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Advanced Modeling, Control and EMI Mitigation Techniques for Switching DC-DC Power Converters

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Switching DC-DC converters are ubiquitous building blocks in modern power electronics systems. Over the last few decades, their development has faced increasingly tight performance requirements, simultaneously minimizing the overall size, weight, and costs. This dual and conflicting demand poses key challenges, requiring the development of novel design and analysis techniques. This dissertation focuses on the development of advanced modeling, control and EMI reduction methods for switching DC-DC converters.

The first Part of the dissertation focuses on small-signal modeling, which is of paramount importance from a practical engineering perspective. First, an enhanced small-signal model capturing the impact that Quasi-Square Wave Zero Voltage Switching (QSW-ZVS) networks have on the converter dynamics is proposed. Synchronous Buck and Boost DC-DC converters embedding the QSW-ZVS network in an additional inner control-loop are considered. The network enables ZVS for the Low-Side and High-Side power MOSFETs in the Buck and Boost converters, respectively. Beyond improving power conversion efficiency, the QSW-ZVS network alters converter dynamics. In this context, an enhanced averaged small-signal model is proposed. The model is validated through both simulations and experimental measurements. Then, the thesis concentrates on small-signal modeling of Ripple-Based Constant On-Time (RBCOT) DC-DC Buck converters. In contrast to fixed-frequency topologies, RBCOT control lacks a clear and general modeling framework. State-of-the-art small-signal models are tied to specific RBCOT control schemes and cannot be easily generalized. A novel unified modeling technique is proposed, that is fully general and exact. The resulting model is complete, in that it provides any input-output transfer functions, and it is accurate for frequency values that are well beyond the converter switching frequency. The validity of the proposed model is verified through both simulations and experimental measurements.

In the subsequent Part, advanced control strategies are proposed. The dissertation presents a novel ByPass (BP) stage and a Load Estimator Compensator (LEC) stage. These stages can be seamlessly integrated within standard control-loop architectures.

The BP stage permits overcoming the voltage regulation limit in the RBCOT Buck converters, due to the intrinsic presence of a minimum achievable OFF time. When the minimum OFF-time condition is reached, the RBCOT modulator stage saturates. As a consequence, the regulation of the converter output voltage is lost. The proposed BP stage only intervenes when there is a persistent saturation condition, restoring the output voltage regulation. In contrast, its intervention does not affect the behavior of the circuit under normal regulating conditions. The LEC stage improves the load transient response of the system, thus minimizing output voltage fluctuations (i.e., mitigating overshoots and undershoots). The LEC stage is conceived to be versatile, i.e., so that its design can be easily tailored to several DC-DC converter control methods. The effectiveness of both the BP and the LEC stages is verified via experimental measurements. The BP stage is implemented in a 0.18 μm Bipolar-CMOS-DMOS process. Experimental results show how the BP stage addresses the voltage regulation limits that arise when the converter operates with minimum OFF time. Analogously, a circuitual implementation of the LEC stage is provided, and its effectiveness is demonstrated on an experimental board. Measurement results show satisfactory performance in terms of overshoot/undershoot mitigation.

The final Part is devoted to the development of advanced ElectroMagnetic Interference (EMI) reduction strategies based on the Spread-Spectrum Clocking (SSC) technique. The dissertation focuses on EMI reduction optimization involving multiple frequency windows with different Resolution BandWidths (RBWs). Two approaches are proposed and analyzed: the Single Triangular Modulation (STM) and the Double Triangular Modulation (DTM). The former relies on the standard and commonly adopted triangular-based spreading. The role of modulation parameters in optimizing EMI mitigation in a multi-RBW environment is investigated. The latter —inspired by a recent Application Note— is much more complex from an implementation perspective, as it is based on two simultaneous triangular modulations employing different modulation parameters. Mathematical models are proposed to provide an estimate of the EMI reduction performance, which is in turn validated via experimental measurements. Results show that the analyzed SSC-based EMI reduction techniques are equally effective in mitigating disturbances in both frequency ranges, thus making the adoption of the DTM approach questionable.