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Hybrid Control Method for CLLLC Resonant Converter with Low Output Voltage Ripple ⋆

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Abstract: In this paper, a hybrid control method of pulse width modulation (PWM) and pulse frequency modulation (PFM) is proposed, which can greatly enhance the control performance of the CLLLC resonant converter to output voltage, reduce the ripple of the output voltage and improve the efficiency of the converter. This paper analyzes the theory of hybrid control and introduces the operating principle of the hybrid control method. In addition, the hybrid control method ensures that the power MOSFETs devices realize zero voltage switching (ZVS) and improve the efficiency of converter. Finally, the performance of the proposed hybrid control method is compared with the traditional PFM control and verified by simulation.

Keywords: hybrid control, CLLLC resonant converter, pulse width modulation (PWM), pulse frequency modulation (PFM), zero voltage switching (ZVS).

1. INTRODUCTION

In recent years, although electric vehicle has been developed rapidly, the power battery is still the key factor restricting its development. The demand of the battery test equipment is increasing to research the performance of power battery better, and the output voltage ripple is a serious problem in the isolation DC-DC circuit of the battery testing equipment, which leads to a large error in the battery testing, which directly affects the starting, accelerating, fast charging and endurance performance index of electric vehicle. Therefore, it is an urgent problem to be solved that reducing the output voltage ripple of isolation DC-DC circuit.

The isolated dual active bridge converter adopts a double full-bridge structure, which is a “full-bridge inverter + high frequency transformer + full-bridge rectification” circuit. The structure includes a high frequency transformer which can provide good electrical isolated performance. Therefore, it is widely used in places where the requirement of safety is high.

In the battery test system, the battery need to be charged and discharged repeatedly, so the equipment should realize the bidirectional flow of energy. At present, the isolated DC/DC converter with the best performance is CLLLC resonant converter. Compared with the LLC resonant converter, a set of LC resonant network is added on the secondary side of the transformer to ensure that the circuit topology is completely symmetrical when the converter operates in the forward or reverse direction, as shown in Fig. 1. Therefore, the forward and reverse operating characteristics of the converter are completely consistent. And both of them have a boost and a buck mode, and the ZVS and ZCS can be realized by the converter regardless of the forward or reverse operation.

The CLLLC resonant converter has a completely symmetrical circuit structure, and has the advantages of high efficiency and high power density of the LLC resonant converter, and can realize bidirectional transmission power. The CLLLC resonant converter has a natural soft switching characteristic, and can realize the ZVS of the primary side switching tube and the ZCS of the secondary side rectifying diode in a wide range of input voltage and full load range. At present, for the CLLLC resonant converter, there are mainly two control methods which are pulse frequency modulation (PFM) and pulse width modulation (PWM). However, the PFM modulation method can achieve ZVS over the full load range, the switching frequency of the full-bridge converter has to be increased to meet the voltage gain requirement under light load conditions. Therefore, the secondary anti-parallel diode will always be in a conducting state and will not fall to zero, so ZCS can not be achieved under light load conditions. PWM modulation method can realize ZVS and ZCS in the full load range and the accurate regulation of the output voltage under the condition of light load while the voltage ripple is greater and the ability of anti-interference is weaker under the condition of heavy load.

The proposed PWM and PFM hybrid control method can realize ZCS at poor load conditions and overcome the problem of high output voltage ripple. The proposed hybrid control method can realize the precise control of the voltage gain in the steady state operation for the entire load range.

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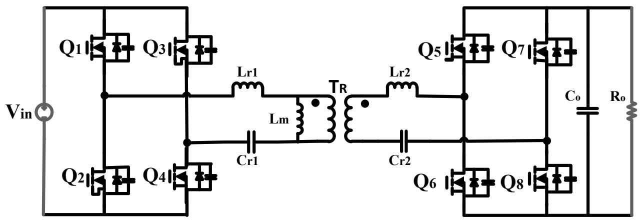


Fig. 1. Bidirectional CLLLC resonant converter topology

In this paper, the topology and working principle of the CLLLC resonant converter are introduced firstly. Then the hybrid PWM and PFM control methods are proposed and analyzed theoretically. Then the operating principles of the hybrid control method are introduced. Finally, the performance of the proposed hybrid control method and the traditional PFM control is compared and verified by simulation.

2. OVERVIEW OF THE CLLLC RESONANT CONVERTER

2.1 Configuration of the CLLLC Converter

The typical full bridge CLLLC resonant converter is shown in Fig. 1, where the MOSFETs $Q_1 - Q_4$ and $Q_5 - Q_8$ respectively constitute two full bridge converters. When the converter works positively, the driving signal of Q_1, Q_4 and Q_2, Q_3 are complementary, which can achieve the inverter function. At the same time, $Q_5 - Q_8$ without driving signal, are using the reverse parallel diode to achieve rectification. When the converter works reversely, the driving signal $Q_5 - Q_8$ can achieve the inverter function, $Q_1 - Q_4$ without driving signal, are using the reverse parallel diode to achieve rectification. At this time, the magnetizing inductance can be equivalent to the secondary side, so the structure is exactly the same as the forward working. In Fig. 1, L_m is the magnetizing inductance of the high-frequency transformer T_R, and the L_{r1} and L_{r2} are resonant inductors, which contain the leakage inductance of the transformer primary side and secondary side, respectively. The C_{r1} and C_{r2} are resonant capacitors, and the $D_{S1} - D_{S8}$ and $C_{S1} - C_{S8}$ are parallel diodes and capacitors of $Q_1 - Q_8$, respectively.

2.2 Operation Principles of the Converter

The DC characteristics of the CLLLC resonant converter can be divided into ZVS and ZCS region, as shown in Fig. 2, the definition of frequency f_{r1} and f_{r2} can be expressed as follows:

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{2}$$

The operating interval of the CLLLC resonant converter are divided into three regions by the resonant frequency f_{r1} and f_{r2}. In region 1, the switching frequency is greater than f_{r1}, and the converter works in the ZVS region at this time. In region 2, the switching frequency is between f_{r1} and f_{r2}, and the converter works in the ZVS region or ZCS region depends on the size of load. In region 3, the switching frequency is less than f_{r2}, and the converter works in the ZCS region. The converter should be avoided to work in region 3 since the noise generated by the MOSFETs switch tube in this region reduces the efficiency of the system.

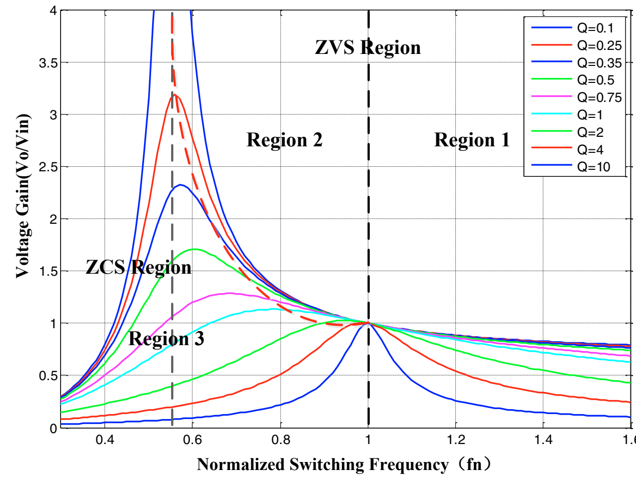


Fig. 2. DC characteristics of CLLLC Resonant Converter

The quality factor Q is defined as equation (3). It can be obtained easily that Q represents the load. From Fig. 2, when the value of Q decreases which indicates that the load becomes light, the peak of voltage gain becomes larger, which makes the converter work in the unstable region, so the switching frequency needs to be increased in order to keep the output voltage constant at poor load.

$$\mathrm{Q} = \frac{\sqrt{L_r/C_r}\pi^2}{8n^2 R_o} \tag{3}$$

3. HYBRID CONTROL FOR CLLLC CONVERTER

3.1 Theoretical Analysis of Hybrid Control

In order to improve the output voltage regulation performance of the CLLLC resonant converter and reduce the ripple of output voltage, this paper proposed a method of PWM and PFM hybrid control and designed a hybrid control algorithm which can select control mode intelligently according to the operating state.

According to Fourier series method, the fundamental harmonic of input voltage can be expressed as follows:

$$V_{in,F} = \frac{4}{\pi} V_{in} \sin\pi\left(\frac{t_d}{T_s}\right) \tag{4}$$

According to the equation (4), the curve of the input voltage with the changing of the duty ratio can be obtained, as shown in Fig. 3(a). When the duty cycle is 50%, the input voltage reaches a maximum value of 1.27 approximately because of the maximum value of the fundamental wave component is $4/\pi = 1.27$.

Under the conventional PFM control, the voltage gain of CLLLC resonant converter is only related to the switching frequency, and the voltage gain can be expressed as follows [6]:

$$G = \left|\frac{kf_n^2}{(k+1)f_n^2 - 1 + jkQ(f_n^2 - 1)f_n}\right| \tag{5}$$

According to the equation (4) and the equation (5), the voltage gain under the PWM and PFM hybrid control can be derived as

$$G' = \frac{4}{\pi}\left|\frac{kf_n^2}{(k+1)f_n^2 - 1 + jkQ(f_n^2-1)f_n}\right| \cdot \sin\pi\left(\frac{t_d}{T_s}\right) \quad (6)$$

From equation (6), the voltage gain can be regulated by two variables f_n and t_d independently, which means that there are two degrees of freedom in hybrid control. According to the equation (6), the graph of the output voltage gain and f_n, D is drawn as shown in Fig.3 (a). It can greatly enhance the output voltage regulation performance of CLLLC resonant converter and reduce the ripple of the output voltage through control the two variables f_n and D.

In order to verify the validity of the equation (6), the CLLLC resonant circuit model was constructed by the Simulink toolbox. The input signal of the switches is switching frequency f_n and duty ratio D which can be regulated. To change its duty cycle from 0 to 0.5 and then regulate normalized frequency and plot eight curves with normalized frequencies from 0.7 to 1.4 respectively. By comparing Fig. 3 (b) and Fig. 3 (c), it is observed that the voltage gain has the same trend and maximum when the normalized frequency is 1 and the duty ratio is 50%, and the maximum value of them are about 1.2. And we can achieve the output voltage less than 1.2 by regulating the transformer turns ratio. Therefore, the simulation results verify the validity of the fundamental wave analysis method and equation (6).

3.2 Operation Principles of the Hybrid Control Method

The PWM and PFM hybrid control method proposed in this paper can enhance the control performance of the output voltage at steady state and reduce the output voltage ripple using two control variables independently. In order to realize the switching of PWM control and PFM control, we must set up a clear switching point.

The output voltage regulation principle of the proposed hybrid control algorithm is shown in Fig. 4 (a). The red circle indicates the critical error of PWM control and PFM control switching, the blue center of circle indicates zero steady error, and the black line indicates accumulated steady state error. In the steady state operation mode, the accumulated steady-state error should tend to zero so that the output voltage tends to reference value gradually. In the red circle, when the accumulated steady state error does not reach the critical error, the output voltage is regulated by PWM control. However, the output voltage will be regulated by PFM control when accumulated steady state error exceeds the critical error outside the red circle. Therefore, the priority of PWM control is higher than PFM control, in other words, we control the switching frequency to regulate the output voltage only if controlling the duty ratio cant achieve a great performance.

The principle of hybrid control algorithm is shown in Fig. 4 (b), the switches of CLLLC resonant converter receive the driving signal from the drive circuit. And the soft start circuit or program is added to the switches tube to prevent the upper and lower bridge switches from being turned on at the same time and reduce the switching loss

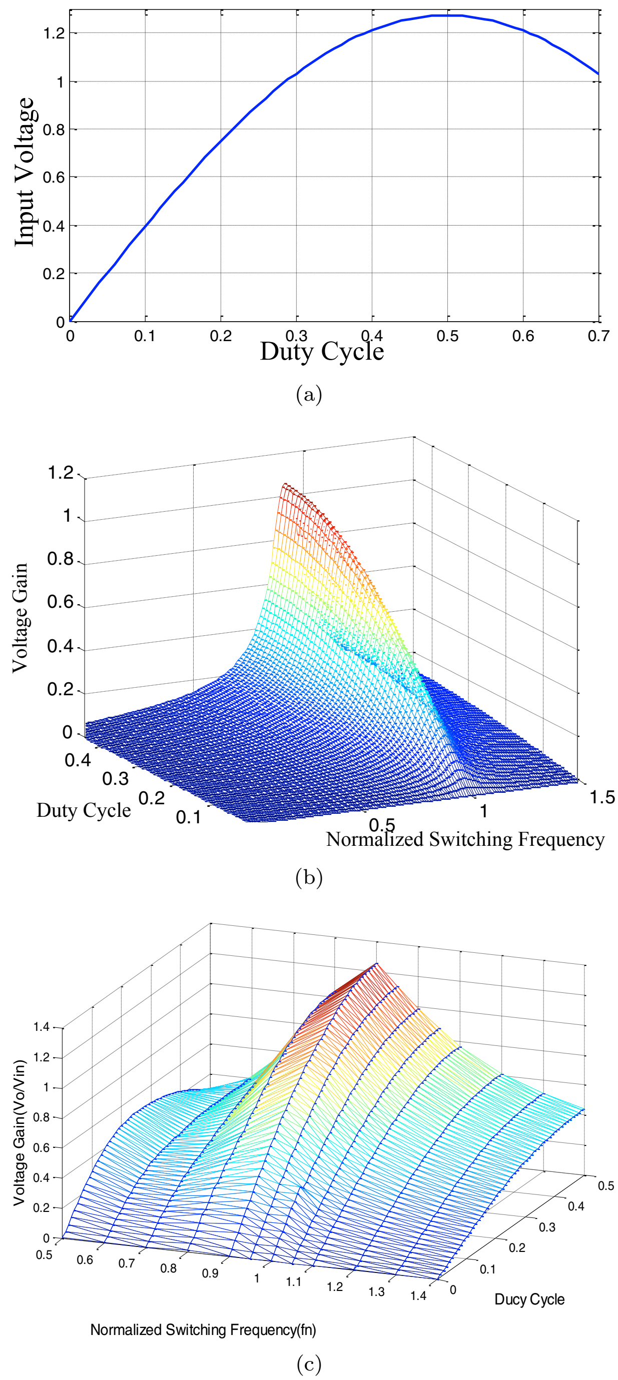
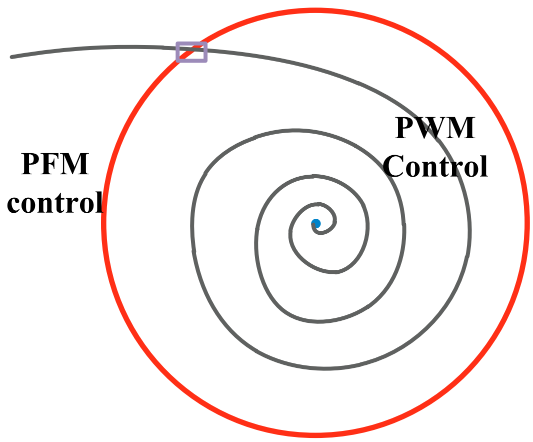
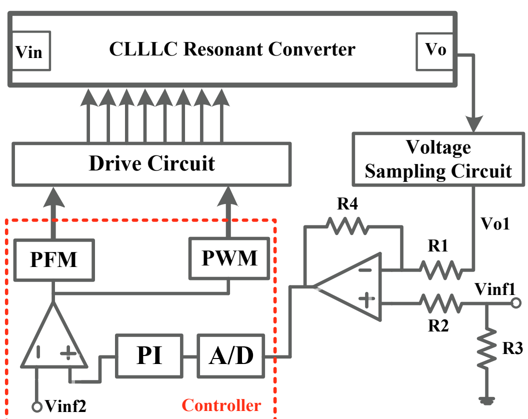


Fig. 3. Voltage gain of CLLLC resonant converter. (a) Input voltage according to the duty cycle at the resonant frequency.(b) Voltage gain surface according to the normalized switching frequency and duty cycle. (c) Simulation result diagram of Simulink circuit model.

of the switch tube. When the circuit operates normally, the voltage sampling circuit detects the output voltage and the steady-state error, the sampling value of output voltage V_{o1} and the reference value of output voltage V_{inf1} were added to the inverting input and non-inverting input and output of the circuit is the output steady-state error value V_{error}. Wherein, the resistors $R1 - R4$ satisfy the following relationship:



(a)



(b)

Fig. 4. PWM and PFM hybrid control algorithm. (a) Output voltage regulation mechanism. (b) The principle of hybrid control.

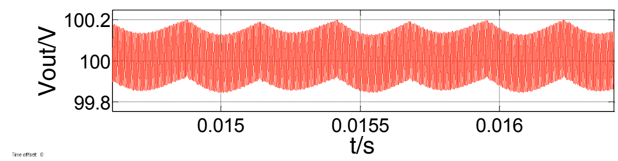
$$R1 = R2, R3 = R4, R1/R3 = 1 \quad (7)$$

Then, the V_error can be expressed as

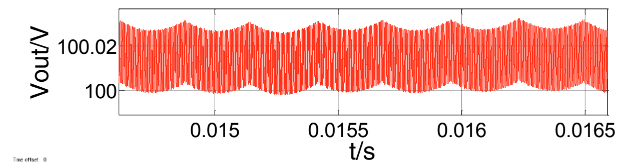
$$V_{error} = V_{\inf 1} - V_{o1} \quad (8)$$

The steady-state error value V_{error} is converted from analog to digital and performed PI compensation. Then we can get the digital value of the steady-state error V_{Derror}. If the digital steady-state error value V_{Derror} is less than the critical error value V_{inf2}, the PWM control signal is output to the drive circuit of CLLLC resonant converter, otherwise, the PFM and PWM control signal is output to the drive circuit of CLLLC resonant converter. While the PFM and PWM control signal is output, the output voltage could be regulated by changing switching frequency and duty cycle, so we can increase or decrease the output voltage rapidly.

For the hybrid control method, the critical error size needs to be designed reasonably to ensure that PWM control region is sufficient. If the critical error is too small, then the PWM control region is small, which may result in the converter working abnormally, producing high frequency noise and reducing the efficiency. When the critical error is too large, the dynamic performance of converter will be poor. Therefore, the appropriate frequency boundary line should be selected in the actual operation.



(a)



(b)

Fig. 5. Simulation waveforms of CLLLC resonant converter. (a) Simulation waveforms by conventional PFM control. (b) Simulation waveforms by hybrid control.

4. SIMULATION RESULTS

The CLLLC resonant converter model is constructed in the Simulink, and the main parameter is shown in table 1. Substituting the values of L_{r1} and C_{r1} in table 1 into equation (1), the resonant frequency of the CLLLC resonant converter model can be derived as 100 kHz. The switching frequency of the CLLLC resonant converter is also 100 kHz, so it is voltage gain is 1. When the transformer ratio is 1:1, the output voltage is equal to the input voltage value.

Table 1. CLLLC parameter design

Parameter	Value
Transformer ratio	1:1
V_{in}	$100V$
V_{out}	$100V$
f_s	$100kHz$
L_{r1}, L_{r2}	$50uH, 50uH$
C_{r1}, C_{r2}	$50.66nF, 50.66nF$
L_m	$500uH$
C_{eq}	$10nF$
t_{dead}	$600ns$

CLLLC resonant converter is controlled by PFM control and hybrid control in steady state operation respectively, and the performance of the output voltage is compared with the simulation results as shown in Fig. 5. In Fig. 5(a), the primary has periodic oscillations because the conventional PFM control method only changes frequency to regulate the output voltage. As a result, the output voltage also has oscillations, which are same to the current ripple due to the output voltage control performance is limited. However, in Figure 5(b), the hybrid control method can control the output voltage more precisely by using the advantages of PWM control at poor load. The voltage ripple decreases around 85%.

5. CONCLUSION

A PWM and PFM hybrid control method was proposed in this paper which greatly enhances the control performance of the CLLLC resonant converter to the output voltage, reduces the ripple of the output voltage and improves the efficiency of the converter. In the process of applying the hybrid control method to the CLLLC resonant converter, which makes the CLLLC resonant converter have soft switching performance and improves the efficiency of the converter. The CLLLC resonant converter model which is built through Simulink operates at a switching frequency of $100kHz$, and the simulation results show that compared with conventional PFM control method, the hybrid control method can reduce the output voltage ripple by 85%.

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