Chapter 7

Summary and Future Work

The fast advance in VLSI technology made smaller, more powerful systems available. At the same time, it calls for high power density, and low profile power system. To achieve these goals, high switching frequency, high efficiency, and advanced packaging technology are the paths. It is the goal of this work to develop technology to meet and exceed these challenges.

7.1 Summary

PWM topologies like asymmetrical half bridge and phase shift full bridge have been widely used for front end DC/DC application. For these topologies, two aspects limited the power density and efficiency. One is high switching loss related to high turn off current. The other one is the problem with hold up time requirement. With hold up time requirement, the input range of front end DC/DC converter is very wide. Performance at high input voltage is essential for the power density of the system since the thermal management is designed according to high input voltage performance. For PWM converter, with wide input range, the duty cycle at high input voltage will be minimal. This will cause many problems: high conduction loss, high voltage stress on semiconductor devices, and high switching loss. With wide input range, the performance at high input voltage is severely impacted.

7.1.1 Improvement of the state of the art topologies

The primary target is to deal with hold up time problem. Two methods were discussed to solve this problem: range winding solution and asymmetrical winding solution.

For range winding solution, extra components and windings are needed. With range winding, converter could be optimized for a much narrower input range so that the performance at high input voltage could be optimized. During hold up time, range winding will provide enough gain to work with low input voltage. This method could be applied to any isolated PWM topologies with similar issue.

For asymmetrical half bridge, asymmetrical winding solution is a simple and effective solution. With asymmetrical winding, the DC characteristic of asymmetrical half bridge could be modified. The duty cycle at high input voltage could be extended. With extended duty cycle, lower voltage rated devices could be used. This will provide significant improvement on the efficiency. This method could only be applied to asymmetrical half bridge.

Secondary conduction loss is the biggest part in total system loss, which is caused by the high forward voltage drop of rectifier. Synchronous rectifier has been widely used in low voltage high current application because of this problem.

For front end DC/DC application, it is not so straightforward. Because of high voltage stress on the rectifier, high voltage devices are needed. When voltage rating is higher than 200V, it is difficult to find a MOSFET could outperform diode rectifier. To use 200V devices, symmetrical half bridge is chosen. Another obstacle is the reverse recovery of the body diodes of synchronous rectifier. For 200V MOSFET, the body diodes are pretty slow. It will introduce high current spike and ringing which is both dangerous and noisy. Quasi-square-wave synchronous rectification is introduced to solve this problem. With QSW operation mode, the conduction of body diodes is totally prevented. It also helps symmetrical half bridge to achieve ZVS for primary switches. This concept could be used to other application with body diode reverse recovery problem too.

7.1.2 LLC resonant converter

Although above solutions could improve the efficiency of PWM converter. None of them deals with high turn off loss of the switches, which limit the switching frequency, as the result, limit the power density achievable for PWM topologies.

Resonant topologies are well known for its low switching loss. Three popular resonant topologies, SRC, PRC and SPRC, were investigated for front end DC/DC application. Unfortunately, all these topologies see big penalties when design for hold up requirement. There is no significant improve of performance compared with PWM topologies.

Although negative outcome of above analysis, the desired characteristic for front end DC/DC application could be extracted, which enable the converter working at resonant frequency at high input voltage. Three components resonant tanks were searched thoroughly. Among 15 three components resonant tanks suitable for voltage source input, resonant tank with two inductors and one capacitor seems could provide the desired characteristic.

With the resonant tank, LLC resonant converter could be constructed. It is not a new topology. But the unique operating mode of this topology enable it to be optimized at high input voltage while is able to cover wide input range at the same time. Compare with PWM topologies, LLC resonant converter could reduce 40% loss at same switching frequency.

7.1.3 DC analysis of LLC resonant converter

To design LLC resonant converter, DC analysis is performed. Two methods, fundamental component simplification and simulation, were used and compared. Fundamental component simplification method is simple to use and could provide the intuitive results. The problem is that when switching frequency is away from resonant frequency the error will be significant, which will prevent us to achieve optimized design. This calls for simulation method, which could provide very accurate characteristic, but with longer time to perform. To achieve optimized design, simulation method is recommended.

7.1.4 Magnetic integration and over load protection

To achieve high power density, magnetic design is very critical. Integrated magnetic can reduce the volume of magnetic components with proper design. The common problem of integrated magnetic structure is not easy to manufacture. A novel integrated magnetic structure for LLC resonant converter is proposed. With this structure, all the magnetic components of LLC resonant converter could be integrated into one magnetic structure. There is no special gapping needed, which make the structure easy to manufacture and mechanically stable. Flux ripple cancellation is also achieved with proposed integrated magnetic structure. Compare with discrete design, 30% reduction on footprint could be expected.

Over load condition is a common fault condition for power converter. To make practical use of a topology, it has to be able to deal with over load situation. For LLC resonant converter, it is working close to resonant frequency; the impedance of resonant tank is very small. This makes over load protection very important function. Three methods could be used to provide over load protection for LLC resonant converter: increasing switching frequency, variable frequency plus PWM control and clamped LLC converter. First two methods is through active control the switches to change the input voltage or the impedance of resonant tank to limit the current during over load condition. The clamped LLC converter uses clamping diodes on resonant capacitor. With clamping diodes, energy could be passed through resonant tank is limited, which will limit the stress during over load condition.

7.1.5 Small signal analysis of LLC resonant converter

With above discussion, the power stage of LLC resonant converter could be designed. To complete the system, feedback control is needed to provide a regulated output. Small signal characteristic of LLC resonant converter is needed to perform this task. For resonant converter, state space averaging method is no longer valid. Two methods were used to reveal this mystic: time domain simulation method and extended describing function method.

Time domain simulation method is based on switching circuit model. The method tries to emulate the function of network analyzer. This method made no simplification. As long as the switching circuit model is accurate, the result will be very close to the real circuit. Extended describing function method is a mathematical method based on describing function method for nonlinear system. With describing function method, more detailed information about the system could be revealed. This method could take any harmonic components of switching frequency into consideration. With these two methods, small signal characteristic of LLC resonant converter is investigated for different switching frequency and load condition.

For the small signal characteristic of LLC resonant converter, there are several interesting phenomenon. When switching frequency is higher than series resonant frequency, the converter acts very similar to SRC. Between series resonant frequency and low frequency resonant frequency, small signal characteristic is more stable compare with previous region. With load change, the change on small signal characteristic is similar to those could be observed in PWM converter, split of double pole could be observed. With information about small signal characteristic of the converter, compensator could be designed.

With the knowledge from this work, LLC resonant converter could be designed for given specifications. From the prototypes built in CPES, LLC resonant converter shows great improvement in efficiency and power density. Compare 200kHz switching frequency design, LLC resonant converter could improve efficiency by more than 3%. Power density could be improved by almost 100%. With 400kHz design of LLC resonant converter, the power density could be improved by more than 200% compare with asymmetrical half bridge converter.

7.2 Future work

7.2.1 Passive integration for LLC resonant converter

Passive components are often the limitation on volume, and cost of the system. For LLC resonant converter, with integrated magnetic technology, all magnetic components could be integrated into single magnetic structure. With planar magnetic, the resonant capacitors could also be integrated into magnetic structure. This way, all the passive components except output cap could be integrated. This integration will provide many benefits: high density, less interconnection, better electric performance.

With passive integration, more complex resonant tank structure could be constructed. With more complex structure, other benefits could be expected as shown in Figure 7.1, Figure 7.2, and Figure 7.3. With another branch in resonant tank, the primary RMS current could be reduced.

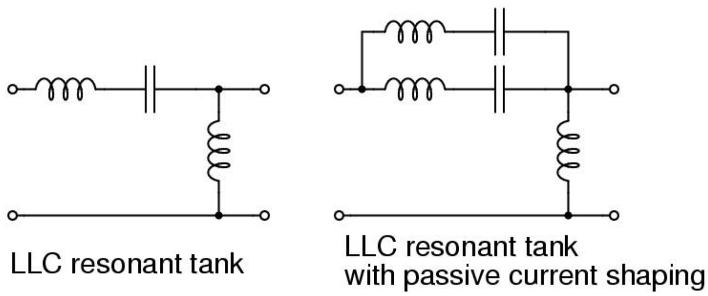

Figure 7.1 LLC resonant tank and LLC resonant tank with passive current shaping

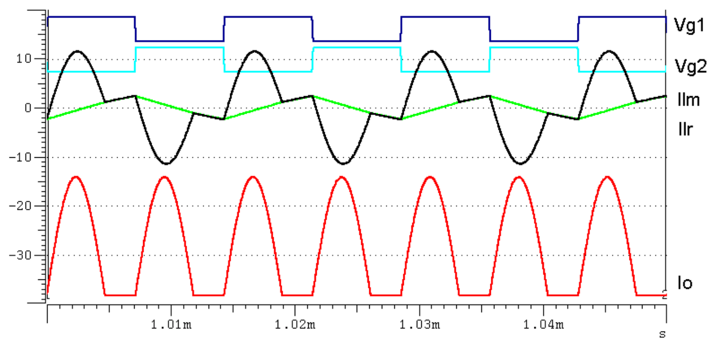

Figure 7.2 Simulation waveform of LLC resonant converter

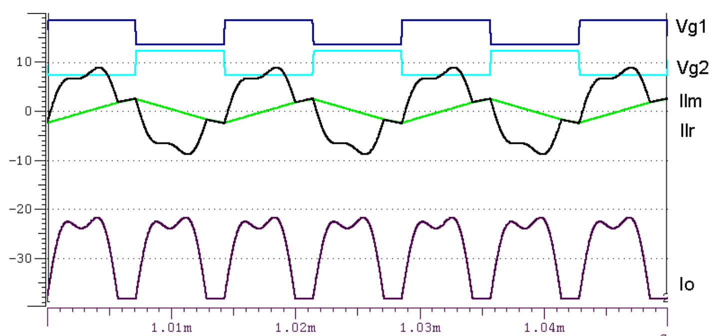

Figure 7.3 Simulation waveform of LLC resonant converter with passive current shaping

7.2.2 LLC resonant converter for other application

The most significant benefit of LLC resonant converter for front end DC/DC application is that it could be optimized for high input voltage. In fact, other than this, there are several other benefits. First, the voltage stress on the secondary rectifier is minimized to two times output voltage only. Second, the output rectifier commutates naturally, there is no reverse recovery problem. Third, switching loss of LLC resonant converter could be minimized. Fourth, without output filter inductor, the transient of LLC resonant converter could be very fast. With all these advantages, LLC resonant converter is a possible candidate for other applications like isolated point of load converter too.

Higher frequency operation of LLC resonant converter

With LLC resonant converter, switching loss could be minimized. By control magnetizing inductance Lm, switching loss could also be controlled. This gave us opportunity to push to higher switching frequency. For some state of the art magnetic material, the optimal operating frequency could be as high as MHz. LLC resonant converter enable us to utilize these new material in front end application. The issue is how to trade off the design between magnetic loss, volume and operating region of the system.

7.2.3 Small signal modeling of resonant converter

In this work, the small signal characteristic of LLC resonant converter is been revealed. Still, a simple and easy to use model is not available yet, which is a major obstacle for people to accept and appreciate this topology. With extended describing function method, it is possible to get an equivalent small signal circuit model when only first order harmonic of switching frequency is considered. Unfortunately, third or even fifth harmonic are needed to model LLC resonant converter. There is still need to develop method to derive simple circuit model for this kind of topologies.