

Over Current Protection Methods for LLC Resonant Converter

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Abstract— LLC resonant converter was getting more and more attention in recent years because of its high efficiency, high frequency operation capability and simple structure. In this paper, the over current protection issue of LLC resonant converter is discussed. Three methods to provide over current protection function for LLC converter are proposed and investigated. They are: increase switching frequency control, variable frequency + PWM control, and diode clamping method. The pros and cons for each method were discussed. Tests were performed to verify the discussion.

Keywords—LLC resonant converter; over current protection

I. INTRODUCTION

The increasing efforts on pushing power converter to higher power density and lower profile have lead us to develop converters capable of operating at high switching frequency with high efficiency. With high switching frequency, size of passive components could be reduced. However, traditional PWM converter will suffer efficiency with higher switching frequency, which will put more loads on thermal management and cannot meet the future requirements of power density and efficiency. For this reason, resonant converters have drawn more and more attentions recently due to its high efficiency and high switching frequency capability.

Fig.1 shows a three elements resonant converter: Half bridge LLC resonant converter. This topology has been discussed in many papers recently [1][2]. It shows many unique characteristics and improvements over previous topologies:

- Simple structure;
- ZVS capability from zero to full load;
- Low MOSFET turn off current, so switching loss of this converter is very low;
- High efficiency at high input voltage, for this converter, the highest efficiency can be achieved at high input voltage, which gives great benefit for applications like telecom power supply with hold up requirements;
- Low voltage stress on secondary rectifier, because for this converter, there is no secondary filter inductor, so the voltage stress on rectifier diodes can be minimized to two times output voltage. With better diodes, the conduction loss can be greatly reduced.

Another good thing about this converter is that the magnetic components of this converter can be easily integrated into one magnetic core [3]. Also, leakage inductance of the

transformer can be absorbed as resonant inductor, so there is no leakage inductance related problems.

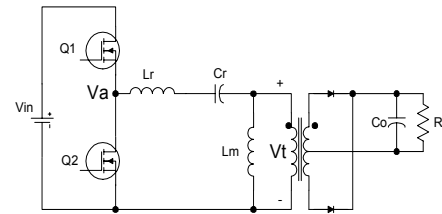


Fig. 1 Half Bridge LLC resonant converter

However, to make practical use of this converter, there are still some issues to be solved. Over current protection issue 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 during over load or short circuit condition, also to limit the inrush current during start up when output voltage is zero so that the power converter can be protected from destructive damage under those conditions.

In many applications, continuous operation in over current condition is required. In order to achieve this target, other than limit the current, healthy operation is also an important consideration, which means when the converter is running into over current protection mode, the operation of semiconductor or other components should be cause destructive damage too, i.e. lost of Zero Voltage Switching.

For traditional PWM converter, during over current condition, duty cycle is reduced to limit the current. For LLC resonant converter, it is working with variable frequency control, the over current protection is different. In LLC resonant converter, the impedance of the resonant tank is pretty small during normal operation. This means the current could reach very high level in very short time. This characteristic makes over current protection design for LLC resonant converter very critical.

In this paper, three different over current protection methods for LLC resonant converter are discussed. First method is increasing the switching frequency. The second method, a combination of variable-frequency-control and PWM control is used to achieve over current protection. In the last method, the power stage is modified to include current limiting function into the converter.

In following sections, each method will be discussed separately. To discuss this issue, an application is chose to demonstrate the methods. The application used here is the

DC/DC converter for Distributed Power System in telecom and server application. The specs for the converter are:

$V_{in} = 300V$ to $400V$, $V_o = 48V$, $P_o = 1000W$, and hold up time: 20ms.

The parameters for the LLC converter used in this discussion is:

$L_r = 16\mu H$, $C_r = 25nF$ and $L_m = 60\mu H$, transformer turns ratio: 4:1.

With above specs and parameters, the switching frequency range for the converter is: 180kHz to 270kHz.

II. METHOD 1: INCREASING SWITCHING FREQUENCY

When converter running into over current protection condition, there are two ways to limit the current. First way is to reduce the voltage applied to the converter. For example, in PWM converter, duty cycle is reduced to limit the current. By reducing duty cycle, the average voltage applied to converter is reduced so that the current can be limited. Second way is to increase the impedance of the converter so to limit the current. This method is used for variable frequency converter. By moving the switching frequency away from resonant frequency, the impedance of the resonant tank will increase so that the current can be limited. Fig.2 shows the average current at different switching frequency and load condition for LLC resonant converter.

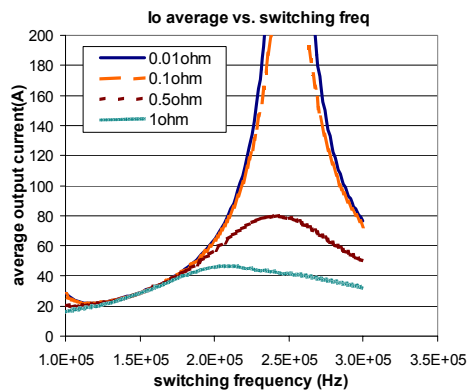


Figure 2 Average Output current vs. Switching frequency for LLC resonant converter

From Fig.2 we can see, by moving switching frequency away from resonant frequency (250kHz), the output current can be limited. There are two directions to move switching frequency: move to high frequency or lower frequency. Since the lower frequency will result in ZCS condition, which is not a desirable working condition for MOSFET, here we will move switching frequency to higher frequency.

The worst case will be short circuit condition. Fig.3 shows the LLC resonant converter in short circuit condition. It can be seen that when short circuit happens, the LLC resonant converter can be simplified as a series resonant tank. By simply analysis the impedance of series tank, the frequency and current relationship can be revealed.

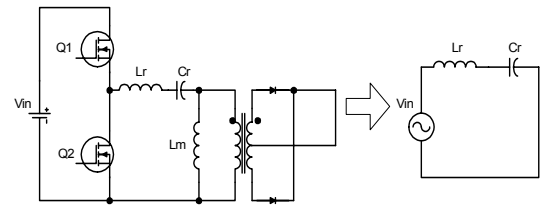


Figure 3 Simplified model of LLC resonant coverter during short circuit condition

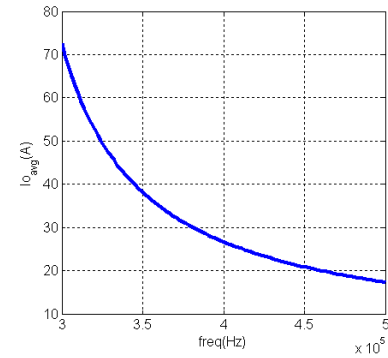


Figure 4 Short circuit average output current vs. switching frequency

From Fig.4, it can be seen that with short circuit condition, switching frequency need to rise to about 380kHz to limit the output current under 27A.

Fig.5 and Fig.6 show the simulation and test waveforms for this condition. In the real test, because of the parasitic parameters, with 358kHz switching frequency, the output current can be limited under 27A.

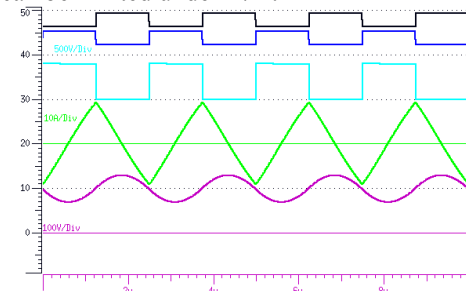


Figure 5 Simulation waveform for short circuit operation with high switching frequency (top to bottom: Q1 Q2 gate signal, Q1 drain source voltage, Transformer primary current and resonant cap voltage)

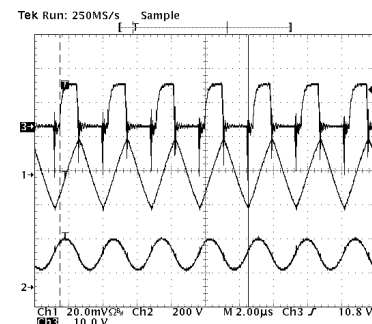


Figure 6 Test waveform (top to bottom: Q1 gate signal, Transformer primary current and resonant cap voltage)

For this method, the converter will be working at pretty high switching frequency compare with normal operation condition. With high switching frequency, there are several considerations:

First the switching loss will increase. During short circuit condition, current stress reaches the highest. Turn off current also reaches the highest. With so high switching frequency, the loss on the device will be very high which will increase the thermal management requirement.

Second, the stress on the magnetic components will be very unbalanced. During over current protection, switching frequency reaches highest level while all the volt-second is applied to the inductor, which means inductor has to be designed according to this highest. For LLC resonant converter, this frequency will be almost double of normal operation frequency; this will make the size of the inductor to be larger.

The benefit of this method is easy to implement. It doesn't need complex control circuit.

III. METHOD 2: VARIABLE FREQUENCY CONTROL PLUS PWM CONTROL

From previous discussion, reduce the voltage applied to the converter can limit the current too. In the second method, variable frequency control and PWM control method are combined.

For this method, the converter has two modes: normal operation mode and current protection mode. During normal operation mode, variable frequency control is used to get high efficiency and clean waveform. During over current protection mode, first switching frequency is increased to limit the current, when switching frequency reaches the limit we set, PWM control mode will be used to reduce the voltage applied to resonant tank as shown in Fig.7. With this method, the output current can be effectively limited. As shown in Fig.8, the current can be limited with duty cycle change. In this graph, when switching frequency is lower than 300kHz, variable frequency control is used. When switching frequency reaches 300kHz, duty cycle control cut in. In Fig.8, a flat area is observed when duty cycle is close to 0.5. In this flat area, the duty cycle change cannot change the current. The reason is for each switching cycle, the body diode of the MOSFET will conduct for some time, duty cycle change must be larger than the body diode conduction time as shown in Fig.9.

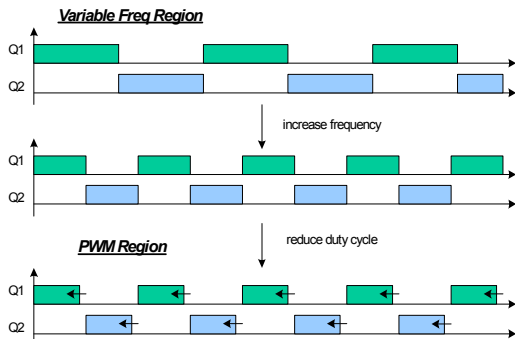


Figure 7 Control Method of Variable freq + PWM control

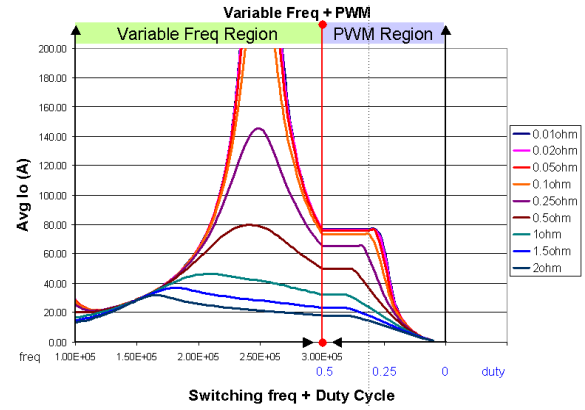


Figure 8 Average output current of LLC resonant converter with variable frequency + PWM control

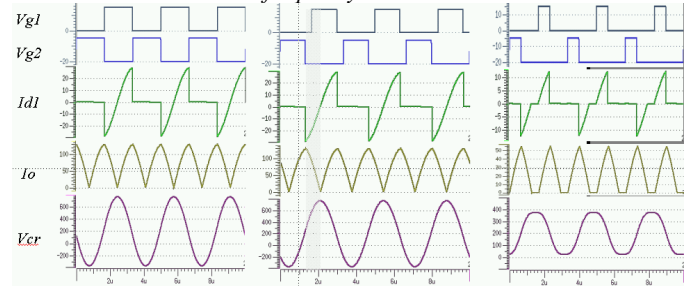


Figure 9 Simulation waveform for $D=0.5, 0.4$ and 0.2 at short circuit condition

Fig.10 shows the simulation result with consideration of output capacitance of MOSFET. The current will resonant instead of stay at zero. Also can be seen from Fig.10 that the ZVS condition of MOSFET is lost because of DCM operation of primary current. Fig.11 shows the test result.

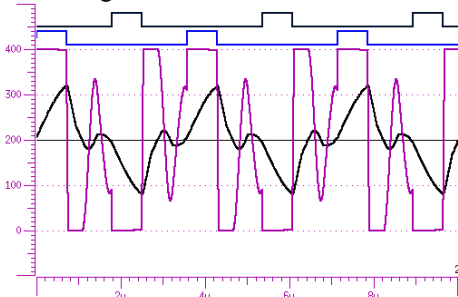


Figure 10 Simulation waveform with output cap (from top: gate signal of Q1 and Q3, V_{ds} of Q1 and primary current I_p)

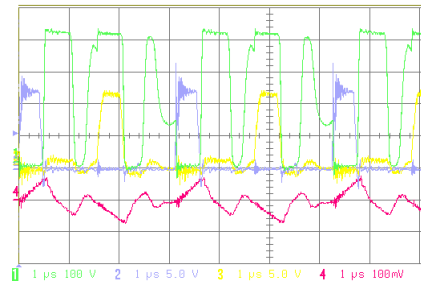


Figure 11 Test waveform for PWM control (Green: V_{ds} of Q1, Blue: gate signal of Q1, Yellow: gate signal of Q2, Red: primary current)

This method can achieve the current limiting function. The concern is operating condition. Since ZVS is lost during

over current protection mode, the switching loss will increase and noise on gate driver will be a problem too. Another issue will be how fast the transition between different modes could be. Since the current could ramp up very fast, a very fast protection is necessary.

IV. METHOD 3: LLC RESONANT CONVERTER WITH CLAMPING DIODE

In this method, the current limit function is built in the power stage. This method can provide cycle-by-cycle current limiting function without control interference. Also, this method provides some other benefits too. Next the detail of this method will be discussed.

For half bridge LLC resonant converter shown in Fig.12, there are several things could be improved. One is the input current is discontinuous as shown in Fig.12. During half of switching cycle, there is no current. This will cause very high current ripple and which will cause noise and loss problem. In order to smooth the input current, splitting the resonant cap will be a solution, as shown in Fig.13.

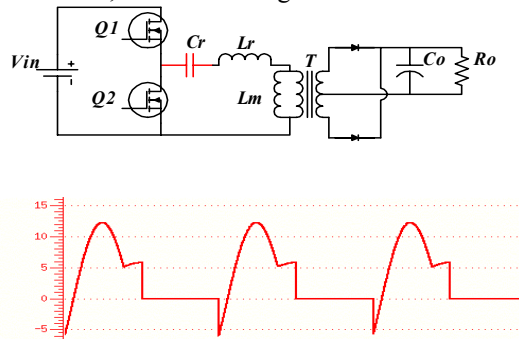


Figure 12 Half Bridge LLC converter and Simulated input current waveforms

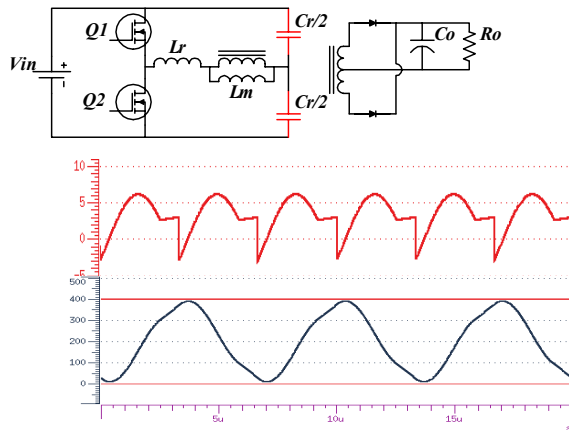


Figure 13 Half bridge LLC with splitting cap and simulated input current and resonant capacitor voltage waveform

Another thing for this topology is that there is no automatic current limiting function in this topology. Looking at the simulation waveform shown in Fig.14, it can be seen that during over current condition, input current is very high and the peak voltage across resonant capacitor will increase to very high too. This is because during over current condition,

more current is going through the resonant tank, which will charge the resonant cap to higher voltage.

Fig.15 shows the LLC resonant converter with clamping diodes. With two clamping diodes across resonant capacitor, first the voltage stress on resonant cap is limited so that a low voltage cap can be used; another benefit is that by limit the voltage on resonant cap, we automatically limited how much current can going through the resonant tank during each half switching cycle, which in turn will limit the output current.

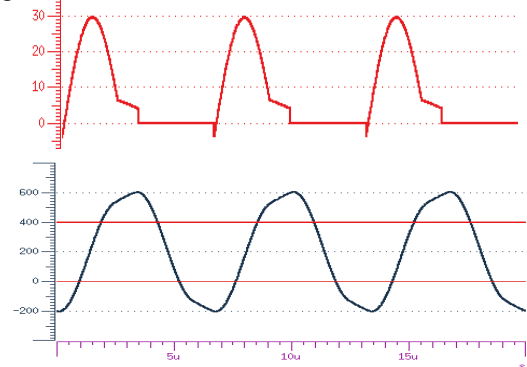


Figure 14 Input current and resonant capacitor voltage at during over load condition

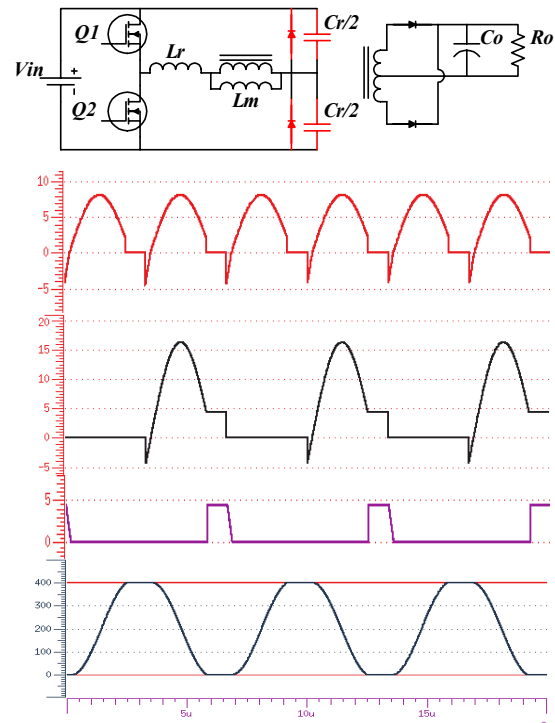


Figure 15 Simulated waveforms for Half Bridge LLC converter with splitting cap and clamping diodes(Top: input current, middle1: switch current, middle 2: clamping diode current, bottom: resonant cap voltage)

From the waveform we can see, with same condition, LLC resonant converter with splitting cap and clamping diodes can greatly reduce the input current ripple, switch current and resonant cap voltage stress. This will protect the converter from destructive damage. Another benefit of this method is that this method doesn't need active control; it is

very simple to implement. Its response speed is fast, which can provide cycle-by-cycle current protection. Fig.16 shows the test waveform during over load condition.

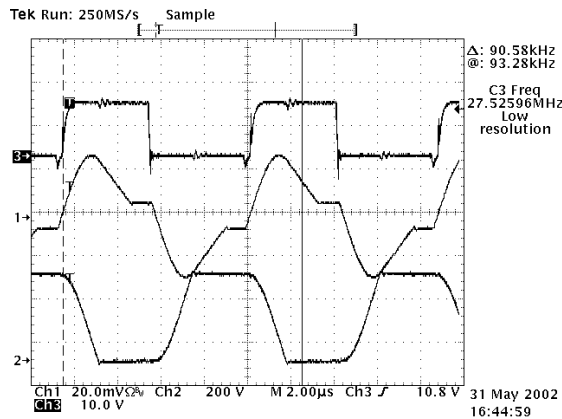


Figure 16 Test waveform for Half Bridge LLC converter with splitting cap and clamping diodes(Top: gate signal, middle: resonant tank current, bottom: resonant cap voltage)

To use this method, there are several concerns. As described before, because of these clamping diodes, the current is limited for each switching cycle. The current can be passed through the resonant tank is related to the input voltage. Also, since this method limit the amount of current flow through resonant tank in each switching cycle, when switching frequency is changing, the average output current will change too. Let's look at an example next.

For the given application, when input voltage is 300V, we set the maxim output current at 25A. When input voltage is 400V, two things changes: input voltage is higher, switching frequency is higher too. From above analysis, this will increase the maxim output current. Instead of 25A at 300V, the maxim output current at 400V will be 34A.

Although with this drawback, the clamping diode is still a effective way to protect the converter. With these clamping diodes, ZVS is ensured at all condition. At high input voltage, although the setting point increased, still it gives us enough time to let the controller to take over and limit the current.

V. SUMMARY

In this paper, three ways of over current protection methods is discussed. For each method, there are some benefits and concerns.

A. increasing switching frequency

This method is simple to use and implement. The main concern is that magnetic design will be greatly affect by how high the frequency will be. Also, during protection, current stress is very high for primary switches. The thermal design for primary switch will be suffered to deal with this condition.

B. Method b: variable frequency + PWM control

For this method, some modification on the control circuit is necessary to implement it. This method will prevent the issues of high frequency operation in method a. We can

choose a lower frequency and use PWM control to limit the current so that magnetic and semiconductor doesn't to be over designed.

The problem of this method is that during protection mode, primary switches will loss ZVS.

C. Method C: LLC resonant converter with splitting cap and clamping diodes

Basically this is a passive method to limit the current. With splitting cap, input current ripple can be reduced greatly. With clamping diodes, the current at over current condition can be automatically limited. The voltage stress on the resonant cap is also kept under a given voltage. ZVS is achieved during over current protection mode.

The problem of this method is that the setting point is a function of input, output voltage. So for different operating point, this setting value will change. It reaches minimal at low line and high output voltage and reaches maximum with high line and low output voltage.

Since each of these three methods has its pros and cons, for different requirement, different over current protection method should be choose. In some case, combination of different method could be used to get better performance too.

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