converter obtained by base-wave analysis is less than the gain obtained by circuit simulation. When the switching angle frequency satisfies $\omega_s < \omega_m$, the normalized gain of the converter obtained by base-wave analysis is greater than that obtained by circuit simulation.

According to the circuit simulation method, the curve that can reflect the actual gain of the converter is more suitable for the parameter design that guides the design of the converter.

5. Simulation Analysis

According to the design method proposed in this paper, a bi-directional full-bridge CLLLC resonant converter with 3.5 kW, 550V to 320V voltage reduction and 6 kW and 320V to 1100V voltage increase is designed. According to the curve of the actual gain of the converter obtained by the circuit simulation method in the previous section, it can be determined that the parameters of the resonant network that meet the above requirements are: Series resonance frequency $f_s = 150$kHz, Transformer ratio $n = 2.5:1$, $L_1 = 80.6\mu H$, $C_1 = 14nF$, $L_m = 161.2\mu H$, $L_2 = 12.9\mu H$, $C_2 = 87.3nF$.

In Matlab/Simulink, the bi-directional full-bridge CLLLC resonant converter is simulated in an open loop forward run. The input voltage is 550V and the load is 30Ω. When the switch frequency is 112kHz, the forward operation output voltage waveform as shown in Figure 10 is known. Under the above parameters, the converter output voltage is 320V, which satisfies the design requirements.

When the converter is running backwards, the input voltage is 320V and the load is 200Ω. When the switching frequency is 105kHz, it is known from the reverse operating output voltage waveform shown in Figure 11 that under the above parameters, the converter output voltage is 1100 V, which satisfies the design requirements.

6. Conclusion

In this paper, an improved design method of resonant network parameters combining with simulation analysis is presented. The influence of resonance parameters on the characteristics of the converter is discussed in depth. The accurate DC voltage gain curve of the converter under different resonant parameters is obtained. The bi-directional full-bridge CLLLC resonant network parameters are designed to achieve forward running full-load power of 3.5 kW, 550V to 320V and reverse running full-load power of 6 kW and 320V to 1100V. The simulation results confirm the feasibility and correctness of this method.

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