

Chapter One

INTRODUCTION

It is the purpose of this work to perform the analysis and design of high-density, low-profile power supplies, including their electrical, thermal, and EMI aspects. Emphasis is placed on forward and flyback converters.

1.1. Background

The ever-increasing demand for size and weight reduction of portable and on-board power modules has spurred significant development and research efforts in high-density, low-profile power supplies. The design of high-density, low-profile power supplies involves circuit topologies, high switching-frequency operations, magnetics designs [E1], soft-switching

techniques [E2], and component selection, most of which have been extensively researched and developed, as outlined in Fig. 1.1. In addition, these power supplies are required to present high efficiency for low power dissipation, appropriate module-paralleling for component height reduction, efficient thermal management and packaging for heat removal, and minimized EMI noises for various EMI regulatory requirements, as shown by the shaded circles in Fig. 1.1. However, the studies in these areas are very limited and need more research efforts to enhance the designs of high-density, low-profile converters. The research and development related to these subjects are summarized in this section as the background of this study.

As the operating voltage of data-processing circuits continues to decrease, maintaining high conversion efficiency presents a major technical challenge. The forward voltage drop of diode rectifiers dissipates more than 50% of power loss in low-voltage power supplies. MOSFET synchronous rectifiers are widely employed to replace less efficient diode rectifiers, especially in low-voltage applications, due to their reduced forward voltage drop compared to that of a diode rectifier [A1-A14]. In forward converters, cross-coupled self-driven SRs are the simplest implementation possible, without increasing the circuit complexity [A5, A6], but they are limited to narrow input voltage ranges ($\leq 2:1$). Different power transformer reset methods, including resonant-reset [A15, A16], RCD-reset [A17], and active-clamp reset [A18, A19] have decisive effects on the performance of the self-driven SRs [A7-A12]. Control-driven SRs can be used for wide input voltage range applications. The timing of SR gate-drive signals is crucial to minimizing body diode conduction and to eliminating cross-conduction [A13, A14]. However, in these individual evaluations, the performance of synchronous rectification as a function of driving schemes and transformer reset methods is not investigated. Also, the experimental results

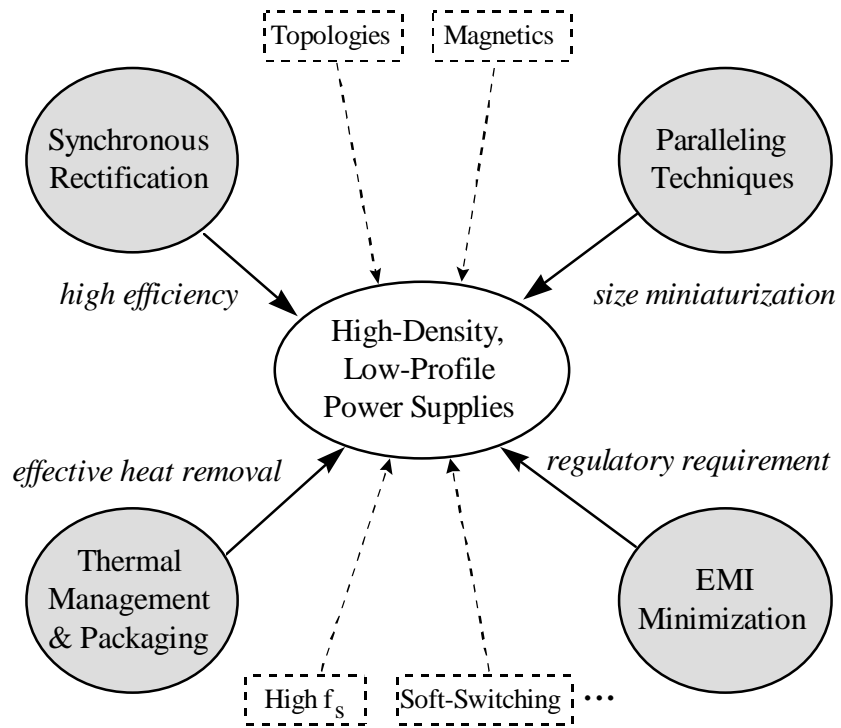


Figure 1.1. Important design aspects of high-density, low-profile power supplies.

are based on specific applications, whose results are difficult to apply to general practices. In the past, synchronous rectification in flyback converters was limited only to post regulation because the rectifier in a flyback converter is current-fed and capacitor loaded, which makes simple secondary-voltage self-driven SR not directly feasible [A23-A25]. In these applications, SRs are utilized as controlled resistors to post-regulate one of the output voltages in multiple-output converters. The conversion efficiencies are not maximized and are penalized by voltage regulation ranges. True flyback SR implementation is yet to be explored, together with the investigation of its performance in various converter operating modes and control schemes.

The advantage of distributed power architectures has been clearly described in [B1, B2]. High-density, high-power power conversion can be achieved by utilizing high-density, lower-power distributed magnetics. The paralleling method enables high power conversion with small-size magnetic components [B1]. Current sharing among paralleled modules is usually ensured by feedback control techniques [B3-B6]. Current sharing by proper power stage implementations can improve the inherent current sharing mechanism and alleviate the control difficulties. The interleaving approach can further reduce filter sizes by ripple current cancellation and ripple frequency increase [B7-B10]. In contrast to the conventional two-choke interleaved forward converter, the one-choke interleaved forward converter was proposed to reduce component count [B11, B12]. However, these two approaches have significantly different operation principles and performances. The understanding and analyses of these approaches are essential in utilizing distributed magnetics for high-density power supplies.

As the densities of power converters continue to grow, thermal issues are becoming extremely important and vital to the product quality [C1]. In addition, power systems of portable

and hand-held electronic equipment are usually housed in completely sealed enclosures, which poses further design challenges to achieving effective heat removal. To optimize thermal performance, improve product reliability, and reduce design cycle, sophisticated thermal modeling is becoming an integral part of the design cycle [C2, C3]. Thermal modeling is a faster and more efficient tool than experimental cut-and-try methods for improving and optimizing the thermal management for high-density power converters [C4]. In the past, thermal analysis has been mainly focused on component-level performance in the free-air environment, or with estimated boundary conditions [C4-C11]. But these components behave differently in the high-power-density environment due to thermal coupling coming from surrounding components. The computational fluid dynamics (CFD) approach calculates heat transfer coefficients based on actual airflow conditions and can predict temperature accurately [C12-C15]. The system-level CFD analysis has begun to be applied to the thermal design of power supplies [C16-C23]. However, a lack of systematic approach incorporating electrical and thermal designs prevents thermal modeling from being widely adapted to the optimization of thermal management for high-density power supply.

EMI emission of switch-mode power supplies needs to be suppressed to reduce susceptibility, and more importantly, to reduce the size of filter components [D1-D3]. This is especially important for high-density power supply designs, not only because of the filter size restraint, but also due to the general trend of high switching frequency to increase power-density. With higher switching frequencies, current and voltage slew rates, di/dt and dv/dt , are usually higher, and the parasitic effects in circuit layout and packaging are more pronounced. Therefore, EMI has become a very challenging design task for high-density power supplies. Generally, the

EMI design is a patch-on procedure performed in the last phase of product development. Noise reduction is commonly accomplished by experimental trial-and-error method [D4-D6]. This approach is time-consuming and difficult for performance optimization. Moreover, design guidelines for general applications are difficult to obtain. An early-stage EMI analysis and layout planning are proven to be cost-effective and efficient in solving noise problems [D7]. Recently, modeling of EMI noise with respect to circuit layout and packing has shown some success in predicting conducted EMI emission [D7-D13]. But to identify noise source and to improve circuit layout, a systematic analysis and design approach for high-power-density power supplies is needed and essential for their EMI noise minimization.

1.2. Objectives and Dissertation Outline

The primary objectives of this research are to tackle the important and integral electrical, thermal, and EMI design aspects of high-density, low-profile power supplies. The major contributions are the analysis and design considerations of high-density, low-profile power supplies, which includes evaluation of synchronous rectification, implementation of converter paralleling, optimization of thermal management, and minimization of conducted EMI noises.

Using forward and flyback converters as examples, this research covers the important design aspects necessary to achieve high-density, low-profile, and high-performance power supplies.

1.2.1. Synchronous Rectification

In Chapter 2, the self-driven and control-driven SRs in the resonant-reset, RCD-reset, and active-clamp-reset forward converters are evaluated and compared. Performance analyses are made based on the general characteristics of MOSFETs and Schottky diodes. Theoretical limits of the efficiency improvement are derived and generalized for forward converters with SRs [A21, A22]. Chapter 2 also presents design trade-offs and performance comparisons of various implementations of the flyback converter with synchronous rectifiers. Specifically, the merits and limitations of the constant-frequency (CF) continuous-conduction-mode, CF discontinuous-conduction-mode (DCM), variable-frequency DCM, and zero-voltage-switched DCM flyback converters with synchronous rectifiers are discussed. The theoretical efficiency improvements of the discussed synchronous rectification approaches relative to Schottky diode implementations are derived. Theoretical results are verified experimentally [A28].

1.2.2. Paralleling Techniques

The transformer paralleling and module interleaving techniques for high-power-density, low-profile conversion are presented in Chapter 3. In the paralleling approaches, current sharing issues are analyzed for different rectifier and heatsink configurations, and verified experimentally. The operation principles and performances of the one- and two-choke implementations of interleaved forward converters are theoretically and experimentally evaluated. Design guidelines for converter paralleling are outlined[B15].

1.2.3. Thermal Management and Packaging Considerations

Chapter 4 discusses the thermal-design considerations for high-power-density converters in sealed enclosures using the computation fluid dynamics (CFD) simulation approach. As an example, an off-line, 36-W flyback adapter is analyzed using CFD thermal modeling and simulation with software Flotherm. The thermal modeling and simulation are performed for a number of packaging approaches. The simulation results are verified experimentally. The design guidelines for optimum thermal performance are outlined [C24].

1.2.4. Minimization of Conducted EMI

Chapter 5 provides an analysis and design methodology for conducted EMI problems. The partial element equivalent circuit (PEEC) method is used for layout parasitics extraction. Parasitics in the EMI filter and the power transformer are determined experimentally. The predictions and designs of EMI noise in an off-line flyback adapter are verified by the EMI emission measurement. Design procedures of a systematic approach developed to suppress conducted EMI noises are given for general high-density, high-frequency power supply designs.

1.2.5. Conclusions and Concurrent Design Concept

The major conclusions of this work are outlined in Chapter 6. Combining the electrical, thermal, and EMI designs, an integrated approach to the design of high-frequency, high-density power supplies is proposed.