magnetic structure is to integrate the two U cores used to build discrete magnetic. With this method, the problem is the mechanical structure is not a stable structure. To improve this structure, a general integrated magnetic structure is developed. With the model, another integrated magnetic structure is developed with same air gap on all legs. With this magnetic structure, the manufacture is easy. There is no mechanical problem. Also, flux ripple cancellation could be achieved with this structure. Compare with discrete design, the integrated magnetic structure could provide same efficiency with 30% less footprint.

5.2 Over load protection for LLC resonant converter

In previous part of this chapter, the design of power stage was discussed. Base on these discussions, the power stage of LLC resonant converter could be designed for given specifications. Magnetic design is also investigated for LLC resonant converter. Till now we got a converter could convert 400V DC to 48V DC output with high efficiency and high power density. However, to make practical use of this converter, there are still some issues to be solved. Over load protection is one critical issue, which will be discussed in this part.

The purpose of over load protection is to limit the stress in the system during over load condition. Another function is 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 some applications, continuous operation in over load condition is required in order to achieve high system availability. 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 load protection mode, the operation of semiconductor and other components should not cause destructive damage too, i.e. lost of Zero Voltage Switching, body diode reverse recovery etc.

For traditional PWM converter, during over load condition, duty cycle is reduced to limit the current. With smaller duty cycle, the current stress could be limited.

For LLC resonant converter, it is working with variable frequency control at constant 50% duty cycle. The over load protection is totally different story. To investigate the over load protection method for LLC resonant converter, following questions need to be answered. First, the intrinsic response of LLC resonant converter to over load situation needs to be understood. Second, methods to improve the intrinsic response need to be developed if the intrinsic response is not safe or healthy.

In this part of the dissertation, first the intrinsic response of LLC resonant converter to over load condition will be investigated. Then three different over load protection methods will be 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 load 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.

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

Lr=12uH, Cr=33nF and Lm=60uH, transformer turns ratio: 4:1.

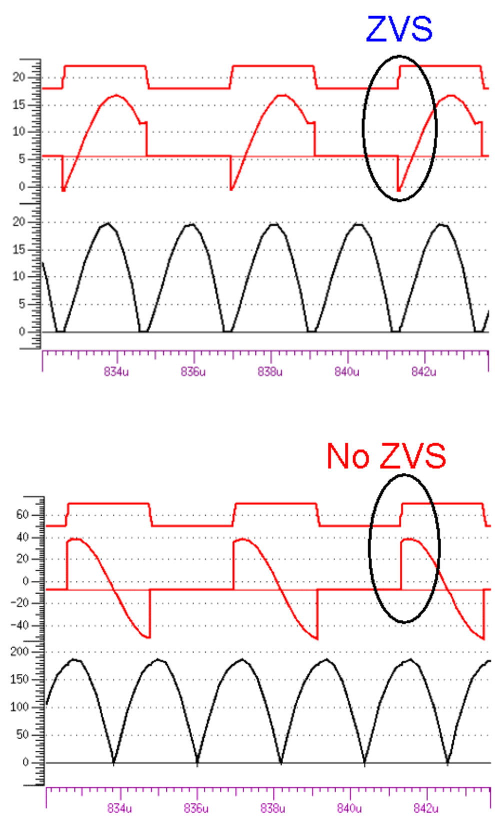
With above specs and parameters, the switching frequency range for the converter is: 170kHz to 250kHz.

5.2.1 Intrinsic response of LLC resonant converter to over load condition

In LLC resonant converter, the impedance of the resonant tank is pretty low during normal operation because it is working close to the resonant frequency of the series resonant tank. This means the current could reach very high level during over load situation. This characteristic makes over load protection design for LLC resonant converter very critical.

During over load condition, the load of the converter increases. The worst scenario will be short circuit of output. In this part, the impact of short circuit output will be investigated for LLC resonant converter.

The simulation waveforms of LLC resonant converter during normal operation and over load operation are shown in Figure 5.24. From the simulation waveforms, lost of ZVS and high current stress could be observed during over load condition. This could be understood through the characteristic of the converter. In Figure 5.25, the DC characteristic of LLC resonant converter is shown. At normal operation, the converter is working at Point A, when over load condition happens, the operating point will move to Point B. As seen in the graph, point A is in ZVS region while point B is in ZCS region. The over load current for different switching frequency is shown in Figure 5.26, the over load current could rise to very high.



(a)

(b)

Figure 5.24 Simulation waveforms of LLC resonant converter at (a) normal operation, and (b) short circuit operation

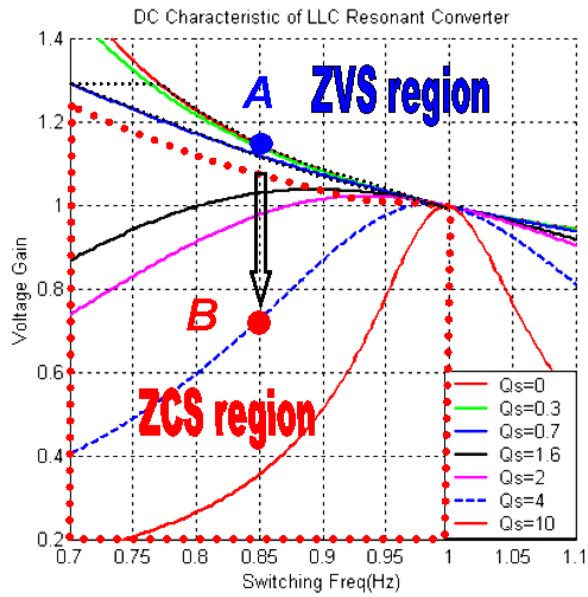


Figure 5.25 Lost of ZVS for LLC resonant converter during over load situation

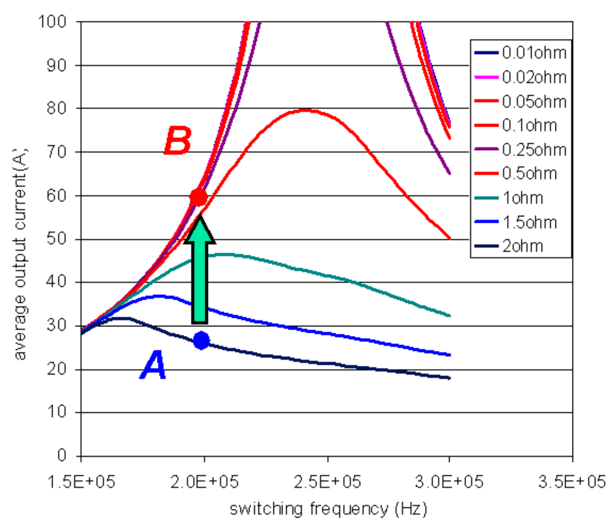


Figure 5.26 High current stress during over load situation for LLC resonant converter

From these results, the major problems for LLC resonant converter during over load condition are: high current stress, and lost of ZVS.

5.2.2 Method 1: Increasing Switching Frequency

When converter running into over load protection condition, there are two ways to limit the current. First way is to reduce the average 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 power stage of the converter so to limit the current. This method is useful for variable frequency controlled converters. By moving the switching frequency away from resonant frequency, the impedance of the resonant tank will increase so that the current can be limited.

To simplify the problem, let’s look at the worst scenario: short circuit of output. Under such condition, the LLC resonant converter could be simplified into a simple series resonant tank as shown in Figure 5.27.

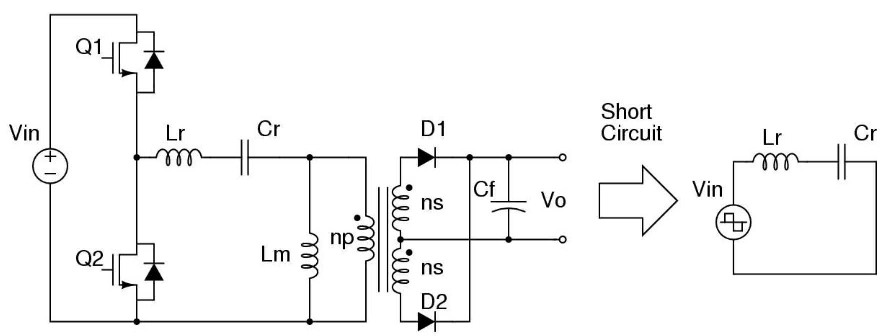


Figure 5.27 Simplified model of LLC resonant converter during short circuit condition

With this model, the switching frequency needed to limit the output current during short circuit situation could be derived. It is shown in Figure 5.28. As seen in the graph, if the desired over load current is 27A, then the switching frequency need to increase to about 400kHz.

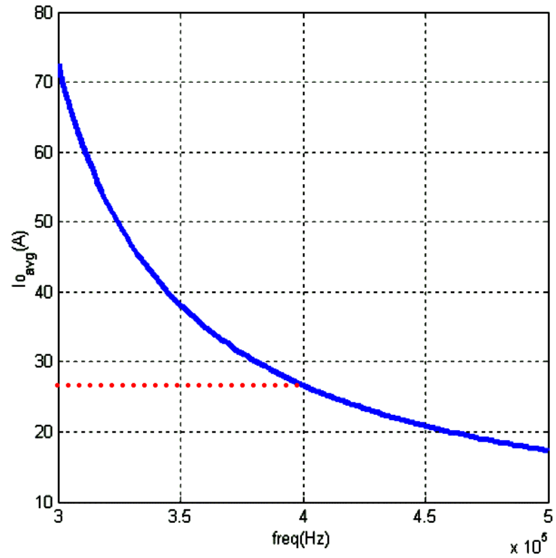


Figure 5.28 Short circuit output current at different switching frequency

Figure 5.29 shows the average for different over load condition. 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 higher frequency or lower frequency in relationship to resonant frequency. Since the lower frequency will result in ZCS condition as shown in Figure 5.30, which is not a desirable working condition for MOSFET, here we will move switching frequency to higher frequency.

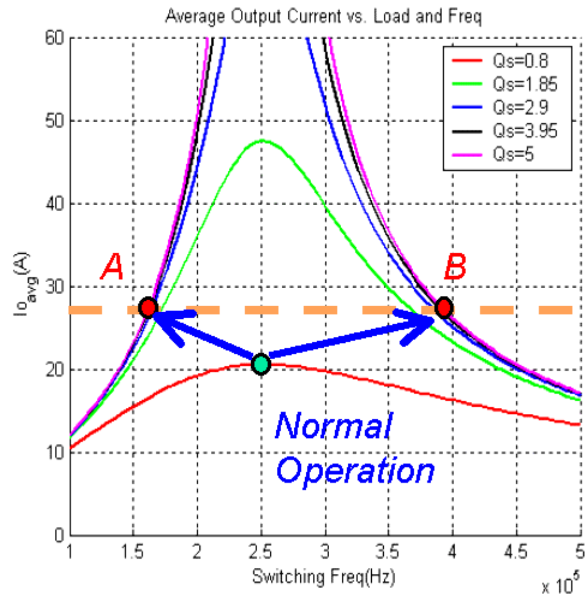


Figure 5.29 Average output current vs. switching frequency under short circuit

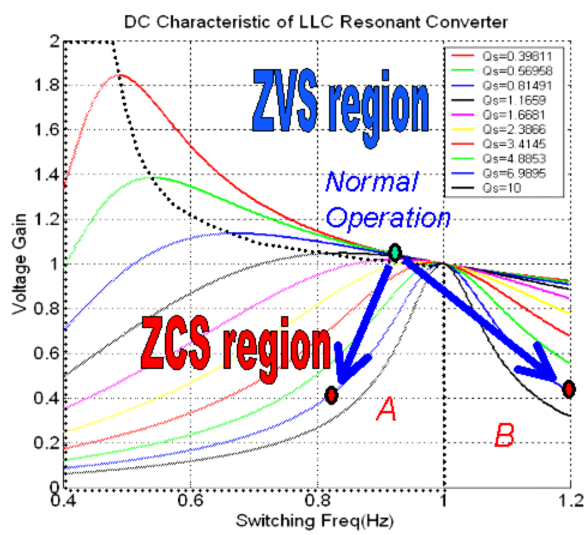


Figure 5.30 Change of operating mode with different switching frequency under protection mode

Figure 5.31 shows the 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 under short circuit condition.

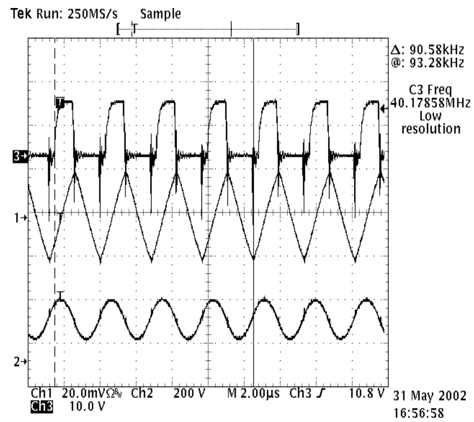


Figure 5.31 Test waveform (top to bottom: Q1 gate signal, Transformer primary current and resonant cap voltage)

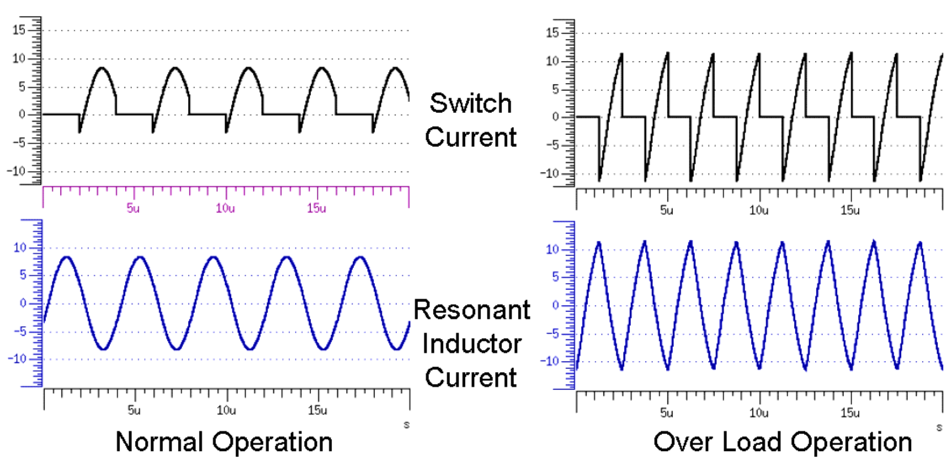


Figure 5.32 Problems with high switching frequency protection mode

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

First the switching loss will increase. As shown in Figure 5.32, 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 load 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.

5.2.3 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 protection mode. During normal operation mode, variable frequency control is used to get high efficiency. During over load 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 Figure 5.33. With this method, the output current can be effectively limited. As shown in Figure 5.34, 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.

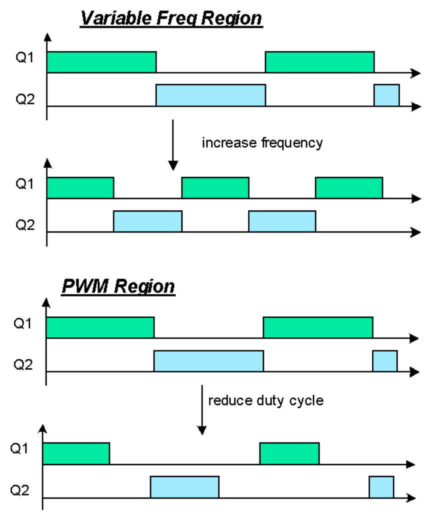


Figure 5.33 Control Method of Variable freq + PWM control

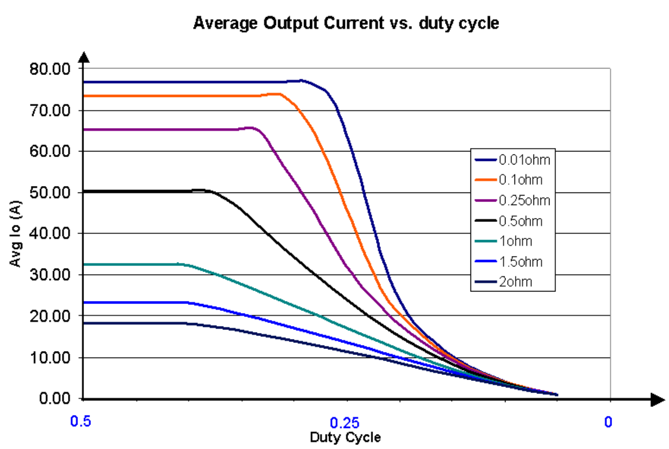


Figure 5.34 Average output current of LLC converter with variable frequency + PWM control

In Figure 5.34, 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 Figure 5.35.

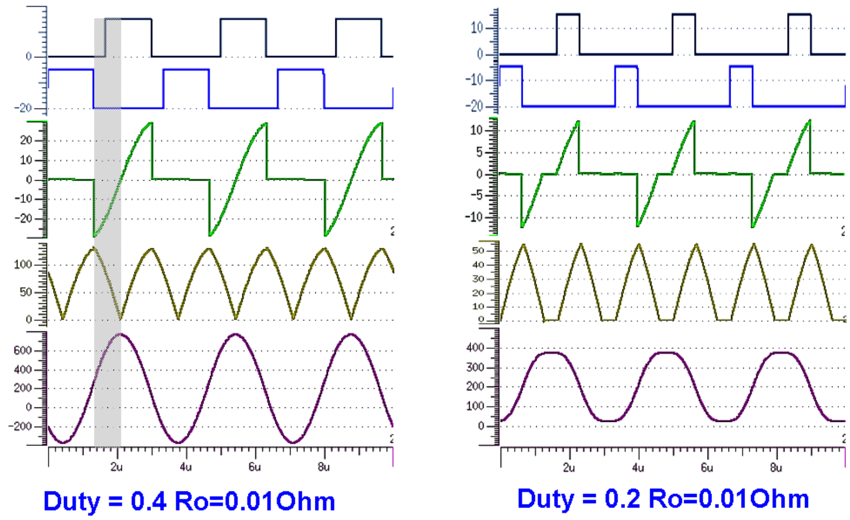


Figure 5.35 Simulation waveform for D=0.5, 0.4 and 0.2 at short circuit condition

Figure 5.36 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. Figure 5.37 shows the test result.

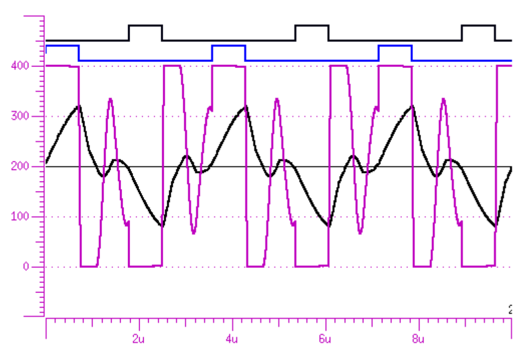


Figure 5.36 Simulation waveform with PWM control

(from top: gate signal of Q1 and Q3, Vds of Q1 and primary current Ip)

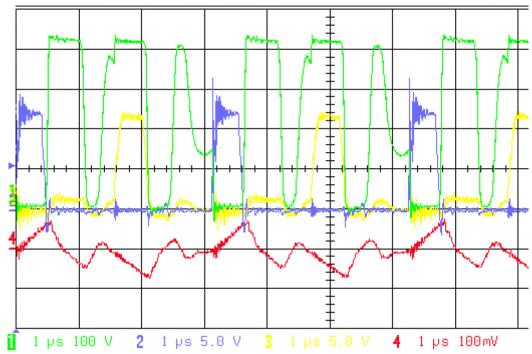


Figure 5.37 Test waveform for PWM control

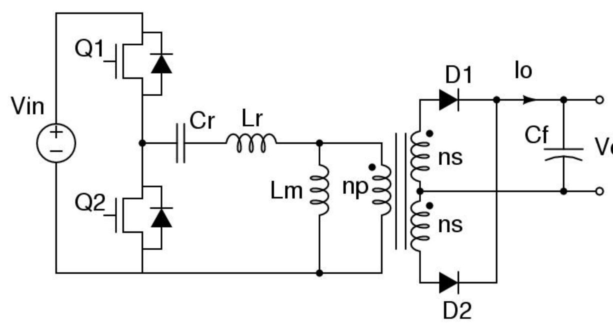
(Top: Vds of Q1, middle: gate signal of Q1, and Q2, bottom: primary current)

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

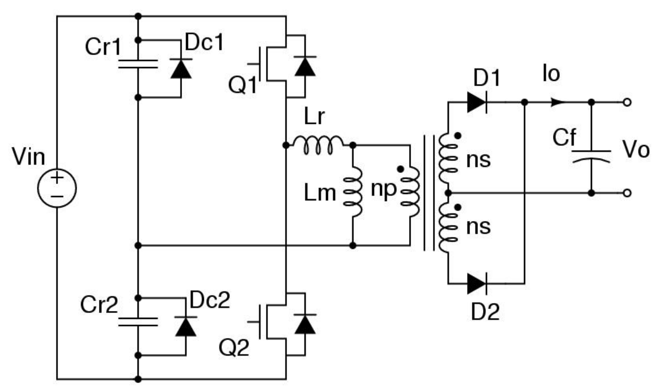
5.2.4 Method 3: LLC resonant converter with clamping diode

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.

Figure 5.38 shows the original LLC resonant converter and proposed LLC resonant converter. The proposed LLC resonant converter is different from previous discussed LLC resonant converter in following aspects: first, the resonant capacitor is spited into two capacitors. Then, two diodes are put in parallel with the resonant capacitor. With this modifications, there are several benefits could be achieved.



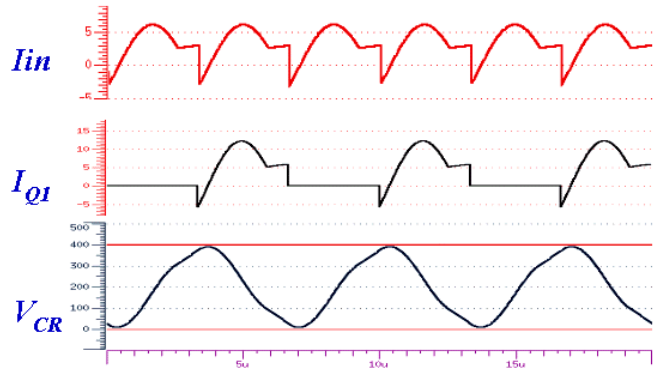
(a)



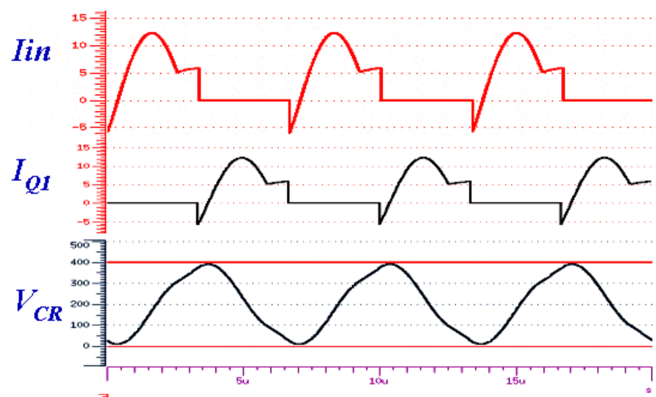
(b)

Figure 5.38 Two LLC resonant converter topologies: (a) Original LLC converter and (b) proposed clamped LLC converter

First benefit is achieved through splitting the resonant capacitor. Figure 5.39 shows the simulation waveforms of these two topologies. As seen from the simulation waveform, with splitting resonant capacitor, the input current will have lower ripple. This will alleviate the stress put on the high voltage bus capacitor.



(a)



(b)

Figure 5.39 Simulation waveforms for two LLC resonant converter topologies: (a) original LLC converter and (b) clamped LLC converter

Another benefit will be over load protection, which is provided by the clamping diodes. Figure 5.40 shows the simulation waveforms of original LLC resonant converter and the clamped LLC resonant converter at over load condition. For original LLC resonant converter, it can be seen that during over load condition, input current is very high and the peak voltage across resonant capacitor will increase to very high too. This is because during over load condition, more current is going through the resonant tank, which will charge the resonant cap to higher voltage. For LLC resonant converter with clamping diodes, 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, the energy could be absorbed by resonant tank is limited as shown in the state plane in Figure 5.41.

Also could be observed from the simulation waveform of clamped LLC resonant converter, under clamped operating mode, ZVS is still achieved.

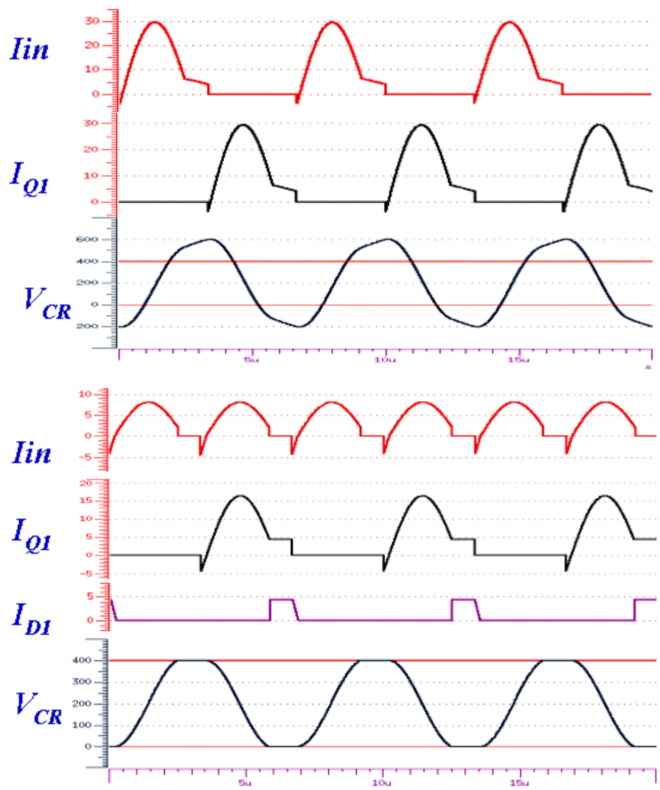


Figure 5.40 Simulation waveforms under over load condition for (a) original LLC converter and (b) clamped LLC converter

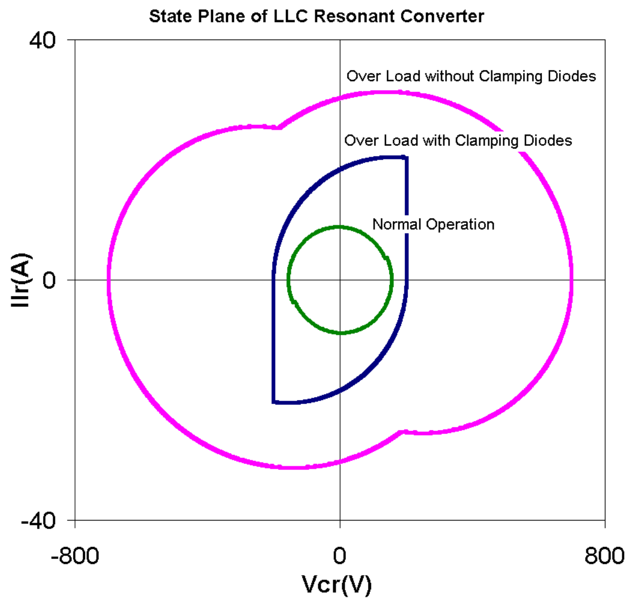


Figure 5.41 State plane of original and clamped LLC resonant converter

The over load current for both topologies are shown in Figure 5.42 and Figure 5.43.

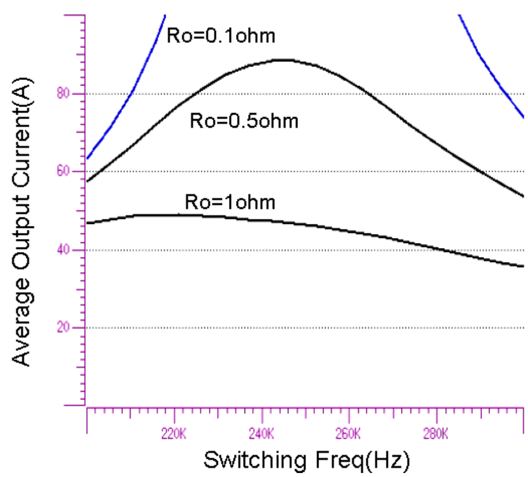


Figure 5.42 Average output current under over load condition for original LLC converter

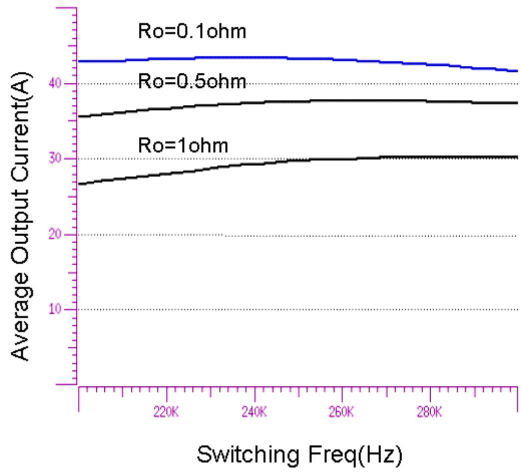


Figure 5.43 Average output current under over load condition for clamped LLC converter

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. During normal operation, these two diodes will not conduct, the clamped LLC converter operates exactly same as original LLC resonant converter in every aspects.

In order to avoid the clamp diodes to impact normal operation condition, the design is chosen as shown in Figure 5.39. Within the expected operating region of the converter, the voltage stress on resonant capacitor is designed to be lower than the clamping voltage. Figure 5.44 shows the design region for clamped LLC resonant converter. During normal operation condition, the voltage stress on the resonant capacitor is always lower than the clamp voltage, which is the input voltage. Figure 5.45 shows the test waveforms with this method. With this method, the converter is tested with short circuit with output current at 32A at switching frequency at 200kHz for over 5 minutes.

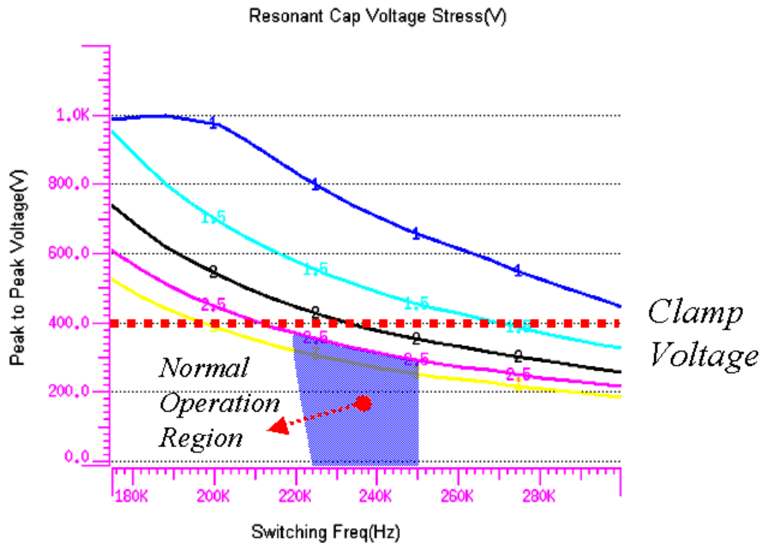


Figure 5.44 Design region of clamped LLC resonant converter

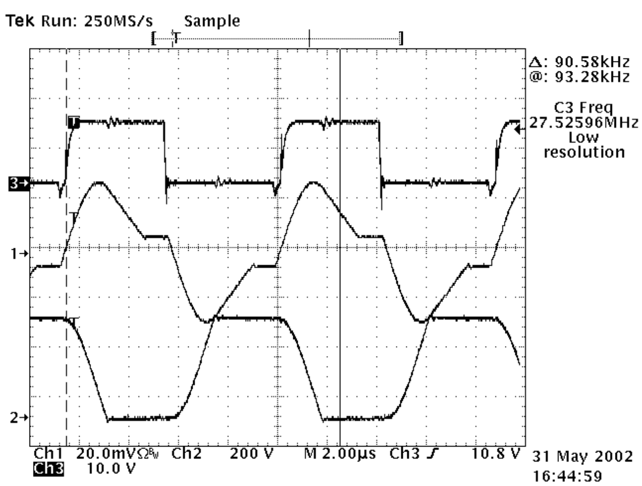


Figure 5.45 Test waveform of LLC converter under clamping mode

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 27A. 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 an 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.

Base on this information, the compensator could be designed and the front end DC/DC converter is a complete system now.

5.3 Integrated power electronics module for LLC

From above analysis and test results, LLC resonant converter demonstrated significant improvements over PWM topologies. With high frequency and high efficiency, the power density of LLC resonant converter is improved by 3 times compared with asymmetrical half bridge.

As seen in chapter 3, with advanced packaging technology, the power density and performance of asymmetrical half bridge converter could be improved