LLC Resonant Converter for Front End DC/DC Conversion

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Abstract - **A new LLC resonant converter is proposed for Front End DC/DC conversion in Distributed Power System. Three advantages are achieved with this resonant converter. First, ZVS turn on and low current turn off of MOSFETs are achieved. The switching loss is reduced so we can operate the converter at higher switching frequency. Second advantage is that with this topology, we can optimize the converter at high input voltage. And last advantage is that with this topology, we can eliminate the secondary filter inductor, so the voltage stress on secondary rectifier will be limited to two times the output voltage, better rectifier diode can be used and secondary conduction loss can be reduced. The converter utilizes leakage and magnetizing inductance of a transformer. With passive IPEM concept, all the passive components and transformer can be build in one magnetic core. The operation and characteristic of this converter is introduced and efficiency comparison between this converter and conventional PWM converter is given which shows a great improvement by using this topology.**

I.   INTRODUCTION

The increasing efforts on pushing to high power density and high efficiency DC/DC converter has lead us to develop converters capable of operating at higher switching frequency with high efficiency. For this reason, resonant converters have drawn lot of attentions due to high efficiency, high switching frequency and high power density. Lots of paper talked about the characteristics and analysis of series resonant converter (SRC) and parallel resonant converter (PRC). Each of those converters has its pros and cons. For example, for SRC, light load output voltage regulation is always a problem for the control design. For PRC, circulating energy will hurt the high line or light load efficiency.

Distributed Power System (DPS) is widely adopted in computer and communication systems because of its high efficiency, high reliability and flexibility. The well-accepted DPS structure is shown in Fig. 1. The front-end converter includes Power Factor Correction (PFC), which provides a 400V intermediate bus, and Front-End DC/DC converters, which convert the 400V DC to an isolated 48V DC bus. For front end DC/DC converter, 1kW module is the most popular power level. One of the front-end DC/DC

converter requirements is wide input range (300V to 400V). The circuit normally works under high input voltage, which is 400V. During hold up time, the input voltage of front end DC/DC converter will drop to 300V. Optimized design should have higher efficiency at high input voltage. This special requirement imposes lot of difficulties on the design of front-end DC/DC converter, since for many PWM topologies the efficiency will drop at high input voltage.
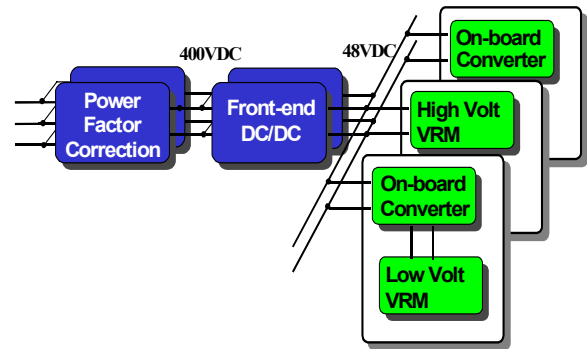

Figure 1 Structure of Distributed Power System

This paper proposed a novel LLC resonant converter. This converter is a three elements resonant converter with two resonant inductors and one resonant capacitor. The advantages of this converter are very low switching loss, high efficiency at high input voltage and low voltage stress on secondary rectifier. This converter can be designed with higher efficiency and high frequency. The two resonant inductors can be realized with leakage and magnetizing inductance of the transformer. Further more, the resonant capacitor can be integrated into transformer with passive IPEM concept. In this paper, the operation and characteristic is discussed. Efficiency is compared between LLC resonant converter and other PWM converters with simulation. It can be seen that this converter offers very good performance.

II.   A NOVEL LLC RESONANT CONVERTER

Figure 2 shows circuit diagram of LLC resonant converter. The circuit has three passive components, Lr, Cr and Lm. The secondary side is a full wave rectifier followed by a capacitive filter. The inverter part of this

diagram is a Half Bridge configuration; in fact, this part can be half bridge with voltage splitting cap, full bridge or other topologies. Since there is a capacitor in series with power train, automatic flux balancing can be achieved. In this converter, two resonant frequencies exist. One is the resonant frequency of Lr and Cr, another one is the resonant frequency of (Lm+Lr) and Cr. The converter is operated between those two resonant frequencies. MOSFET Q1 and Q2 are ZVS turn on and turn off at small current, which is decided by inductance Lm, and this characteristic is load independent. Since there is no inductor at secondary side, the voltage of stress of diode D1 and D2 is clamped to two times output voltage at all load range and input voltage range. In this topology, Lr and Lm are at the exactly position of leakage and magnetizing inductance of a transformer. So we can realize Lr and Lm with transformer leakage and magnetizing inductance. This way, the converter can have very few components number and high power density.
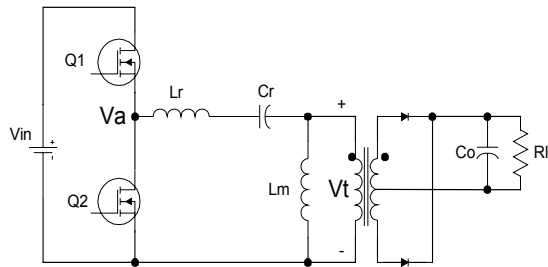

Figure 2 LLC resonant converter

Figure 3 shows the simulation waveform of LLC resonant converter. The waveforms are resonant tank input voltage Va, series resonant inductor Lr current I_Lr; magnetizing inductor Lm current I_Lm, output current Io and transformer primary voltage Vt. The operation can be divided into three modes.

Mode 1 (t0 to t1): At t0, Q2 is turned off, resonant inductor current flow through the body diode of Q1. Resonant tank voltage change polarity. Resonant inductor current and magnetizing current begin increase. The increase rate of resonant inductor current I_Lr is higher than I_Lm. Series resonant between Lr and Cr begins. Output current begins to increase. Since during this mode, the body diode of Q1 is conducting, Q1 can be ZVS turned on during this mode.

Mode 2 (t1 to t2): The time duration of this mode is close to half the resonant period of Lr and Cr. During this mode, the voltage on magnetizing inductor is clamped to output voltage since output rectifier is conducting. At t2 point, resonant tank current I_Lr equals to magnetizing current I_Lm. Output current reach zero.

Mode 3 (t2 to t3): At t2, the two inductor current I_Lr and I_Lm equals. The voltage on transformer primary side drops to lower than output voltage. Both of the output rectifier diodes see reverse voltage. So during this period,

output current is discontinue. Magnetizing inductor Lm plus resonant inductor Lr resonant with Cr. Since Lm is much larger than Lr, this resonant frequency is lower than resonant frequency during mode 2. At t3, Q2 is turned off with magnetizing current so turn off loss is very small too.

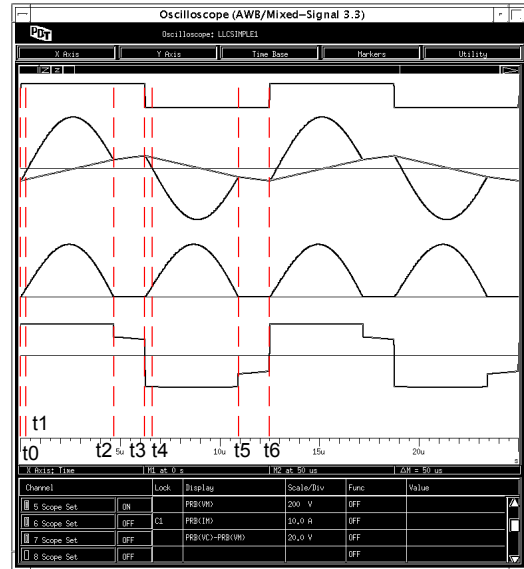Then the next three modes are similar to Mode 1,2 and 3.

Figure 3 Simulation waveform of LLC Resonant Converter

From the simulation waveform we can see, the MOSFETs are turned on with ZVS. At the turn off point of MOSFET as t3 and t6, the current is much smaller than load current, so we can reduce the turn off loss. Also, the secondary side diode current reduce to zero and stay off, the reverse recovery is eliminated also. So the switching loss in this circuit is very small, it means we can operate this converter at high frequency.

To understand and design the LLC resonant converter, DC characteristic is important. Analysis of this kind of three elements resonant converter is quite complex. In traditional method, assumption like Fundamental Element Simplification (FES) was made to simplify the analysis, which is not suitable for this circuit. In this paper, we use simulation to analysis the converter. Our method is to do frequency sweep at different load, at each point, we run the simulation to get a steady state operation and record the circuit condition. With reasonable simulations, we can get the characteristics curves of the converter. The simulation software used in this paper is Simplis by Power Design Tool. This software has a POP function, which can find the steady state operation point of a converter in very short time. With this function, we are able to run hundreds of simulation in reasonable time.

Figure 3 shows the DC characteristic of LLC resonant converter get from simulation. The frequency f1 and f2 in the picture are defined as following:

$$f1 = \frac{1}{2\pi\sqrt{LrCr}}$$

$$f2 = \frac{1}{2\pi\sqrt{(Lr+Lm)Cr}}$$

Observe the DC characteristic of the LLC converter; we can see that the peak of the gain happens close to the resonant frequency of f2. The resonant frequency f1, which is the resonant frequency of Lr and Cr is not observable in the characteristic picture. Another thing interesting is that for this converter, the gain characteristic is like a Boost, instead of Buck function of ordinary SRC. Operate the converter within frequency range f1 and f2 can give us load independent low switching loss and high efficiency at high input voltage. Also, the voltage gain of the converter is insensitive to load change also. These characteristics make this converter attractive and prospective for front end DC/DC application.
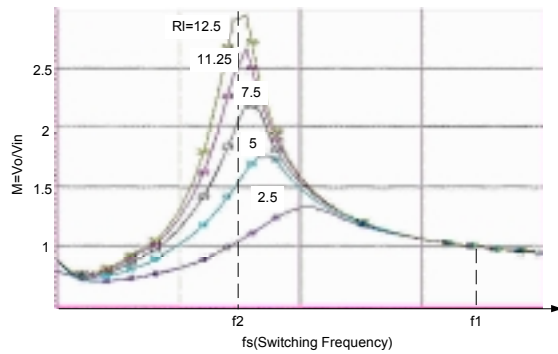

Figure 4 DC characteristic of LLC Resonant Converter

To design a LLC resonant converter, there are three resonant elements to design. There are lots of trade offs in this design. In this paper, we are not going to go to this topic. Next part of the paper, we will just show the efficiency comparison between LLC resonant converter and PWM converter.

III. EFFICIENCY COMPARISON

In this part, the efficiency of LLC resonant converter is compared with Asymmetrical Half Bridge. Asymmetrical Half Bridge is choosing as candidate because this topology is simple and high efficiency. Comparison is based on simulation. We build the circuit model for both converters in Simplis base on same design specs. Figure 5 shows the three topologies been compared. The design specs for both converters are:

Vin=300 to 400V, Vout=48V and Pout=1kW, switching frequency for PWM 100kHz and switching frequency for LLC is from 80kHz to 120kHz.

We choose this frequency because for the PWM converter, most of the designs now are around this frequency. When we increase the switching frequency, the results will be more favorable to LLC resonant converter

since the switching loss in LLC resonant converter is much less than PWM converter.

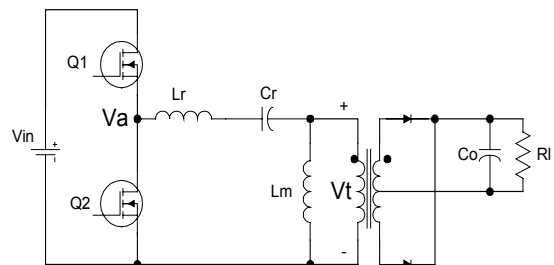The devices we used for two converters are:

Primary switches: IXFN21N50 500V 21A MOSFET

Asymmetrical Half Bridge secondary rectifier: RHRG1540, 400V ultra fast diode, forward voltage drop 1.7V.

LLC resonant converter secondary rectifier: IXYSS20-015A, 150V shottoky diode with forward voltage drop 0.72V.
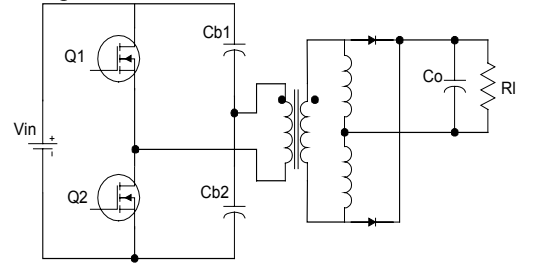
Asymmetrical Half Bridge with Current Doubler

LLC Resonant Converter

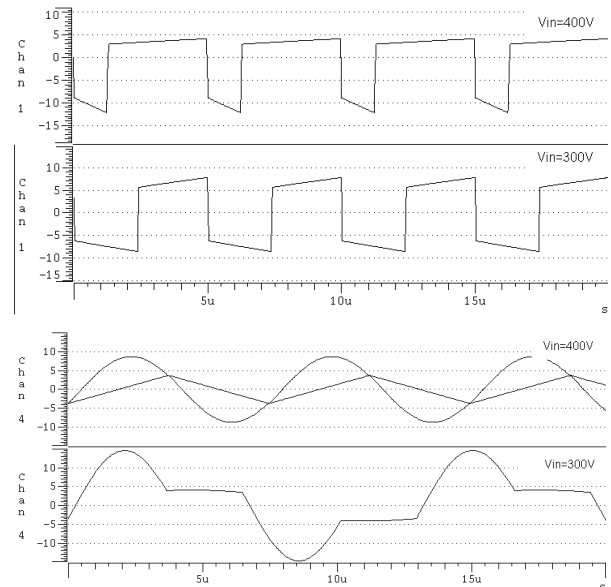Figure 5 Circuit diagrams for Efficiency Comparison

Figure 6 Simulated input current waveform of Asymmetrical Half Bridge and LLC resonant converter at different input voltage

Figure 6 shows the simulated input current waveform for two converters at different input voltage at full load. We can see that for Asymmetrical Half Bridge converter, the current waveform is highly asymmetrical at high input voltage. This will increase both the conduction loss and switching loss when the converter works in this condition. So the efficiency of the converter will be hurt by wide input range. This asymmetrical duty cycle will also increase the voltage stress of the secondary rectifier. This increase of voltage stress will make the choosing of rectifier diode very difficult since high voltage diode's conduction loss is high.

For LLC resonant converter, we can see that at high input voltage, the input current have lower peak value and RMS value, so the conduction loss is much lower at high input voltage. Also, the secondary side voltage stress is fixed at two times output voltage in this converter, so we can use lower voltage diode. This will reduce the conduction loss a lot.

For resonant converter, high current stress or voltage stress is always a concern since the increase of conduction loss will compensate the benefit get from reduced switching loss. In the front-end converter, the secondary conduction loss is dominant. Since we are using diode rectifier, so the conduction loss doesn't increase so much when the average current is constant. So the conduction loss will not increase so much.

Figure 7 shows the primary conduction loss comparison. This figure is based on the simulated data. Because for PWM converter, at high input voltage, the duty cycle is small, so the RMS current is even higher than LLC resonant converter. When the input voltage decrease, the duty will become more symmetrical and the resonant converter will show higher RMS current and higher conduction loss. But this is not a problem for this case since our normal working condition input voltage will be within 360V to 400V. Only during fault condition would the circuit work at so low input voltage. So even with LLC resonant converter, the increasing of conduction loss is not a problem.

Figure 8 shows the primary switching loss comparison of Asymmetrical Half Bridge and LLC resonant converter based on the datasheet. We can see that the switching loss of LLC is 60% lower than PWM converter. With higher switching frequency, the difference will be significant in the total loss.

From previous discussion we already know that the voltage stress on the secondary rectifier in LLC resonant converter is lower than asymmetrical half bridge. For PWM converter, the highest voltage stress on secondary diode will be higher than 300V. We have to use 400V diode. For LLC converter, the voltage stress is limited to two times output voltage, so 150V shottkey diode can be used. For our comparison, RHRG1540, which has forward voltage drop of 1.7V, is used for PWM converter. For LLC

converter, we choose IXYSS20-013A, which has forward voltage drop of 0.72V. This will reduce the secondary conduction loss from 34W to 14.4W. This means 2% efficiency improvement.
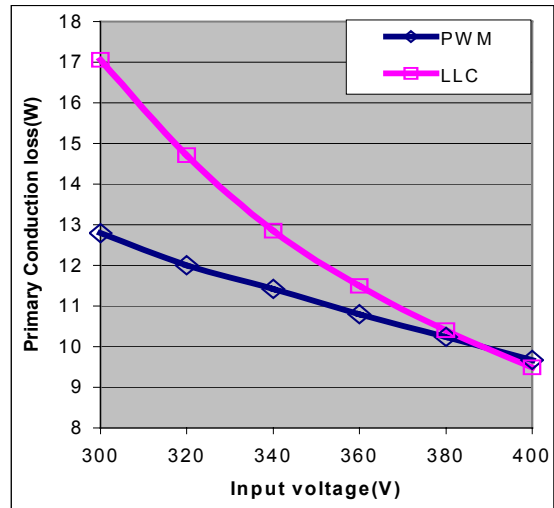

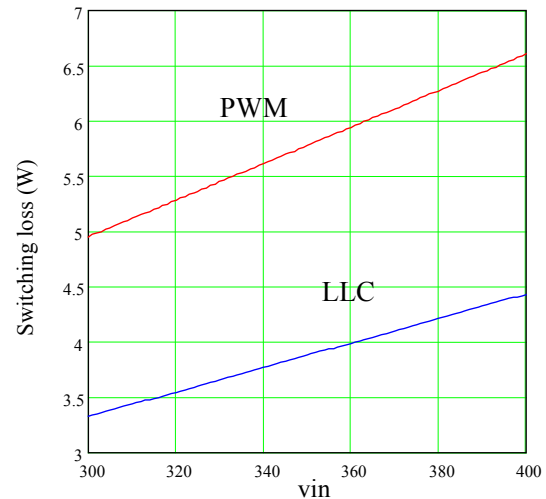Figure 7 Primary conduction loss comarison

Figure 8 Primary side switching loss comparison

Another thing we didn't put here is the rectifier diode reverse recovery loss. In PWM converter, the diode turns off at very high current; this will cause very high reverse recovery loss. In LLC resonant converter, since the diode current resonant to zero, this part of loss will be much smaller also.

From above analysis we can see that for LLC resonant converter, the conduction loss and switching loss is low compare with Asymmetrical Half Bridge Converter. With low switching loss, this converter is able to operate at higher switching frequency.

IV. CONCLUSION

In this paper, a novel LLC three elements resonant converter is proposed. Operation modes of the converter are discussed. DC characteristic of the converter is generated with simulation tool. This converter can achieve high efficiency at high input voltage. Besides of very low switching loss, the conduction loss of this converter is lower than PWM converter because of the elimination of secondary filter inductor. The efficiency comparison of this converter with asymmetrical half bridge shows that this converter can get 2 to 3% improvement on the efficiency.

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