Chapter 1.

Introduction

1.1 Background and Objectives

With fast advance in very large-scale integrated circuit (VLSI) technology, more and more transistors can be integrated into smaller silicon chips. As a result, more powerful, compact digital systems are becoming available. At the same time, these exciting changes in VLSI also imposed exciting challenges on power management for these digital systems. The challenges come from several aspects of changes in digital system. First, as more and more transistors are integrated into the integrated circuit chip, the power required to operate the chip is increasing very rapid. Second, with the transistors working at higher frequency, the supply voltage is reducing with fast transient speed and tight regulation requirement. Third, as VLSI technology is moving very fast, the power management requirement is becoming a fast moving target.

Distribute power system (DPS) as shown in Figure 1.1, is been widely used for server and telecom power systems which represents the most advanced digital systems. In a distributed power system, power is processed by two stages. First stage converts AC input to 48V intermediate DC bus. This DC voltage is then distributed to the load side. The load converter, which is located on the load side, processes the power second time by converting DC distribution bus to whatever voltage needed by the load.

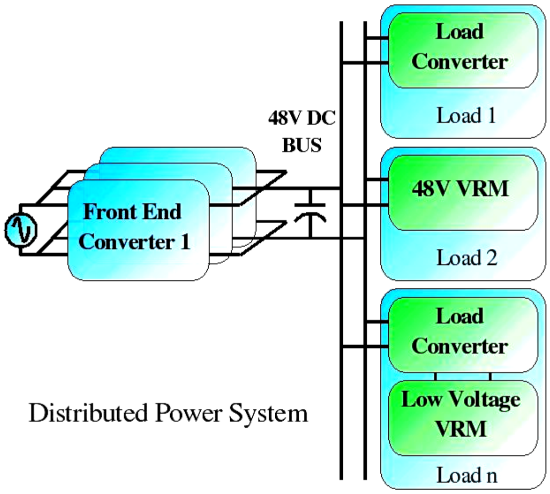


Figure 1.1. Distributed power system structure

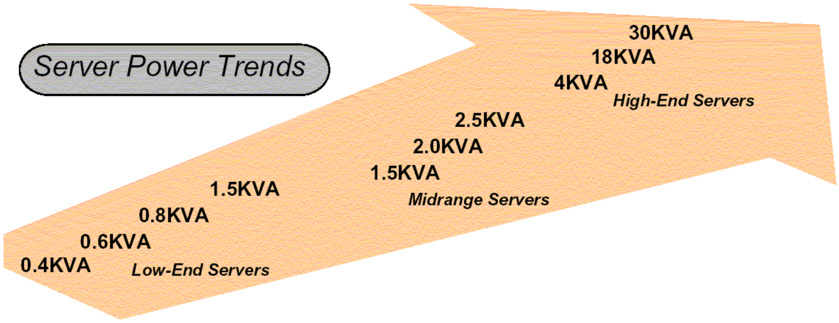
Many advantages of distributed power system prompted its use in these applications. First, with fast dropping on supply voltage of digital system, it is not realistic to delivery the power with such low voltage. DPS uses much high voltage to distribute power. This greatly reduces the loss associated with power distribution. Second, since the second stage (load converter) is placed very close to the load. The impact of parasitic is minimized. This converter can have very fast transient response to provide the fast current slew rate to the load. Third, for a distributed power system, front-end converter is independent of the load requirement. Each load converter is also independent to other load. This provides significant benefit for the fast changing system requirement. With distributed power system, when technology changes, only the load converter associated with that load need to be redesigned, the impact on whole system is minimized.

Beside these aspects, DPS also provides other benefits. First, DPS is an open architecture, modularized solution. The power system can be reconfigured as load system been expended or upgraded. It is a system which can grow as needed. Second, with modularized design, high reliability can be achieved with N+1 redundancy [A7].

Because of these advantages of DPS, it is been widely adopted for different applications [A4][A5][A6][A8]. DPS is been adopted exclusively in high end sever system and telecommunication system. Even for the most cost sensitive application like Personal Computer, DPS concept is been partly adopted. For today's personal computer, a hybrid power system is used. For critical components like CPU and Video Adapter, the distributed power system concept is used. For less critical components like modem-card or network-card, it still use centralized power system structure. With increased clock speed, very soon the memory will also have dedicated power supply. More DPS structure could be expected.

Although for DPS, the front-end converter is not so closely related to the load, still other aspects of the load requirement imposes lot of new challenges to the front-end converter. The major impacts come from following aspects. First, as integration level increases with surprising speed, more and more transistors are integrated to the system with faster switching frequency. The digital system is becoming more and more power hungry and compact. As a supporting subsystem, people tend to give fewer budgets for the power supply system. So the requirement for the power system is to provide higher power with smaller volume. Another significant difference, which is driving the industry, is the profile. For the digital system, all the components now can be build with very low profile. So people expect to build the system with low profile too. With lower profile, more computational power could be build into smaller rack; this will reduce the system and maintains cost. This calls for a power supply to have compatible profile with digital components. Traditional systems normally have a profile of 1.5U to 2U (1U=1.75inch), now the industry is moving toward 1U power system. These trends could be observed in Figure 1.2, Figure 1.3 and Figure 1.4.

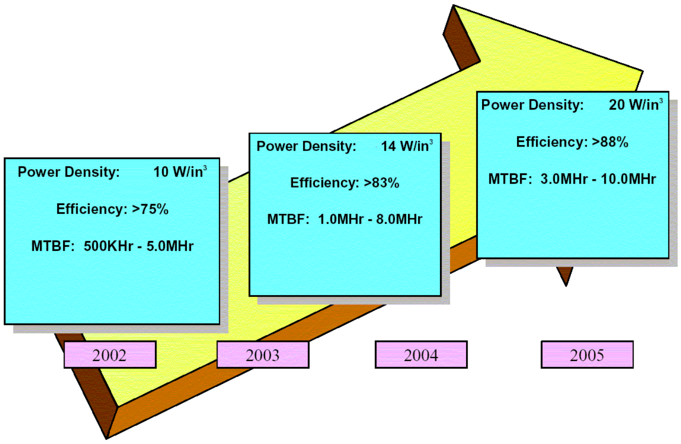
In Figure 1.2 [A1], the trend for computer server system power requirement is shown. For high-end server system, the power level will increase by factor of 6 in recent 5 years.



(From IBM Power Technology Symposium 2002, by Dr. Thai Q. Ngo, IBM)

Figure 1.2. Trend for server system power level

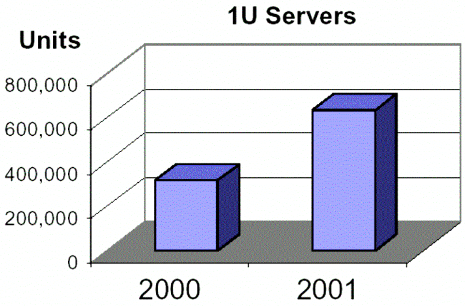
In Figure 1.3[A1], the trends for power density, efficiency and lifetime are shown. Within next several years, the power density needs to increase by a factor of 2. Efficiency needs to increase by more than 5%. To achieve this efficiency improvement, 30 to 50% reduction of system loss is required.



(From IBM Power Technology Symposium 2002, by Dr. Thai Q. Ngo, IBM)

Figure 1.3. Trend for AC/DC power supply for server

In Figure 1.4[A1], the need for 1U system is showed for 2000 and 2001. As seen in the picture, within one years time, the need for 1U system doubled. As for now, more and more server system are built with 1U profile as can be seen in all the major server manufactures like DELL, APPLE, GATEWAY etc.



(From IBM Power Technology Symposium 2002, by Anthony Stratakos, Volterra)

Figure 1.4. Trend toward lower profile system

From above discussions, we can see that the trends for front-end system are strongly affected by the digital system evolutions. The power density is expected to double. Loss is expected to reduce by more than 30%. And profile is expected to reduce by 50%. Next the state of the art technology will be reviewed and paths to achieve these goals will be discussed.

1.2 State of the art topologies

Inside front-end converter, two-stage approach is widely adopted as shown in Figure 1.5. With two-stage approach, there are two power conversion stages inside the front-end converter. First stage converts AC input to a loosely regulated 400V intermediate DC bus with power factor correction. Second stage, front-end DC/DC converter, will convert 400V DC into a tightly regulated 48V DC bus, which will be distributed to the load converter. For a single-phase system, 1kW system is the most popular power level because of its flexibility for 2 to 3 kW system. Also, at this power level, the choice of power devices is around the optimal.

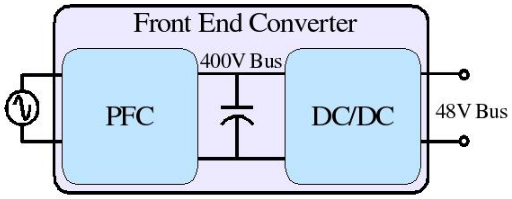
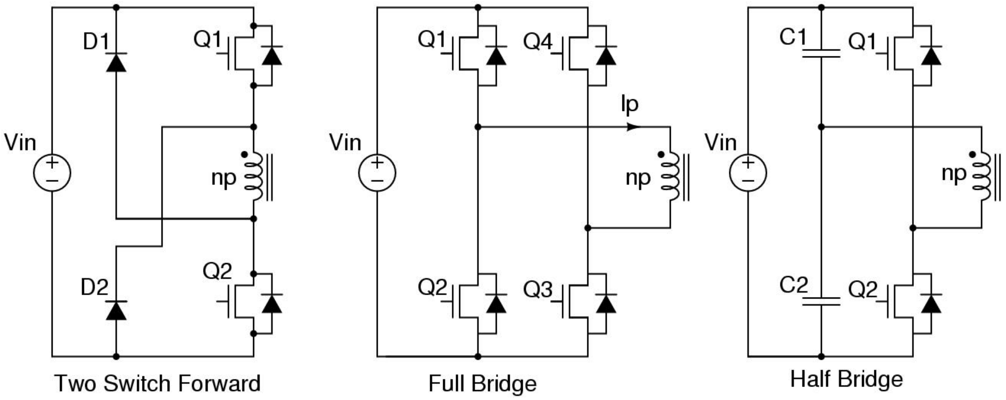


Figure 1.5. Two stage structure of front-end converter

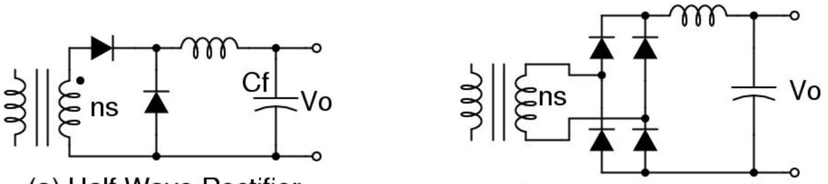
In this dissertation, the design challenges, issues and solutions for the second stage – Front-end DC/DC converter in a 1kW system will be discussed.

Most front-end DC/DC converter designs evolve around full-bridge, two-switch forward, and half-bridge converters, as shown in Figure 1.6. Among the possibilities and for the power level under consideration (1 kW), half-bridge converter and full bridge converter provide the best combination of simple structure, low device stress and soft switching capability. Most industry products use these two topologies.

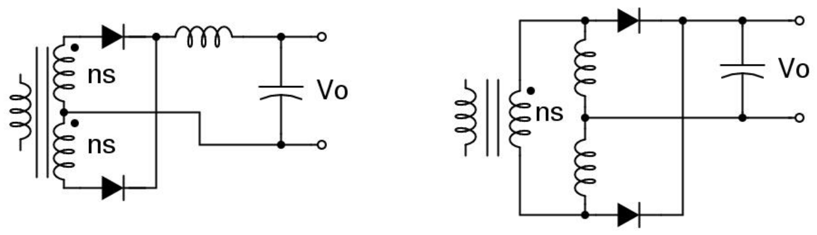


Two Switch Forward Full Bridge Half Bridge

Figure 1.6 Primary inverter topologies



(a) Half Wave Rectifier (b) Full Bridge Rectifier



(c) Center Tapped Rectifier (d) Current doubler Rectifier

Figure 1.7 Secondary rectifier topologies

Figure 1.7 shows possible configurations for secondary-side rectification. It is well understood that certain combinations of primary- and secondary-side topologies are deemed less desirable. Each secondary-side rectification has its advantages and disadvantages, which will be discussed in detail in chapter 2.

In Figure 1.8, a state of the art front-end system use full bridge and center tapped rectifier is shown. The magnetic components and heat sinks in the system are outlined. The upper half part of the picture is dedicated to PFC converter and lower part is the front end DC/DC converter. For DC/DC part, it is clearly that heat sink and magnetic are the biggest parts, which occupied more than 80% of the total system volume. To improve power density and profile, size reduction of heat sink and magnetic components are necessary.

Several methods could be used to reduce the heat sink and magnetic:

High switching frequency: higher switching frequency could result in volume reduction of passive components.

High efficiency: thermal management is a big part of the system. To achieve high power density, reduction on the volume for thermal management is an effective way.

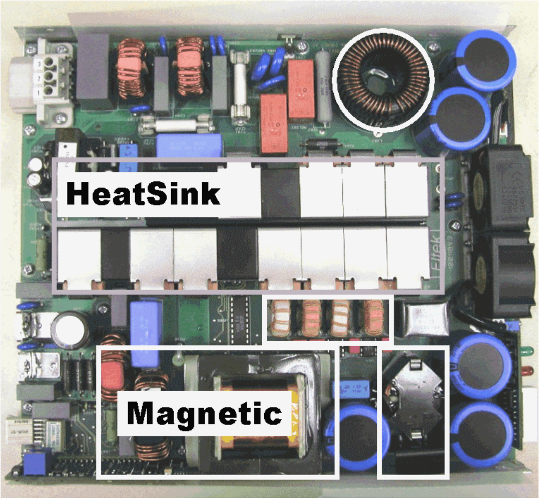


Figure 1.8 The state of the art front-end system

However, these two methods don't come together easily. With high switching frequency, efficiency often will suffer. The reduced efficiency is because of high switching loss and also the reverse recovery of the secondary-side diodes. The diode re-verse recovery causes voltage overshoot and ringing across the devices, which impacts on the selection of device breakdown voltage. The loss due to diode reverse recovery is also a great part of the total loss. Snubbers (such as those with active clamping or saturable cores) are used to deal with this problem. Nevertheless, these solutions also have limitations. Due to the large current in the secondary side, the conduction loss of the diode is another important part of the overall loss. The use of Schottky diodes can reduce the reverse-recovery problem. For the front-end dc–dc converter, the secondary diode voltage stress is normally close to 200 V. As a result, it is difficult to find suitable Schottky diodes for such a high voltage, and then other solutions are required.

Other than high switching loss, several other obstacles prevent us from switching so fast. High stress and high EMI noise caused by parasitic components are two major problems too.

Another obstacle for front end DC/DC converter design is the hold up time requirement: when the input AC line is gone, system needs to work for 20ms with full power. With hold up time, the result is wide input range for front end DC/DC converter. The performance at high input voltage is critical to system power density and efficiency while performance at low input voltage is not so important. For current state of the art topologies, however, this wide input range greatly impairs the performance of the converter at high input voltage.

To overcome these obstacles and develop a high switching frequency, high efficiency solution to achieve high power density and low profile, following techniques need to be improved:

Advanced devices and material: at high switching frequency, the size of the magnetic component is limited by the magnetic loss. With better magnetic material, the size of the magnetic components could be significantly reduced. Loss on power semiconductor is the biggest part in total system loss. With better devices like CoolMOS, this loss could be reduced so that less thermal stress is imposed to the thermal management.

Advanced packaging techniques: this includes advanced passive packaging and advanced active packaging. With advanced packaging technique, several aspects of improved could be expected. First, the utilization of space could be improved. With integration of capacitor into magnetic components, the total volume is greatly reduced. Second, with advanced packaging of active devices, the electrical performance of the system could be improved which will results to higher efficiency, lower noise. Third, advanced packaging could provide better thermal performance, which will help to reduce the volume of thermal management.

Advanced power converter topology: for those state of the art topologies, high turn off loss and low efficiency at normal operating condition limits the ability of higher switching frequency and efficiency. With more advanced topology, switching loss need to be minimized so that high switching frequency could be achieved with high efficiency. Also, a desired topology need to be able to be optimized at high input voltage so that hold up time requirement will not impose serious penalty.

1.3 Outline of dissertation

This dissertation is divided into five chapters. They are organized as following.

First chapter is background review of 1kW front-end DC/DC power converter in Distributed Power System. The trends for this application are high power density, high efficiency and low profile. To achieve these targets, high switching frequency, high efficiency topology needs to be developed. Soft switching topologies like phase shift full bridge and asymmetrical half bridge has been the standard industry practice. For these topologies, the switching frequency is pushed to 200kHz. Then the turn off loss will be so high that increase frequency will not improve the power density. To achieve the future target, higher switching frequency is a must. This calls for more advanced technology.

The primary target of this dissertation is to develop technique to achieve high frequency, high efficiency front-end converter that could be optimized at high input voltage while be able to cover wide input range.

Chapter 2 presents several techniques developed to improve the performance of state of the art topologies. One problem for the state of the art topologies is the hold up requirement. With hold up requirement, front-end DC/DC converter needs to be designed with wide input range. Within the range, only the performance at high input voltage is critical. Unfortunately, for all those topologies, wide range design always penalizes the performance at high input voltage.

Range winding solution and asymmetrical winding asymmetrical half bridge are two methods developed for wide input range issue. Quasi Square Wave synchronous rectifier is developed to reduce the secondary side conduction loss.

Range winding solution provides the best performance possible for the state of the art topologies. Adding extra winding and devices could divide wide input range divided into two ranges. The converter could be optimized for a narrow range and use range winding to deal with wide input range. This method can be applied to any topology.

Although range winding solution is effective, it needs extra windings, diodes, switches and control circuit. For asymmetrical half bridge converter, asymmetrical winding asymmetrical half bridge is a simpler and effective solution. With this solution, the duty cycle at high input voltage could be extended. With extended duty cycle, the voltage stress of output rectifier diodes could be reduced. With lower voltage rated diodes, the conduction loss and switching loss could be reduced greatly. This method is simple and effective, but it cannot be extended to other topologies like phase shift full bridge. Also, the output current will be discontinuous with this method.

Quasi-square-wave synchronous rectification is a method to implement synchronous rectifier in front-end application. Compare 200V diode and MOSFET, 50% reduction of conduction loss could be achieved at 20A output current. For 300V MOSFET, the benefit will be very limited. To use 200V devices, symmetrical half bridge is chosen. Two issues make the result not so promising: body diode reverse recovery problem of synchronous rectifier and hard switching of primary switches. Quasi-square-wave operation mode solved these two problems with minimized penalty. With QSW operation, the body diode of synchronous rectifier will never conduct, which totally prevented the reverse recovery problem. Secondary inductor current also helps the primary switches to achieve zero voltage switching at whole load range.

Although these techniques could improve the performance of the state of the art topologies, the high stress on the power devices and high switching loss problem is not been answered yet.

Chapter 3 investigated advanced packaging technology, which could help reduce the stress and loss due to parasitic components. Passive integrated technology is also been discussed which could provide significant improvement on power density of passive components. Two integrated power electronics modules were developed for front end DC/DC converter: active IPEM, which integrated totem pole switches and drivers; passive IPEM, which integrated all the passive components in front end DC/DC converter except the output filter capacitor. With IPEMs, the power density of front end DC/DC converter is improved by more than 3 times.

With advanced packaging technology, the performance of front end DC/DC converter could be improved, yet still the high switching loss and hold up time problem impose huge penalty on front end DC/DC converter design. Advanced topology still is needed to solve these two problems.

Chapter 4 investigated the resonant topologies for this application. First many traditional resonant topologies are been investigated. They are Series Resonant

Converter (SRC), Parallel Resonant Converter (PRC) and Series Parallel Resonant Converter (SPRC). All three topologies possess same problem as those PWM topologies: performance cannot be optimized at high input voltage for wide input range. At high input voltage, circulating current and switch turn off current reaches maximum.

Another resonant topology: LLC resonant converter, fortunately, seems to be exactly what fits this application. With LLC resonant converter, first the circulating energy is minimized at high input voltage. The turn off current of switches is controllable and could be minimized. This topology is also capable of cover wide input range. Compare with state of the art topologies, 3% improvement of efficiency could be achieved. It is almost 40% reduction of the loss. With DC analysis, the operating region and design of LLC resonant converter is presented.

Chapter 5 discussed two improvements for LLC resonant converter. To meet the profile and power density challenges, magnetic design is the most critical part in the system. A novel integrated magnetic structure is presented for LLC resonant converter. With integrated magnetic, all the magnetic components of a LLC resonant converter are integrated into one magnetic core. High power density can be achieved.

Overload protection is another problem been addressed in this dissertation. To make practical use of this topology, methods to deal with abnormal situation is as important as the efficiency. Three methods to deal with over load situation were discussed. With increase switching frequency, the output current could be limited with the penalty of larger magnetic core size. With hybrid control of PWM and variable frequency control, previous problem could be prevented. The problem is lost of soft switching capability. The last method, which is a modified LLC resonant topology by adding clamp diodes to the resonant capacitor, can effectively control the output current with fast response.

With above analysis, an open loop LLC resonant converter could be designed work very well. Next step is to close the voltage feedback loop. To do this, an understanding of the small signal characteristic of LLC resonant converter is essential.

Chapter 6 is dedicated to the small signal modeling of LLC resonant converter. Traditional state space averaging method can no longer apply for resonant converter. Several different methods have been reported for this topic. Many of them made lot of simplifications, which makes the result not accurate. In this dissertation, two methods are used to extract the small signal model of LLC resonant converter. One method is based on simulation. It treats the converter as a black box. By inject small signal perturbation and monitor the output response at different perturbation frequency and operating point, a complete small signal characteristic of LLC resonant converter could be gained. This method is easy to implement and accurate as long as the circuit model is accurate. The drawback of this method is lack of intuition and time consuming. Another method is used as a complementary to the simulation method: extended describing function method proposed by Dr. Eric Yang. It is a general modeling tool for periodical operating system based on COSMR software package. With this method, a small signal model could be derived with zeros and poles identified. Compare these two methods, ETD method is fast but need state space model of the circuit in every situation while simulation method is accurate and easy but time consuming. Finally, based on the information gathered from above analysis, the feedback control could be designed for LLC resonant converter.

With these analysis and test verification, LLC resonant converter is been proved to be an excellent candidate for front-end DC/DC conversion. The analysis and design are also been explored, although this exploration is far from completion, it enables industry to appreciate this topology as a possible for next generation front-end DC/DC converter.