Analysis and Optimization of LLC Resonant Converter with a Novel Over-Current Protection Circuit

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Abstract—**A novel over-current protection method for LLC resonant converter has been proposed in this paper. This method is very attractive for its good current limit ability, especially under short circuit condition. Moreover, its current limit point range is easy to be optimized. Detailed theoretical analysis and optimization design considerations have been presented. An experimental prototype converter based on the proposed method was built up to verify the theoretical analysis.**

Keywords- LLC; Over-current protection

I. INTRODUCTION

Recently, LLC resonant converter has drawn more and more attention because it has some unique characteristics and improvements over other topologies[1]-[4], such as ZVS capability from zero to full load, low voltage stress on secondary rectifier, high efficiency at high input voltage etc.

To make practical use of this converter, there are still some issues to be solved. Over-current protection is one critical issue which will be discussed in this paper. The purpose of over-current protection is to limit the current stress in the system under overload or short circuit condition and the inrush current during start up so that the power converter will not be damaged under those conditions.

There are totally three different over current protection methods for LLC resonant converter that have been mentioned in the past years. The first method is increasing the switching frequency. It's simple, but the frequency becomes too high to keep acceptable current, which results in great loss on devices and brings more critical demand on thermal management. Another concern is that magnetic design will be greatly affected by this high switching frequency.

The second method is a combination of varied-frequency control and PWM control. With this method, a lower frequency can be chosen compared to the first method. PWM control is used to limit the current so that magnetic component and semiconductor don't need to be over designed. However, primary switches will lose ZVS under over-current protection mode.

The last one is a modified LLC topology with splitting caps and clamping diodes[4]. The current can be automatically limited by clamping the voltage across the splitting resonant capacitors and ZVS of primary switches can still be achieved during over current protection mode. The problem of this method is that the setting current-limit point is a function of input voltage. Unfortunately, the primary current and voltage across resonant capacitors are large at low line while they are small at high line. Hence the current limit point at high line is much higher than that of low line so that it can't limit the current effectively. Moreover, the voltage across splitting capacitors should be designed to be smaller than 1/2 input voltage, which limits the optimization of circuit parameters.

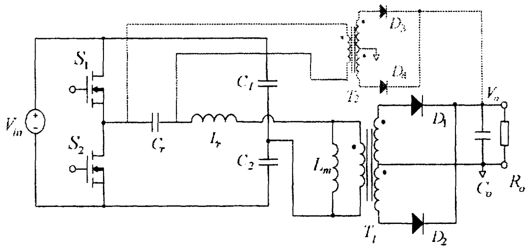


Fig.1 LLC topology with proposed current limit circuit

In this paper, a novel over-current protection circuit for LLC resonant converter is proposed as shown in Fig.1. Detailed theoretical anlysis and optimization design considerations on the proposed circuit will be presented in the following sections.

II. THEORETICAL ANALYSIS

As shown in Fig.1, the proposed over-current protection circuit for LLC resonant converter is formed by a small transformer T_2 and two diodes D_3 and D_4. In normal operation conditions, the protection circuit doesn't work. When over-current or short-circuit conditions occur, primary curren will increase rapidly. And the voltage across resonan capacitor C_r will also increase. When the voltage across resonant capacitor C is larger than output voltage referred to the primary side of transformer T_2, clamping diode D_3 or D_4 begins to conduct. Hence the voltage across C_r is clamped and the primary current is also clamped. Because the output voltage is usually constant, the current limit point range is narrow compared to that of the modified LLC topology with splitting caps and clamping diodes. Moreover, the current-limit point range can be further narrowed by optimizing the circuit parameters.

In LLC converter, the operation frequency range is relative to the ratio of L_m/L_r, which can be expressed as:

$$\frac{f_{\min}}{f_r}=\frac{\pi^2}{\pi^2+4\frac{L_m}{L_s}(1-\frac{V_{in\min}}{2nV_o})} \tag{1}$$

where L_m is the magnetizing inductor of the main transformer, L_s is the resonant inductor; f_s is the resonant frequency which is usually chosed as the rated operation frequency.

According to equation (1), the relation curve of operating frequency range *vs.* L_m/L_r can plotted as shown in Fig.2. From Fig.2 we can see, the smaller the ratio of L_m/L_r, the narrower operating frequency range.

On the other hand, because current limit is realized by clamping the voltage across the resonant capacitor in the proposed over-current protection method, the current-limit point range is relative to the voltage range across the resonant capacitor. In order to have a good current limit effect, it is required that the voltage across the resonant capacitor does not change much. This voltage is relative to the frequency of the converter, which can be derived as:

$$\frac{V_{c\max}}{V_{c\min}}=\frac{[nV_o-\frac{V_{in\min}}{2}+\frac{4I_oL_m(1-\frac{V_{in\min}}{2nV_o})f_r}{(\frac{f_{\min}}{f_r}-1)\cdot n\frac{f_{\min}}{f_r}}](\frac{f_r}{f_{\min}}-1)n}{4I_oL_m(1-\frac{V_{in\min}}{2nV_o})\cdot f_r} \tag{2}$$

Where $V_{c\max}$ is the maximum voltage across the resonant capacitor occurring at the lowest input voltage point while $V_{c\min}$ is the minimum value occurring at the highes input voltage point. The relation curve of $V_{c\max}/V_{c\min}$ *vs.* $f_{\min}/f_r$ according to equation (2) is plotte in Fig.3.

As shown in Fig.3, $V_{c\max}/V_{c\min}$ decreases when $f_{\min}/f_r$ increases. Along with Fig.2, we can find that if a small ratio of L_m/L_r is selected, a narrow operating frequency range can be achieved and a small ratio of voltage change across C_r can also be achieved. Hence a relatively narrow current-limit point range can also be achieved.

Another outstanding merit of this proposed circuit is its inherent current limit ability during short circuit condition, especially when it is combined with increasing frequency

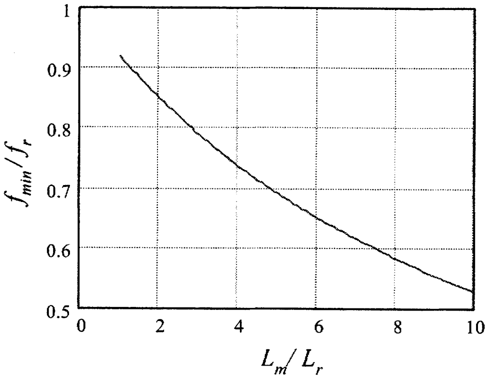


Fig.2 Operating frequency range *vs.* L_m/L_r (full load)

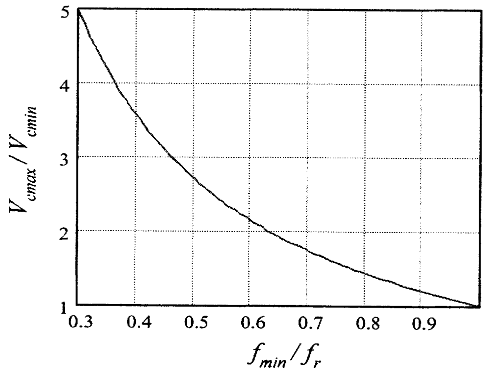


Fig.3 Ratio of voltage across resonant capacitor *vs.* $f_{\min}/f_r$ (full load)

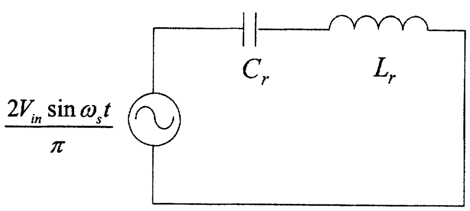


Fig.4 Simplified model of half-bridge LLC resonant converter during short condition

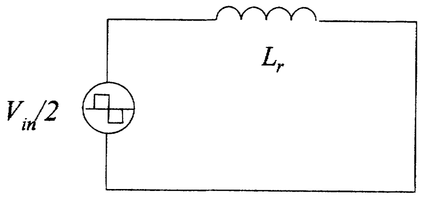


Fig.5 Simplified model of half-bridge LLC converter with propos over-current protection circuit during short condition

method. During short circuit condition, the equivalent circuit model of the traditional LLC resonant converter is simplified as a series resonant tank while the LLC resonant converter with the proposed over-current protection circuit is simplified as an inductor, as shown in Fig.4 and Fig.5 respectively. Obviously, the equivalent imepedance of the latter is much larger hence its short circuit current is much smaller.

Fig.6 shows the calculated average output currents of the LLC converter the proposed over-current protection circuit combined with increasing frequency under short circuit condition. For comparison, the short current of LLC converter with the conventional increasing frequency method is also shown in Fig.6. Calculation parameters are shown in Table.1, which have been optimized already according to the analysis mentioned above. From Fig.6 we can see that if the average output current is to be set at 12.5A, the frequency with conventional increasing frequency method should be increased to 385 kHz, while with the proposed method the switching it is just need to be increased to 265 kHz. It means that the maximum switching frequency can be greatly reduced.

Table.1 Converter parameters and main components

Main parameters:	Resonant parameters:
V_{in}: 300V~400VDC	*Transformer turns ratio:9:5:5*
V_o: 110VDC	*Transformer core: EE42C*
I_o: 10A	*L_m: 54uH*
Primary switches: IRFP22N50	*Resonant inductor core: RM10*
Output rectifiers D1&D2: MBR3030PT	*L_r: 13.5uH*
Turns ratio of auxiliary transformer: 14:5:5	*C_r: 44nH*
	f_s: 150kHz~200kHz
Auxiliary transformer core: RM10	
Clamping diodes D3&D4: MBR2030PT	

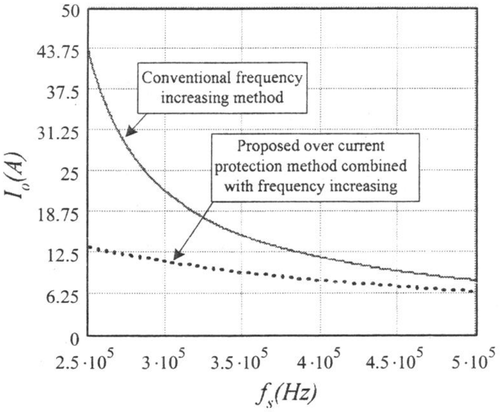


Fig.6 Calculated average output current during short circuit condition

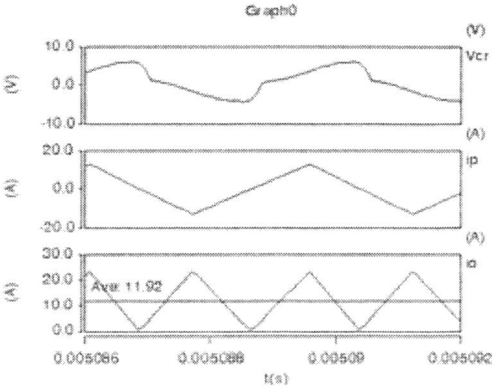


Fig.7 Simulated waveforms of half-bridge LLC converter with proposed over-current protection circuit during short condition

Fig.7 shows the simulated waveforms of LLC converter with proposed over-current protection circuit during short condition. The average output current is 11.92A at 265kHz during short circuit condition. The tiny discrepancy is caused by the parasitical parameters that are introuded in the simulation circuit..

II. EXPERIMENTAL RESULTS

An 1100W prototype converter based on the optimized parameters is built up to verify the proposed over-current protection method for LLC resonant converter. Circuit parameters and components are the same with those shown in Table.1.

Main waveforms under normal operation mode are shown in Fig.8~Fig.11. Fig.8 and Fig.9 show the waveforms at low line input Fig.12 where the waveforms at high line input are shown in Fig.10 and Fig.11. It can bee seen that the ratio of V_{cmax}/V_{cmin} is about 1.67 and the ratio f_{min}/f_{max} is about 0.75, which is in consistent with with the calculate curve shown in Fig.3.

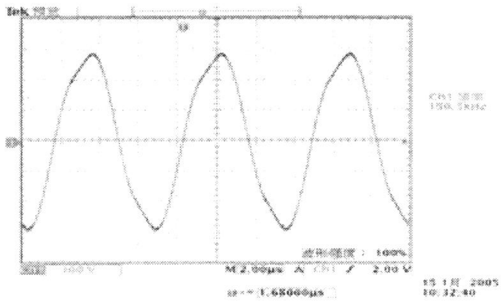


Fig.8 Voltage waveform across resonant capacitor (V_{in}=300V)

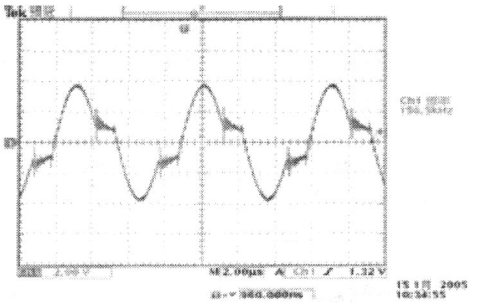


Fig.9 Primary current waveform (V_{in}=300V)

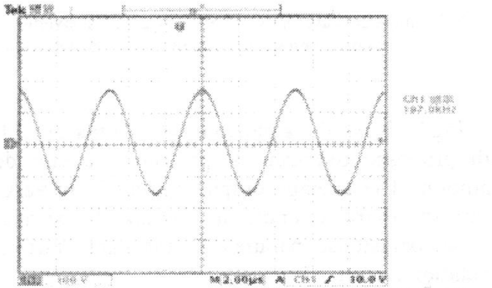


Fig.10 Voltage waveform across resonant capacitor (V_{in}=400V)

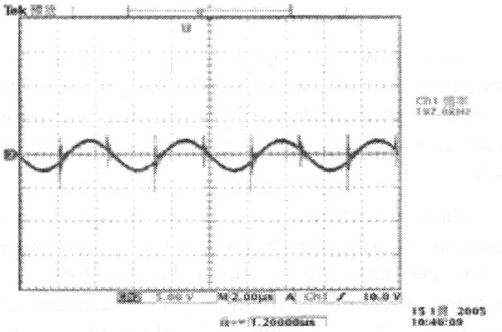


Fig.11 Primary current waveform (V_{in}=400V)

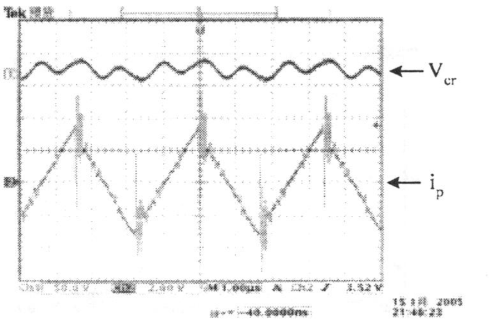
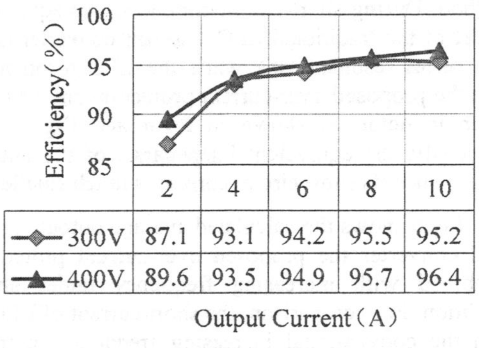


Fig.12 Test waveforms under short circuit condition (V_{in}=400V)



	2	4	6	8	10
◆ 300V	87.1	93.1	94.2	95.5	95.2
▲ 400V	89.6	93.5	94.9	95.7	96.4

Fig.13 Measured efficiencies

Fig.12 shows the primary waveforms under short circu condition, which fit well with the simulated waveforms.

Fig13 shows the measured efficiencies at different inp voltage under full load condition. An efficency of 96.4% ca be achived at 400V input and full load condition.

III. EXPERIMENTAL RESULTS

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ACKNOWLEDGMENT

This research work is supported by NSFC No.50237030.

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