Chapter 4

LLC Resonant Converter

4.1 Introduction

In previous chapters, the trends and technical challenges for front end DC/DC converter were discussed. High power density, high efficiency and high power are the major driving force for this application. Hold up time requirement poses big penalty to the system performance. Two methods were proposed in chapter 2 to solve this problem and improve the efficiency. Range winding solution could improve the performance at high input voltage significantly, but with extra devices, windings and control circuit. Asymmetrical winding solution provides a simpler solution, but could only apply to asymmetrical half bridge topology. Also it introduced other problems like discontinuous output current and unbalanced stress.

To catch up with and move ahead of the trend, higher switching frequency, higher efficiency and advanced packaging are the paths we are taking now. Within all these issues, a topology capable of higher switching frequency with higher efficiency is the key to achieve the goal.

With the techniques proposed in chapter 2, the performance at normal operation could be improved. But none of these methods dealt with the switching loss problem of PWM converter. Even with Zero Voltage Switching technique, the turn on loss could be minimized; turn off loss still limits the capability of the converter to operate at higher switching frequency.

Resonant converter, which were been investigated intensively in the 80's [B1]-[B7], can achieve very low switching loss thus enable resonant topologies to operate at high switching frequency. In resonant topologies, Series Resonant Converter (SRC), Parallel Resonant Converter (PRC) and Series Parallel Resonant Converter (SPRC, also called LCC resonant converter) are the three most popular topologies. The analysis and design of these topologies have been studied thoroughly. In next part, these three topologies will be investigated for front-end application.

4.2 Three traditional resonant topologies

In this part, these three topologies will be evaluated for front end DC/DC application. The major goal is to evaluate the performance of the converter with wide input range. For each topology, the switching frequency is designed at around 200kHz.

4.2.1 Series resonant converter

The circuit diagram of a half bridge Series Resonant Converter is shown in Figure 4.1 [B8]-[B13]. The DC characteristic of SRC is shown in Figure 4.2. The resonant inductor Lr and resonant capacitor Cr are in series. They form a series resonant tank. The resonant tank will then in series with the load. From this configuration, the resonant tank and the load act as a voltage divider. By changing the frequency of input voltage Va, the impedance of resonant tank will change. This impedance will divide the input voltage with load. Since it is a voltage divider, the DC gain of SRC is always lower than 1. At resonant frequency, the impedance of series resonant tank will be very small; all the input voltage will drop on the load. So for series resonant converter, the maximum gain happens at resonant frequency.

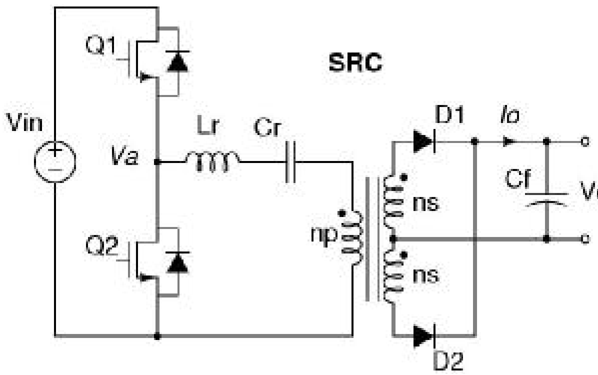

Figure 4.1 Half Bridge Series Resonant Converter

For front end DC/DC application, a SRC is designed to meet the specifications with following parameters:

Transformer turns ratio: 5:2,

Resonant inductance: 37uH,

Resonant capacitance: 17nF.

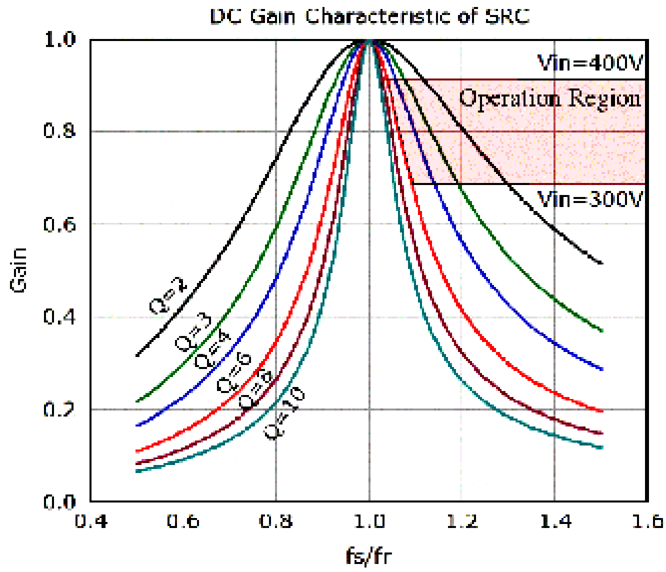

Figure 4.2 DC characteristic and operating region of SRC

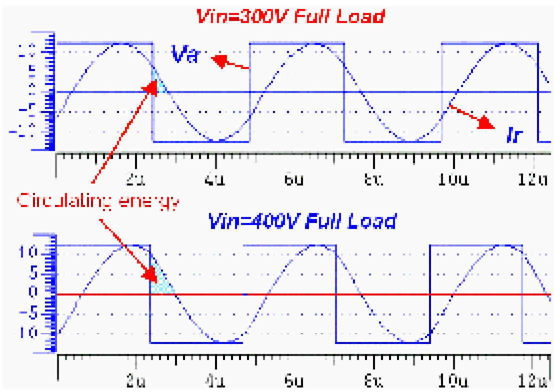

Figure 4.3 Simulation waveforms of SRC

With above parameters, the range of Q is from 6 (Full load) to 0 (No load). With above design, the operating region of the converter is shown in Figure 4.2 as shaded area. Simulation waveform is shown in Figure 4.3. From the operating region graph and simulation waveforms, several things could be observed:

Operating region is on the right side of resonant frequency fr. This is because of zero voltage switching (ZVS) is preferred for this converter. When switching frequency is lower than resonant frequency, the converter will work under zero current switching (ZCS) condition. In fact, the rule is when the DC gain slope is negative; the converter is working under zero voltage switching condition. When the DC gain slop is positive, the converter will work under zero current switching condition. For power MOSFET, zero voltage switching is preferred.

It can be seen from the operating region that at light load, the switching frequency need to increase to very high to keep output voltage regulated. This is a big problem for SRC. To regulate the output voltage at light load, some other control method has to be added.

At 300V input, the converter is working close to resonant frequency. As input voltage increases, the converter is working at higher frequency away from resonant frequency. As frequency increases, the impedance of the resonant tank is increased. This means more and more energy is circulating in the resonant tank instead of transferred to output.

From simulation waveforms, at 300V input, the circulating energy is much smaller than 400V input situation. Here the circulating energy is defined as the energy send back to input source in each switching cycle. The more energy is sending back to the source during each switching cycle, the higher the energy needs to be processed by the semiconductors, the higher the conduction loss.

Also from the MOSFET current we can see that the turn off current is much smaller in 300V input. When input voltage increases to 400V, the turn off current is more than 10A, which is around the same level as PWM converter.

With above analysis, we can see that SRC is not a good candidate for front end DC/DC converter. The major problems are: light load regulation, high circulating energy and turn off current at high input voltage condition.

4.2.2 Parallel resonant converter

The schematic of parallel resonant converter is shown in Figure 4.4 [B14]-[B17]. Its DC characteristic is shown in Figure 4.5. For parallel resonant converter, the resonant tank is still in series. It is called parallel resonant converter because in this case the load is in parallel with the resonant capacitor. More accurately, this converter should be called series resonant converter with parallel load. Since transformer primary side is a capacitor, an inductor is added on the secondary side to math the impedance.

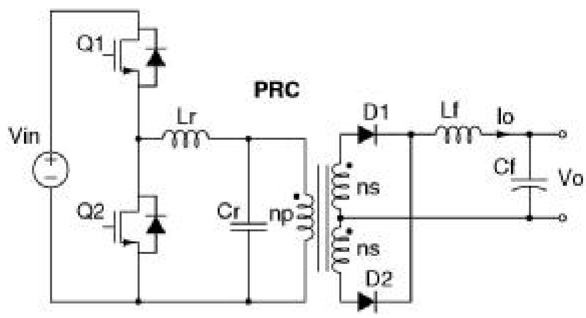

Figure 4.4 Half bridge parallel resonant converter

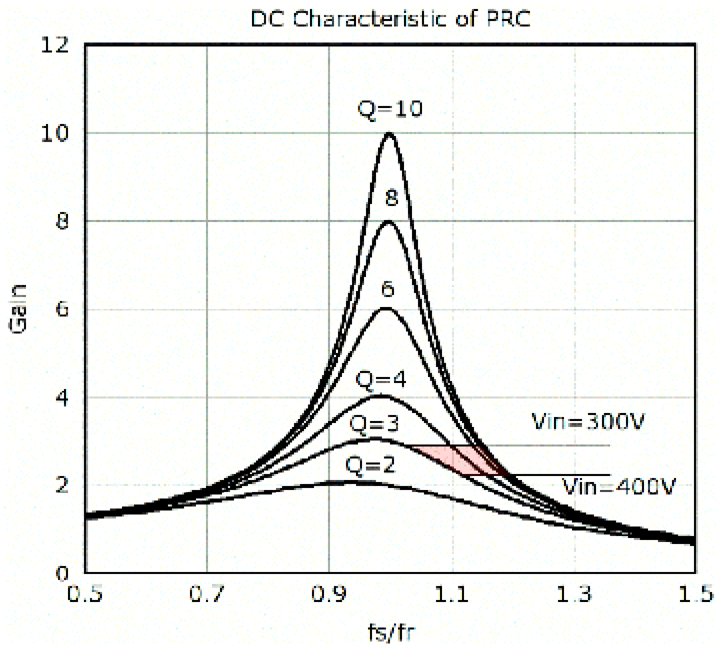

Figure 4.5 DC characteristic and operating region of PRC

The parameters of parallel resonant converter designed for front end DC/DC application are:

Transformer turns ratio: 9:1,

Resonant inductance: 58uH,

Resonant capacitance: 11.7nF.

With above parameters, the range of Q for this converter is 3 (Full load) to ∞ (No load). The operating region of PRC is shown in Figure 4.5 as shaded area. Simulation waveform is shown in Figure 4.6. From the operating region graph and simulation waveforms, several things could be observed:

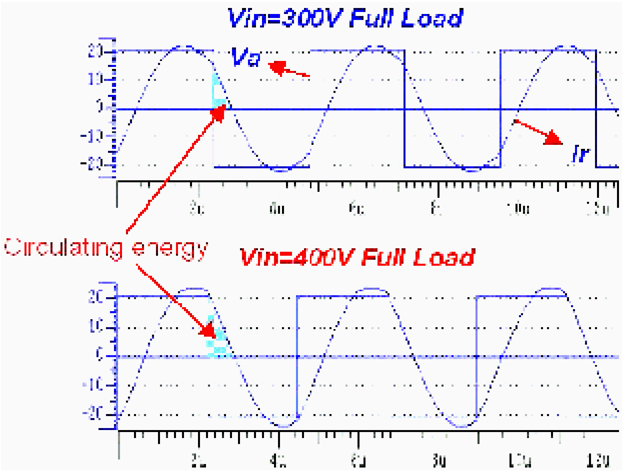

Figure 4.6 Simulation waveforms of PRC

1. Similar to SRC, the operating region is also designed on the right hand side of resonant frequency to achieve Zero Voltage Switching.

Compare with SRC, the operating region is much smaller. At light load, the frequency doesn't need to change too much to keep output voltage regulated. So light load regulation problem doesn't exist in PRC.

Same as SRC for PRC, the converter is working close to resonant frequency at 300V. At high input voltage, the converter is working at higher frequency far away from resonant frequency.

From simulation waveforms, at 300V input, the circulating energy is smaller than 400V input situation. Compare with SRC, it can be seen that for PRC, the circulating energy is much larger. Also from the MOSFET current we can see that the turn off current is much smaller in 300V input. When input voltage increases to 400V, the turn off current is more than 15A, which is even higher than PWM converter.

For PRC, a big problem is the circulating energy is very high even at light load. For PRC, since the load is in parallel with the resonant capacitor, even at no load condition, the input still see a pretty small impedance of the series resonant tank. This will induce pretty high circulating energy even when the load is zero.

With above analysis, we can see that PRC is not a good candidate for front end DC/DC converter too. The major problems are: high circulating energy, high turn off current at high input voltage condition.

4.2.3 Series parallel resonant converter

The schematic of series parallel resonant converter is shown in Figure 4.7 [B18]-[B20]. The DC characteristic of SPRC is shown in Figure 4.8. Its resonant tank consists of three resonant components: Lr, Cs and Cp. The resonant tank of SPRC can be looked as the combination of SRC and PRC. Similar as PRC, an output filter inductor is added on secondary side to math the impedance. For SPRC, it combines the good characteristic of PRC and SRC. With load in series with series tank Lr and Cs, the circulating energy is smaller compared with PRC. With the parallel capacitor Cp, SPRC can regulate the output voltage at no load condition. The parameters of SPRC designed for front end DC/DC application are:

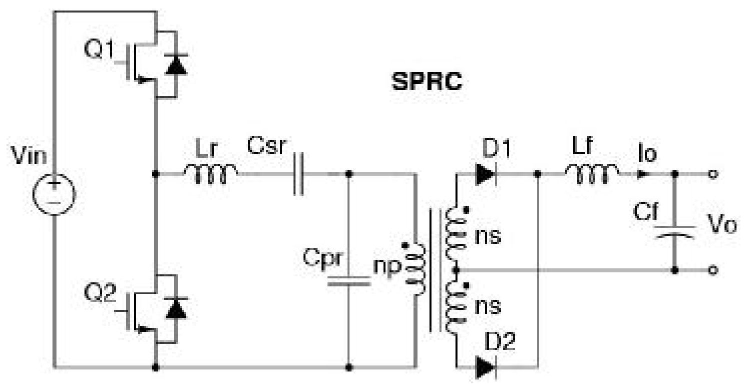

Figure 4.7 Half bridge series parallel resonant converter

Transformer turns ratio: 6:1,

Resonant inductance: 72uH,

Series resonant capacitor Cs: 17.7nF,

Parallel resonant capacitor Cp: 17.7nF,

Range of Q: 1 (Full load) to ∞ (No load)

The DC characteristic and operating region of SPRC are shown in Figure 4.8. Simulation waveform is shown in Figure 4.9. From the operating region graph, several things could be observed:

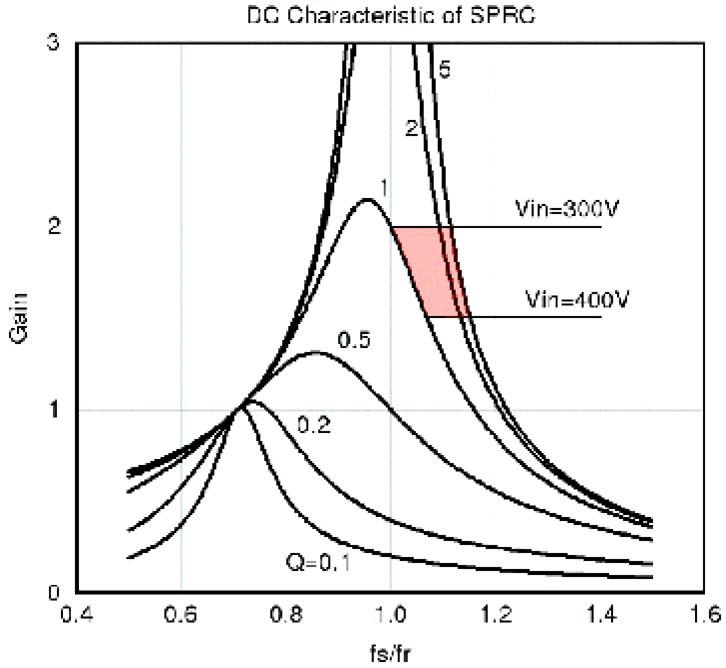

Figure 4.8 DC characteristic and operating region of SPRC

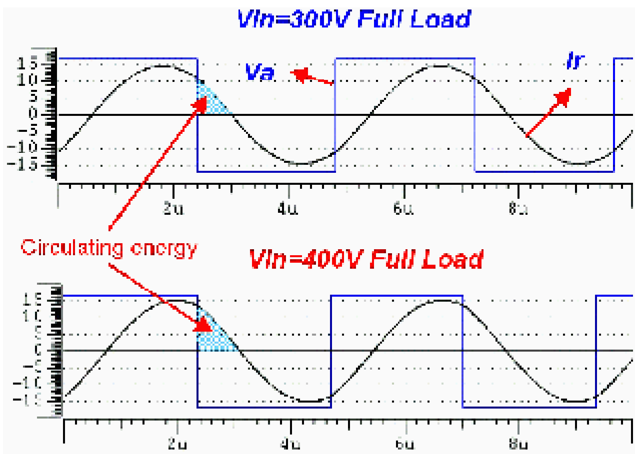

Figure 4.9 Simulation waveforms of SPRC

2. Similar to SRC and PRC, the operating region is also designed on the right hand side of resonant frequency to achieve Zero Voltage Switching.

From the operating region graph, it can be seen that SPRC narrow switching frequency range with load change compare with SRC.

Compare the switching waveforms, the input current in much smaller than PRC and a little larger than SRC. This means for SPRC, the circulating energy is reduced compare with PRC.

Same as SRC and PRC,, the converter is working close to resonant frequency at 300V. At high input voltage, the converter is working at higher frequency far away from resonant frequency.

Same as PRC and SRC, the circulating energy and turn off current of MOSFET also increase at high input voltage. The turn off current is more than 10A.

With above analysis, we can see that SPRC combines the good characteristics of SRC and PRC. Smaller circulating energy and not so sensitive to load change. Unfortunately, SPRC still will see big penalty with wide input range design. With wide input range, the conduction loss and switching loss will increase at high input voltage. The switching loss is similar to that of PWM converter at high input voltage.

By analysis, design and simulation of SRC, PRC and SPRC, the conclusion is that these three converters all cannot be optimized at high input voltage. High conduction loss and switching loss will be resulted from wide input range. To achieve high switching frequency and higher efficiency, we have to look for some other topologies.

4.3 LLC resonant converter

Three traditional resonant topologies were analyzed in above part. From the results, we can see that all of them will see big penalty for wide input range design. High circulating energy and high switching loss will occur at high input voltage. They are not suitable for front end DC/DC application.

Although above analysis give us negative results, still we could learn something from it:

For a resonant tank, working at its resonant frequency is the most efficient way. This rule applies to SRC and PRC very well. For SPRC, it has two resonant frequencies. Normally, working at its highest resonant frequency will be more efficient.

To achieve zero voltage switching, the converter has to work on the negative slope of DC characteristic.

From above analysis, LCC resonant converter also could not be optimized for high input voltage. The reason is same as for SRC and PRC; the converter will work at switching frequency far away from resonant frequency at high input voltage. Look at DC characteristic of LCC resonant converter, it can be seen that there are two resonant frequencies. One low resonant frequency determined by series resonant tank Lr and Cs. One high resonant frequency determined by Lr and equivalent capacitance of Cs and Cp in series. For a resonant converter, it is normally true that the converter could reach high efficiency at resonant frequency. For LCC resonant converter, although it has two resonant frequencies, unfortunately, the lower resonant frequency is in ZCS region. For this application, we are not able to design the converter working at this resonant frequency. Although the lower frequency resonant frequency is not usable, the idea is how to get a resonant frequency at ZVS region. By change the LCC resonant tank to its dual resonant network, this is achievable.

As shown in Figure 4.10, by change L to C and C to L, a LLC resonant converter could be built. The DC characteristics of these two converters are shown in Figure 4.11 and Figure 4.12. The DC characteristic of LLC converter is like a flip of DC characteristic of LCC resonant converter. There are still two resonant frequencies. In this case, Lr and Cr determine the higher resonant frequency. The lower resonant frequency is determined by the series inductance of Lm and Lr. Now the higher resonant frequency is in the ZVS region, which means that the converter could be designed to operate around this frequency.

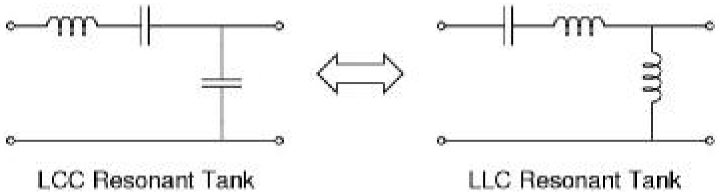

Figure 4.10 LCC and LLC resonant tank

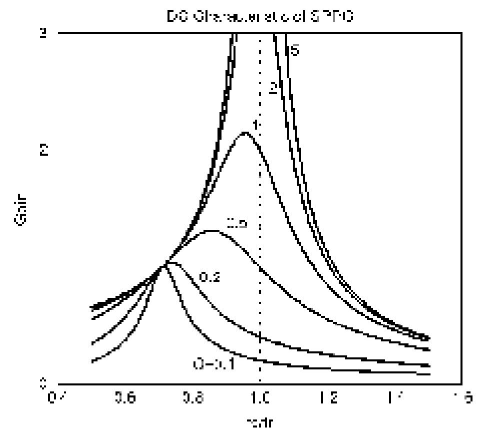

Figure 4.11 DC characteristic of LCC resonant converter

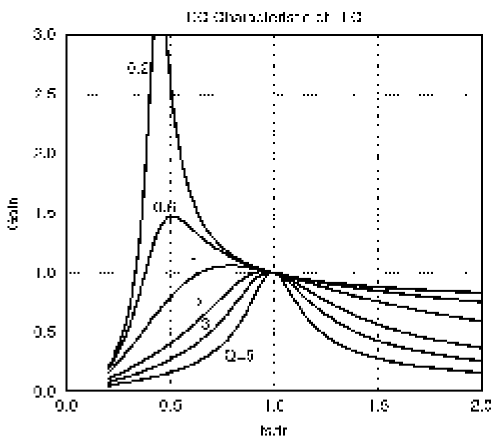

Figure 4.12 DC characteristic of LLC resonant converter

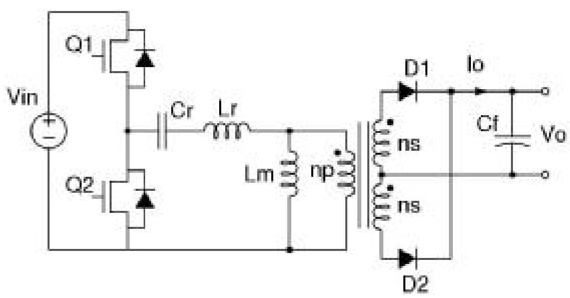

Figure 4.13 Half bridge LLC resonant converter

As a matter of fact, LLC resonant converter existed for very long time [B-10] [B-24]. But because of lack of understanding of characteristic of this converter, it was used as a series resonant converter with passive load. Which means it was designed to operate in switching frequency higher than resonant frequency of the series resonant tank of Lr and Cr. When operating in this region, LLC resonant converter acts very similar to SRC. The benefit of LLC resonant converter is narrow switching frequency range with light load and ZVS capability with even no load.

In this dissertation, some unexplored operating region of LLC resonant converter will be investigated. Within these operating regions, LLC resonant converter will have some very special characteristic, which makes it an excellent candidate for front end DC/DC application.

To design LLC resonant converter, DC analysis is essential. The detailed DC analysis is discussed in Appendix B. Two methods were discussed: fundamental simplification method and simulation method. The error is showed too.

4.4 Operation of LLC resonant converter

The DC characteristic of LLC resonant converter could be divided into ZVS region and ZCS region as shown in Figure 4.14. For this converter, there are two resonant frequencies. One is determined by the resonant components Lr and Cr. The other one is determined by Lm, Cr and load condition. As load getting heavier, the resonant frequency will shift to higher frequency. The two resonant frequencies are:

$$fr1 = \frac{1}{2 \cdot \pi \cdot \sqrt{Lr \cdot Cr}}$$

$$fr2 = \frac{1}{2 \cdot \pi \cdot \sqrt{(Lm + Lr) \cdot Cr}}$$

With this characteristic, for 400V operation, it could be placed at the resonant frequency of fr1, which is a resonant frequency of series resonant tank of Cr and Lr. While input voltage drops, more gain can be achieved with lower switching frequency. With proper choose of resonant tank, the converter could operate within ZVS region for load and line variation.

There are some interesting aspects of this DC characteristic. On the right side of fr1, this converter has same characteristic of SRC. On the left side of fr1, the image of PRC and SRC are fighting to be the dominant. At heavy load, SRC will dominant. When load get lighter, characteristic of PRC will floating to the top. With these interesting characteristics, we could design the converter working at the resonant frequency of SRC to achieve high efficiency. Then we are able to operate the converter at lower than resonant frequency of SRC still get ZVS because of the characteristic of PRC will dominant in that frequency range.

From above discussion, the DC characteristic of LLC resonant converter could be also divided into three regions according to different mode of operation as shown in Figure 4.15. Our designed operating regions are region 1 and region 2. Region 3 is ZCS region. The converter should be prevented from entering region 3. The simulation waveform for region 1 and region 2 are shown in Figure 4.16 and Figure 4.17. In fact, there are many other operating modes for LLC resonant converter as load changes. Those different modes are listed in Appendix B.

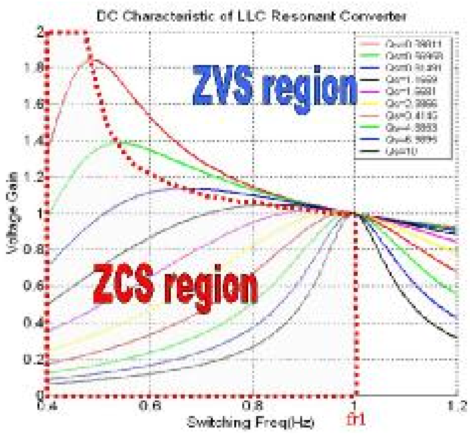

Figure 4.14 DC characteristic of LLC resonant converter

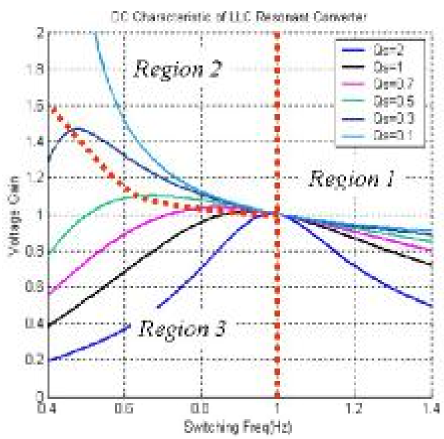

Figure 4.15 Three operating regions of LLC resonant converter

In region 1, the converter works very similar to SRC. In this region, Lm never resonates with resonant capacitor Cr; it is clamped by output voltage and acts as the load of the series resonant tank. With this passive load, LLC resonant converter is able to operate at no load condition without the penalty of very high switching frequency. Also, with passive load Lm, ZVS could be ensured for any load condition. Here the operation will not be discussed in detail. There are several other modes of operation for light load condition. They will be discussed in Appendix B.

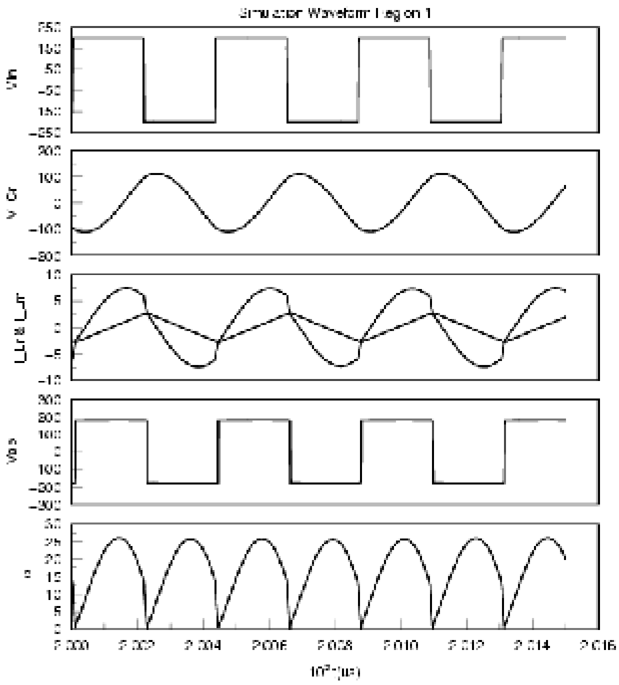

Figure 4.16 Simulated operation waveforms in region 1

In region 2, the operation of LLC resonant converter is more complex and interesting. The waveforms could be divided into clearly two time intervals. In first time interval, Lr resonant with Cr. Lm is clamped by output voltage. When Lr current resonant back to same level as Lm current, the resonant of Lr and Cr is stopped, instead, now Lm will participate into the resonant and the second time interval begins. During this time interval, the resonant components will change to Cr and Lm in series with Lr, which is shown in the waveforms as a flat region. In fact, that is a part of the resonant process between Lm+Lr with Cr. From this aspect, LLC resonant converter is a multi resonant converter since the resonant frequency at different time interval is different. Because of the resonant between Lm and Cr, a peak on the gain appears at resonant frequency of Lm+Lr and Cr. Next the operating of LLC resonant converter in region 2 will be discussed in detail. It is divided into three modes.

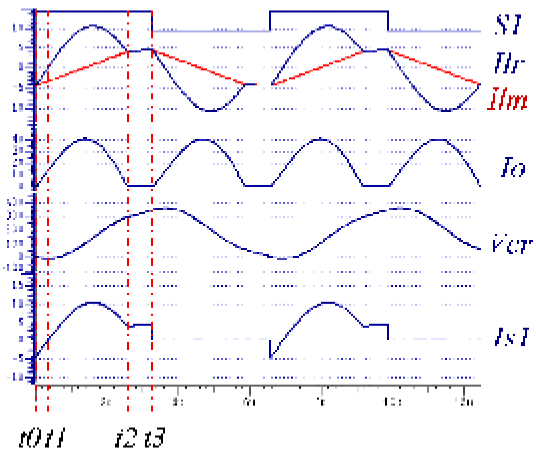

Figure 4.17 Simulation waveforms in region 2

Mode 1 (t0 to t1):

This mode begins when Q2 is turned off at t0. At this moment, resonant inductor Lr current is negative; it will flow through body diode of Q1, which creates a ZVS condition for Q1. Gate signal of Q1 should be applied during this mode.

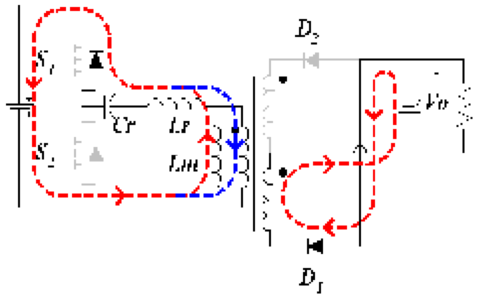

Figure 4.18 Circuit diagram during mode 1 in region 2

When resonant inductor Lr current flow through body diode of Q1, I_{Lr} begins to rise, this will force secondary diode D1 conduct and Io begin to increase. Also, from this moment, transformer sees output voltage on the secondary side. Lm is charged with constant voltage.

Mode 2 (t1 to t2)

This mode begins when resonant inductor current I_{Lr} becomes positive. Since Q1 is turned on during mode 1, current will flow through MOSFET Q1.