Chapter Five

Summary and Future Work

The advances in VLSI technologies impose a new challenge for delivering high-quality power to modern microprocessors. The challenges of the VRM come from the requirements of low voltage, high current, fast transient responses and high efficiency. Multiphase technology enables the use of small inductances in VRMs to improve the transient response and has become the standard industrial practice.

It is the purpose of this work to develop high-efficiency, high-power-density, fast-transient VRMs to power present and future generations of low-voltage, high-current microprocessors. This dissertation has addressed the following issues:

- Advanced VRM topologies: high efficiency, high power density, and fast transient response for low-voltage, high-current applications.
- Innovative integrated magnetics: low core loss, low winding loss and easy manufacturability for high efficiency and high power density.
- Optimization of multiphase VRMs: a methodology for determining the appropriate number of channels for the optimal design of multiphase VRMs.

5.1. SUMMARY

5.1.1. Topology Improvement for Multiphase VRMs

Today's multiphase VRMs are almost universally based on the buck topology. With increased voltage and decreased output voltage, the multiphase buck converter suffers from a very small duty cycle. It is very difficult for the multiphase buck converter to achieve a desirable level of efficiency while providing a fast transient response. Loss analysis indicates that the efficiency drop is mainly caused by the switching loss of the top switches when the duty cycle is reduced.

In order to improve the efficiency without compromising the transient performance, the multiphase tapped-inductor buck converter has been explored, which employs multi-winding coupled inductors to extend the duty cycle. Under the same transients, the multiphase tapped-inductor converter has a much larger steady-state duty cycle, and consequently, it has a higher efficiency than does the multiphase buck converter. However, the multiphase tapped-inductor buck converter suffers from a voltage spike problem caused by the leakage inductance between the coupled windings.

An improved topology, named the multiphase coupled-buck converter, has been proposed. This innovative topology enables the use of a larger duty cycle with a clamped and coupled structure. Therefore, the leakage energy can be recovered, and the voltage spike across the device can be clamped. With its extended duty cycle, the multiphase coupled-buck converter has a significantly lower switching loss for the top switches than does the multiphase buck converter. Both analyses and experiments have proved that under the same transients, the multiphase coupled-buck converter has an efficiency that is significantly better than that of the multiphase buck converter.

The proposed concept in the multiphase coupled-buck converter can be extended to other applications. Correspondingly, the benefits of the multiphase coupled-buck converter can also be extended to its isolated counterpart, which is the push-pull forward converter with the current-doubler rectifier. Compared to the isolated counterpart of the multiphase buck converter that is the push-pull converter, the push-pull forward converter has clamped device voltage and recovered leakage, energy and therefore a higher efficiency.

5.1.2. Magnetic Integration for Multiphase VRMs

The use of integrated magnetic components in multiphase VRMs has been investigated in order to reduce the complexity of the magnetics, to reduce the size, and to improve the efficiency.

All the magnetic components can be integrated into a single core, in which the windings are wound around the center leg and the air gaps are placed on the two outer legs. However, studies show that the core structure of the integrated magnetics requires precise adjustment and is not mechanically stable. The existence of air gaps on the two outer legs also causes EMI issues. A large amount of leakage inductance exists in the integrated magnetics, causing severe parasitic ringing, decreasing the duty cycle, and impairing the efficiency.

An improved integrated magnetic structure has been proposed to solve these problems. In the proposed topology, all the windings are wound on the two outer legs, the core structure has an air gap in the center leg, and there are no air gaps in the two outer legs. This kind of core is easier to manufacture. The windings are physically located on the same legs. The interleaved winding technique can be used to minimize leakage inductance.

In the proposed integrated magnetics, the air gap in the center leg introduces coupling between the two output filter inductors. With the coupled output inductors, both the steady-state and dynamic performances of multiphase VRMs can be improved. Another benefit of the proposed integrated magnetic structure is the flux ripple cancellation effect in the center leg. With the small flux ripples in the center leg, the core loss in the center leg can be reduced. The fringe effect of the air gap becomes insignificant and the winding loss can also be reduced.

Unlike conventional magnetic integrations, the input filter has also been integrated into the proposed integrated magnetic structure. The input inductor is formed by the leakage inductance between the transformer’s primary windings. This leakage inductance can be carefully designing the winding. With the proposed integrated magnetics, it is possible to use only a single magnetic core for the whole converter.

5.1.3. Optimization of Multiphase VRMs

An optimization methodology has been proposed for multiphase VRMs, in order to determine the appropriate number of channels for an optimal design.

The formulation of the optimization problem has been discussed. Two constraints exist, corresponding to the requirements of the transient responses and the minimum efficiency. Four design variables need to be traded off; they are the channel number, switching frequency, control bandwidth, and output inductance. The selection of the objective function is the preference of individual manufacturers or designers. Minimized weighted volume and cost could be the objective function for most of today's multiphase VRMs.

The general method of the optimization has been proposed. As a dependent variable, the control bandwidth is eliminated from the four design variables. The optimization problem can be illustrated by a series of surfaces in a three-dimensional space, with the objective function as the vertical axis, the switching frequency and the output inductance as the two horizontal axes, and the channel number as the parameter. The proposed optimization method first looks for the lowest points of these surfaces, which represent the optimal designs for the given channel numbers. For most of today's multiphase designs, these lowest points correspond to the design of the minimum efficiency and the critical inductance. Connecting these lowest points together forms a curve, and the optimization solution is located at the lowest point of this curve.

Two optimization examples have been provided in order to demonstrate the optimization procedure. Both are performed on typical VRM 9.0 designs for the latest Pentium 4® processors. The first example has a simple objective function, to minimize the number of output capacitors. A more realistic objective function is used for the second example, to minimize the cost of multiphase VRMs. The optimization results are compared with the industry practice. The optimization results provide not only the appropriate channel number, but also the complete design, including the output inductance value, the switching frequency, and total number of input and output capacitors required. The more generalized formulation has been discussed. Its objective function could be to minimize the weighted volume and cost of multiphase VRMs.

5.2. FUTURE WORK

5.2.1. Efficient Synchronous Rectification

Under high-frequency operation, the body diode of the synchronous MOSFET generates significant loss. This happens when the inductor current is forced to flow through the body diode of the synchronous MOSFET. The body diode conducts the full current, which results in severe switching loss due to the reverse recovery of the body diode. New driving schemes or topologies, such as to overlap the switches to force the current to always flow through the channel of the synchronous MOSFETs could be an interesting research area.

5.2.2. Passive Integration

Passive components often become the limitation of volume and cost of the whole VRM. In order to improve the electrical performance and packaging densities, an integration approach is being developed. The integrated magnetics proposed in Chapter 3 have integrated all the magnetic components into a single core. Its winding configuration is particularly suitable for further integration of some capacitors. An effective means of integrating passive components, such as inductors, capacitors and transformers could be an interesting research area.

5.2.3. VRM Optimization

Following the proposed optimization methodology in Chapter 4, one should be able to involve more detailed specification and components into the optimization. The objective function of the optimization can also be made to be more sophisticated and practical. Moreover, applying the proposed optimization methodology to predict the performance of the VRM with new devices and circuits could be an interesting research area.