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PEEC-BASED VIRTUAL DESIGN OF EMI INPUT FILTERS

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presented by
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For my family
Mojoj porodici

Abstract

The design of power electronic systems in compliance with the ElectroMagnetic Compatibility (EMC) standards represents a difficult task with increasing requirements for high power density and high efficiency. In practice, a systematic EMC analysis of power converter systems that evaluates the possible high frequency disturbance is usually not performed due to complexity and limited time. The EMC aspects are typically considered in the end phase of the design process that leads to higher design costs and prolongs the time to market. Therefore, the virtual prototyping is increasing in importance as it enables engineers to obtain a detailed insight into the electromagnetic performance of power electronic systems before any hardware prototypes are constructed.

ElectroMagnetic Interference (EMI) filter circuits with passive components are typically used to attenuate the EMI noise inserted at power lines to the required levels specified by EMC standards and hence prevent the interference with other line-connected equipment. As a necessary part, an EMI filter introduces additional cost and volume, which is about 30 % of the total volume, and thus it should be properly built and placed within the power converter system. Moreover, as the space constraints become more pronounced with the trend for higher power density, the PCB (Printed Circuit Board) design and the placement of EMI filter components have to be carried out carefully. So far, EMI filter design has been mostly based on engineer's practical experiences, which commonly results in non-optimal EMI filter solutions. The EMC analysis based on numerical techniques such as the Finite Element Method (FEM) represents another approach used to obtain practical guidelines for good EMC design and iterative develpement. However, the FEM-based commercial tools also require an engineer's expertize and the FEM simulations are often time consuming and computationally expensive for the 3D structures used in power electronics applications. Thus, so far a fast and accurate EMC tool for comprehensive EMC modeling of power converter systems has been missing in the engineering practice.

This doctoral dissertation presents research conducted on the EMC analysis of EMI input filters using 3D electromagnetic modeling based on the Partial Element Equivalent Circuit (PEEC) method. Coupling between two numerical techniques, the PEEC method and the Bound-

ary Integral Method (BIM), i.e. PEEC-BIM method, is proposed for the detailed electromagnetic modeling of EMI filter inductors. This enables the 3D PEEC-based modeling to become a useful EMC tool for the prediction of the High Frequency (HF) performance of EMI input filters and power converter systems, which is affected by PCB component placement, and self- and mutual-parasitic effects. It is shown that the developed PEEC-BIM method enables detailed EMC analysis taking into account different electromagnetic effects of the PCB layout, e.g. self-parasitics, mutual coupling, and electrostatic shielding. Since the calculation of these effects is quite cumbersome employing analytic equations or measurements, the extraction of the parasitics via the 3D PEEC-BIM modeling is a useful approach for the assessment of dominant parasitic effects that determine the HF response of the EMI filters. In comparison to other numerical techniques implemented in 3D field solvers, such as the well-known FEM, it is shown that the PEEC-BIM method is more suitable for EMC modeling of power electronics application with respect to accuracy and computational efficiency.

The developed PEEC-BIM modeling approach is used to evaluate the applicability of the parasitic cancellation techniques proposed in literature regarding the efficient cancellation of the self-parasitic and mutual-coupling effects in complete EMI filter circuits. The accuracy and modeling features are verified by the transfer function and impedance measurements of single-phase single-/two-stage EMI filter circuits. Good agreement of less than 5 dB difference between the PEEC-BIM modeling results and the measurements is achieved in a wide frequency range from DC up to 30 MHz. Special care is paid to the construction of the measurement setup in order to achieve transfer function measurements with minimal external disturbance. The PEEC-BIM modeling capabilities are finally demonstrated on the modeling example of a practical EMI filter for a single-phase PFC boost rectifier input stage. It is shown that the PEEC-BIM method implemented in an EMC modeling environment enables a step-by-step EMC analysis distinguishing the impact of various electromagnetic effects on the EMI filter performance and allowing an optimal EMI filter design. Accordingly, the research presented in this thesis provides a good basis for building an EMC modeling environment for virtual prototyping of EMI input filters and power converter systems.

Kurzfassung

Die steigende Nachfrage an leistungselektronischen Systemen mit hoher Leistungsdichte und hoher Effizienz stellt für die Entwicklung der Systeme, konform mit Normen der elektromagnetischen Verträglichkeit (EMV), eine besondere Herausforderung dar. In der Praxis werden meist keine systematischen EMV-Analysen von Leistungsumrichtern durchgeführt, welche die möglichen hochfrequenten Störungen untersuchen. Die EMV-Gesichtspunkte werden typischerweise erst in der Endphase des Entwicklungsprozesses berücksichtig, was zu höheren Entwicklungskosten und längeren Produkteinführungszeiten führt. Deshalb wird die virtuelle Prototypenentwicklung immer wichtiger, da diese den Ingenieuren einen detaillierten Einblick in die elektromagnetischen Eigenschaften der leistungselektronischen Systeme ermöglicht, bevor ein Hardware-Prototyp aufgebaut wird.

In der Regel werden EMV-Filter mit passiven Komponenten zur Reduktion der elektromagnetischen Beeinflussung des Netzes auf das erforderliche Niveau eingesetzt, um so eine Störung der mit dem Netz verbundenen Geräte auszuschliessen. Die notwendigen EMV-Filter erzeugen zusätzliche Kosten und ein erhöhtes Bauvolumen, welches typ. 30 % des Gesamtvolumens beansprucht. Daher sollten die EMV-Filter den Performanceanforderungen entsprechend ausgelegt und in das Design der Leistungsumrichter integriert werden. Darüber hinaus müssen die Platzierung der Filterkomponenten und das PCB-Layout in Hinblick auf die Performance sehr durchdacht sein, da aufgrund des andauernden Trends der Leistungsdichtesteigerung die Volumenbeschränkung verschärft wird. Das EMV-Filterdesign basiert meistens auf den Erfahrungen der Entwicklungsingenieure, was gewöhnlich nicht zu einer optimalen EMV-Filterauslegung führt. Die EMV-Analyse basierend auf numerischen Berechnungstechniken, wie der Finite-Elemente-Methode (FEM), ist eine Möglichkeit für eine praktische Überprüfung der EMV-Filterstruktur. Allerdings erfordern die FEM-basierten kommerziellen EMV-Berechnungstools ebenso Ingenieur-Fachwissen und die FEM-Simulationen für die drei-dimensionalen (3D) Strukturen sind oft zeitaufwendig und rechenintensiv. Ein neuartiges, schnelles und genaues EMV-Berechnungstool für eine umfassende EMV-Modellierung von leistungselektronischen Systemen fehlt bislang in der Ingenieurspraxis.

Die vorliegende Dissertation beinhaltet die Analyse von EMV-

Eingangsfilter mit Hilfe elektromagnetischer 3D Modellierung basierend auf der PEEC-Methode (“Partial Element Equivalent Circuit”). Die Kopplung von zwei numerischen Techniken - der PEEC-Methode und der Grenzintegral-Methode (BIM, “Boundary Integral Method”), die sogenannte PEEC-BIM-Methode wird vorgestellt, welche eine detaillierte elektromagnetische Modellierung von EMV-Filterinduktivitäten gestattet. Das ermöglicht den Einsatz der 3D PEEC-basierenden Modellierung als mächtiges EMV-Berechnungstool zur Bestimmung des Hochfrequenzverhaltens von EMV-Eingangsfiltern und Leistungsstromrichtern, welche von der Platzierung der PCB-Komponenten sowie von eigen- und durch Kopplung bedingten parasitären Effekten beeinflusst werden. Es wird gezeigt, dass die entwickelte PEEC-BIM- Methode eine detaillierte EMV-Analyse ermöglicht, die verschiedene elektromagnetische Effekte des PCB-Layouts berücksichtigt, wie eigenparasitäre Effekte, wechselseitige Kopplungen und elektrostatische Schirmung. Da die Berechnung dieser Effekte unter Anwendung von analytischen Gleichungen oder Messungen kaum möglich byw. sehr zeitaufwendig ist, ist die Bestimmung der Störeffekte mithilfe der 3D PEEC-BIM-Modellierung eine geeignete Herangehensweise zur Beurteilung der dominanten parasitären Effekte, welche das Hochfrequenzverhalten der EMV-Filter bestimmen. Im Vergleich zu anderen numerischen Methoden, welche für 3D-Feldberechnungen implementiert werden, wie beispielsweise die FEM, wird gezeigt, dass die PEEC-BIM- Methode in Hinblick auf die Genauigkeit und Berechnungseffizienz besser für die EMV-Modellierung leistungselektronischer Applikationen geeignet ist.

Der entwickelte PEEC-BIM-Modellierungsansatz wird darüber hinaus zur Evaluation der praktischen Anwendbarkeit von, in wissenschaftlichen Publikationen vorgeschlagenen Methoden zur Auslöschung von eigenparasitären und Kopplungseffekten der EMV Filterkomponenten bzw. von gesamten EMV-Filterschaltungen verwendet. Die Genauigkeit und Modellierungsmöglichkeiten werden durch Messungen der Übertragungsfunktion und Impedanz an einphasigen ein-/zweistufigen EMV-Filterschaltungen verifiziert. Eine gute Übereinstimmung von weniger als 5 dB Abweichung resultiert bei dem Vergleich zwischen der PEEC-BIM-Modellierung und den Messungen innerhalb eines weiten Frequenzbereichs von DC bis zu 30 MHz. Ein besonderes Augenmerk wird auf den Messaufbau gelegt, um Übertragungsfunktionen mit minimalen externen Störungen messen zu können. Die Leistungsfähigkeiten der PEEC-BIM-Modellierung werden abschliessend für ein EMV-Eingangsfilter eines einphasigen Gleichrichters mit Leistungsfaktorkorrektur (PFC) demonstriert. Es wird gezeigt, dass die in einer EMV-Entwicklungsumgebung implementierte PEEC-BIM-Methode eine Schritt-für-Schritt EMV-Analyse ermöglicht, welche den Einfluss verschiedener elektromagnetischer Effekte auf die EMV-Filterperformance verdeutlicht und somit ein optimales EMV-Filterdesign ermöglicht. Dementsprechend bieten die in dieser Doktorarbeit präsentierten Forschungsergebnisse eine gute Basis zum Aufbau einer EMV-Entwicklungsumgebung für die virtuelle Prototypenentwicklung von EMV-Eingangsfiltern und leistungselektronischen Systemen.

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Želim da zahvalim iz sveg srca mojim roditeljima i mom bratu Ivi sto su uvek uz mene. Bez vas ovaj doktorat ne bi bio uspešan. Vi ste moja najveća podrška sve ove godine - Hvala vam!

Contents

1 Introduction

The design of power electronic systems according to Electromagnetic Compatibility (EMC) standards requires special engineering experience and extends the development time. The later the EMC analysis is performed during the design process, the smaller are the degrees of freedom for solving EMC problems and an increase of costs and time to market can be expected, as shown in Fig. 1.1.

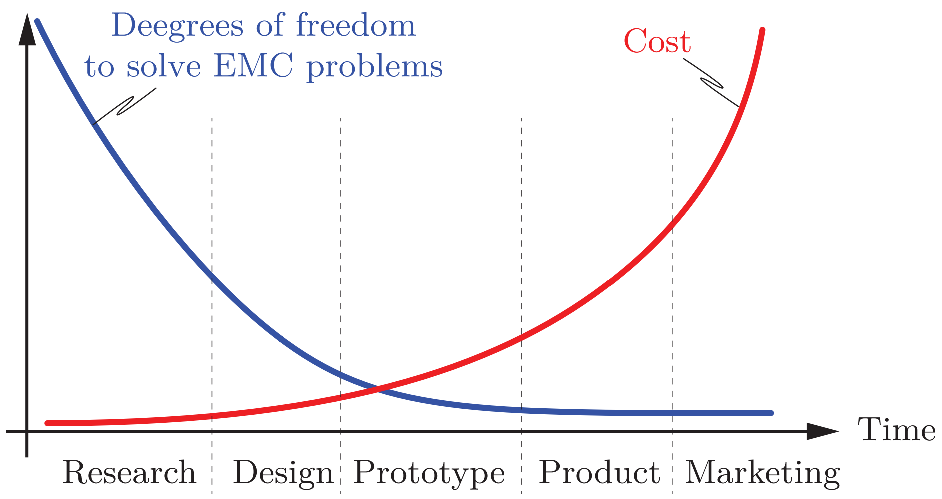

Figure 1.1: Relative cost of introducing full EMC in a product at different design stages between initial research and final marketing [1].

Therefore, the prediction of the EMC behavior represents an important design step and needs to be included in the early design stages. The motivation for the EMC analysis of power converter systems, the present challenges and the overview of the thesis structure with the main research tasks are summarized in this chapter.

1.1 Motivation

The EMC analysis is a tool for the characterization and prediction of the high frequency (HF) performances of power converters. It is based on the understanding of the Electromagnetic Interference (EMI) noise mechanisms, including the generation and propagation of EMI noise within a power converter system. The main task of the EMC analysis is the identification of the dominant noise sources and propagation paths. The second step is then the control of EMI noise emissions including the measures to be taken in order to reduce the area of the current carrying loops behaving like antennas, and to prevent non-compliant EMC behavior due to the mutual coupling of the filter components and parasitic HF effects. The EMC analysis enhances the EMC design of power converters from the trial-and-error approach to higher levels that allow power electronics engineers to gain a deep insight into the HF behavior prior to the final hardware implementation stage.

The EMC modeling and calculation of power converters is regarded to be not a straightforward task. The existing equivalent models of power converters can correctly describe their electrical functionality but lack in accuracy in the HF range, when the detailed behavioral models of power switching devices have to be taken into account and the parasitic effects become more pronounced. Moreover, the prediction of the HF phenomena that originate from the non-ideal electrical behavior is quite difficult, and so, there has been an ever-increasing need for the EMC tools that can be used for the purpose of the parasitic extraction and EMC virtual prototyping. In the HF range, the parasitic effects emanate from all power converter elements, such as capacitors, magnetic components, power diodes, power transistors, PCB traces, wires, and cables. A large number of studies about the prediction and quantitative assessment of parasitics has been carried out, however, a comprehensive, fast and easy-to-use Computer-Aided Design (CAD) tool is still missing, what points to the motivation of the research presented in this PhD thesis.

The wide field of applications of Switched Mode Power Supplies (SMPS) and the stringent EMC regulatory requirements are the main drivers for the comprehensive EMC analysis and the development of various methods for reducing the EMI noise intrinsically generated by SMPS. Power electronics engineers have developed different techniques to decrease EMI noise caused by fast switching operations of power converters, with a special attention dedicated to the design of EMI input filters. EMI input filters are employed at the interface between the SMPS and the power line in order to provide the necessary EMI noise attenuation defined by the EMC standards. The design challenges of practical EMI input filters result from the influence of the self-parasitics and mutual couplings of EMI filter components on the transfer function, which is hard to directly measure, and thus to evaluate, cf. Fig. 1.2.

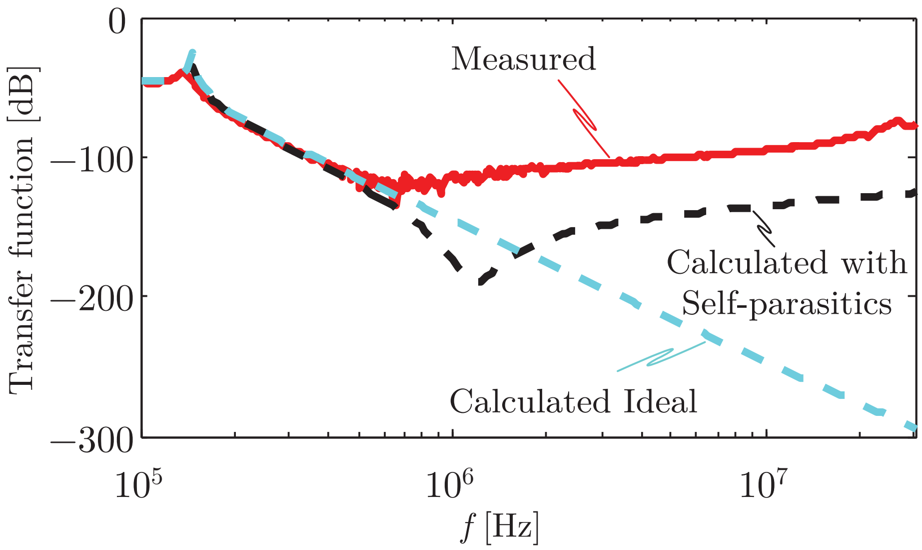

Figure 1.2: EMI filter transfer functions: measured, and calculated taking into account only self-parasitics, and assuming ideal behavior of components.

Moreover, EMI filters are prone to the electromagnetic stray fields that have to be taken into account with their integration into power electronic systems. All previously mentioned challenges highlight the need for a fast and accurate CAD tool for power electronics engineers, used during the design phase of EMI input filters.

Currently, in practice, there are two approaches used to efficiently model the HF behavior of EMI filters and power converters and to extract the parasitic parameters that significantly degrade the EMI filter performances in the HF range. The first approach is based on the lumped elements equivalent circuit method, which is using the representation of an EMI filter as a two-port network. An EMI filter is described by its equivalent electric circuit comprising resistors, capacitances and coupled inductors. The self-characteristics of individual components are extracted from impedance measurements and the coupled inductors are calculated from the S-network parameters gained also via the measurements using a network-spectrum analyzer. Namely, this approach requires a set of measurements to be performed in order to correctly characterize all mutual couplings within an EMI filter. The main challenge of this approach is to accuratelly define an equivalent circuit that corresponds to the real physical behavior, and furthermore the complexity of such a circuit can be computationally very expensive, as illustrated in Fig. 1.3 for simple buck converter.

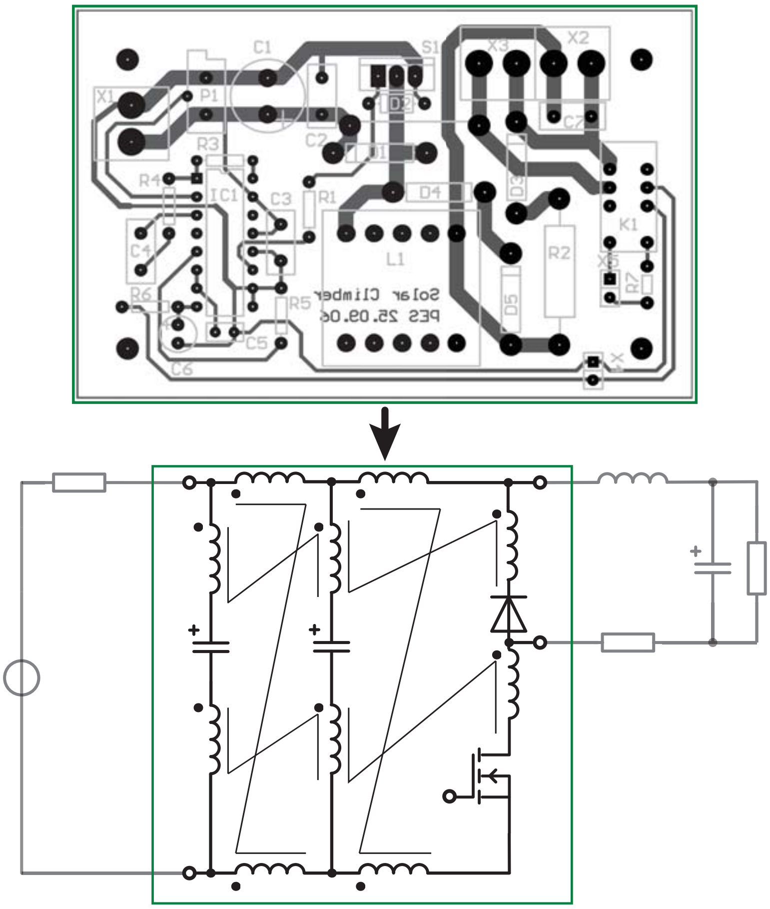

Figure 1.3: Equivalent circuit used to model a PCB layout showing the degree of complexity.

The second approach is via numerical methods, which leads to the Finite Element Method (FEM) and the Partial Element Equivalent Circuit (PEEC) Method as the well-known and most suitable numerical methods for EMI/EMC modeling of power electronics systems, respectively. The numerical methods are based on Maxwell's field equations describing mathematically the geometry of a physical structure and its material properties. The practical implementation and solving of these methods represent the main difficulty for power electronics engineers as it is based on the fundamentals of electromagnetics and computational mathematics, which is rather the focus of the Computational Electromagnetics (CEM) than the Power Electronics (PE) society. Therefore, the applicability of these numerical techniques to the EMI/EMC problems in power electronics, especially for the parasitics extraction, and thus for the design of EMI input filters, is highly based on commercially available software tools. Commercial software can be compared from the aspects of accuracy, speed, flexibility, user-friendliness of the GUI, and its applicability to special applications. Nowadays, with increased computational power of personal computers, the PEEC modeling methodology turns out to be the most suitable method for three-dimensional (3D) EMC modeling and simulation of EMI filters and power converters, as it is presented in this thesis. Accordingly, the main goal of this PhD work is building a virtual prototyping environment for EMI/EMC design of EMI filters and power converters allowing the 3D PEEC-based CAD tool to become the state-of-the-art for the practical EMI filter design.

Importance of the PEEC method for 3D Electromagnetic Modeling in Power Electronics
The PEEC method was developed by Ruehli in the 1970s for 3D electromagnetic modeling of the interconnections within high-density Integrated Circuits (IC) [2]. The PEEC method is based on the integral formulation of Maxwell's field equations and it can be solved in both the time and the frequency domain. The PEEC modeling methodology allows to establish a relation between the circuit theory and the field theory and hence enables efficient solving of so-called circuit-field coupled problems. As the EMI/EMC problems of power electronics can be defined as circuit-field coupled problems, the PEEC method turned out to be very suitable for EMC analysis and modeling in power electronics. The application of the PEEC method in power electronics however, has been delayed as the PEEC-based systems require powerful computational platforms that were unavailable in the 1970s-90s. Nowadays, with the tremendous advancement of computer technology, PEEC models can be integrated easily into standard circuit solvers due

to its circuit description and its capability of a subsequent model order reduction [3].

The first enhancement to the basic PEEC method was introduced in the 1990s taking into account retardation effects and accurate modeling of dielectrics [4, 5]. This enabled the full-wave PEEC based modeling from DC to high frequency. Afterwards, the PEEC modeling was extended for non-orthogonal geometries [6,7], and dispersive dielectrics [8]. Presently, the main challenge of the PEEC method as a linear modeling approach is the modeling of non-linear magnetic components. PEEC-based modeling of nonlinearity, anisotropy, and other magnetic properties is not straightforward, and thus, it is not performed in practice. Accordingly, PE engineers prefer employing FEM-based electromagnetic simulators to extract the parameters of magnetic components for complete EMI/EMC modeling, as described in e.g. [9, 10]. Concerning power electronics applications, this difficulty has influenced the PEEC-based modeling of magnetic components like magnetic inductors and transformers, and it has been seen as the main obstacle to developing a 3D CAD tool for the prediction of EMI/EMC performances of power electronic components and full power converter circuits.

The central topic of this PhD thesis is a new PEEC-based method developed and implemented into a 3D CAD tool, GeckoEMC, which allows the modeling of practical EMI filter inductors. Accordingly, it represents the main contribution of this PhD thesis to the engineering research field dedicated to EMI/EMC modeling and simulation in power electronics.

The current status of the EMC modeling and simulation aimed for power electronics is briefly summarized in the following:

(i) EMC analysis has been performed adopting the simplifications of the actual physical properties of the power components, which leads to either over-design or under-design, i.e. non-optimal design, of the EMI input filters. It has been shown that self-parasitics and mutual coupling effects have to be taken into account when building the EMC models in order to accurately predict the HF performances of power converter systems. This implies a need for a fast and accurate parasitics extraction tool allowing also a comprehensive EMI/EMC modeling of full power electronics circuits.

(ii) The design of the EMI filters is typically performed as trial-and-error process that requires great practical experience and specific knowledge in different fields such as EMC, EMI, and power converters. The selection of the filter topology, and costs and space constraints represent important factors that influence the design of EMI filters to achieve the required noise attenuation with minimal constructional efforts. Therefore, virtual prototyping has been seen as a useful design approach allowing the evaluation of EMI filters with the same topology but different PCB layouts without the need to build different hardware prototypes.

These points are furthermore addressed in more details in this PhD thesis restricting the scope of the research to the single-phase EMI input filters for off-line Switched Mode Power Supplies (SMPS). However, the studied concept of EMC/EMI modeling and simulation are valid in general and it is also applicable to three-phase EMI filters described in [11, 12] based on analytical approximative models.

1.2 Thesis Structure

The main aim of this PhD research is to build a fast 3D CAD PEEC-based virtual prototyping platform, which enables the prediction of the electromagnetic behavior of power electronic converter systems with high accuracy. An EMC modeling environment offers power electronics engineers to efficiently design power electronic systems in compliance with the EMC standards. Moreover, it offers a feature for a comprehensive study of EMI input filter performances and the prediction of its HF behavior taking into account all parasitic and mutual coupling effects.

In **Chapter 2**, the main theory behind the EMC analyses of power converter systems is presented. The starting point is a brief introduction to EMC standards and terminology defined by international and national institutions in order to emphasize the main EMC requirements that have to be met by all power electronic systems. The measurements of conducted and radiated EMI noise levels that have to be performed in accordance to the EMC norms are described. The focus is placed on the EMC problems of commonly used SMPS, which in turn represent potential EMI noise generators, if operated with high switching frequency. The EMC analysis of SMPS is presented as systematic approach, including the identification of dominant noise sources and propagation paths, and furthermore, the implementation of different EMI mitigation techniques. The design of EMI input filters is performed as final step to ensure an EMI noise emission below the specified limits. The challenges, which arise with the design of EMI filters in practice, are investigated.

The topic of **Chapter 3** is 3D electromagnetic modeling and simulation based on numerical techniques with the focus on EMC problems of power electronic systems. The main idea is to introduce the Partial Element Equivalent Circuit (PEEC) method to power electronic engineers as a useful EMI/EMC modeling technique, emphasising its electromagnetic modeling capabilities. The basic principles of the Finite Element Method (FEM) and the PEEC method are furthermore explained in order to point out to main differences between the differential and integral numerical methods and their applicability for the EMI/EMC modeling in power electronics. A brief overview of the existing EMI/EMC simulators dedicated to EMI/EMC modeling of power electronic systems is presented. The modeling of some practical EMI/EMC problems using the developed PEEC-based EMI/EMC simulator is also shown.

The key contribution of this dissertation is presented in **Chapter 4**. This chapter covers the physical and mathematical interpretation of the PEEC modeling approach. The novel extension of the standard PEEC method for modeling of magnetic components used in power electronics, the PEEC-Boundary Integral Method (PEEC-BIM), is described in detail. The modeling of EMI filter inductors is defined as the main task and therefore, the toroidal core shape is investigated first, which is typically used for the design of EMI filter inductors. The developed model of EMI filter inductors is implemented into the developed GeckoEMC tool and verified by both impedance and stray field measurements.

In **Chapter 5**, the PEEC-BIM based modeling of EMI filter capacitors and inductors and PCB layouts are described with respect to their HF characteristics in the wide frequency range up to 30 MHz. The self-parasitics are characterized by the equivalent series inductance ESL and the equivalent series resistance ESR of capacitors and the equivalent parallel capacitance EPC of inductors, which are modeled via the PEEC-BIM method. The geometry and material characteristics of the PEEC-based models are determined to match the measured ESL, ESR, or EPC and actual components properties. The experimental verification of mutual coupling effects shows that the developed PEEC-based models correctly describe both the internal and external electromagnetic behavior of EMI filter components. The PEEC-BIM models are also used for the investigation of different parasitics cancellation techniques proposed in literature. It is shown that the PEEC-BIM modeling can be used to assess the influence of these cancellation techniques on the overall EMI filter behavior. Measurements are performed in order to validate the proposed 3D modeling approach, analyzing different EMI filter structures with the influence of various effects on EMI filter performance such as components parasitics, mutual couplings, PCB layout, component placement, grounding, and electrostatic shielding.

In **Chapter 6**, single-phase single- and two-stage EMI filters are examined applying the PEEC-BIM modeling and simulation. A detailed 3D PEEC-BIM modeling of a practical EMI filter for a PFC rectifier stage is presented. The capabilities of the proposed PEEC-BIM method are demonstrated step-by-step, distinguishing the influence of different passive components on the EMI filter performance. It is shown that parasitic effects can degrade EMI filter performances in the HF range, and therefore, the 3D EMC modeling represents a highly useful tool for the prediction of the EMI filter behavior prior to building hardware prototypes. It also allows to find an optimal EMI filter structure, which is in turn limited by the space constraints in practice. An experimental verification is carried on to validate the proposed method. A good measurement setup consisting of a vector-network analyzer and isolation 1:1 transformers has been built to measure the filter transfer function with minimal external disturbance. The comparison between the PEEC-BIM simulation and the measurements with different transformer configurations allows assessing the electromagnetic disturbance introduced by the measurement set-up itself.

Chapter 7 summarizes the overall results presented in the dissertation and some ideas for future research.

1.3 List of Publications

The parts of this thesis have been published in IEEE journals and international conference proceedings. The list of publications, which resulted from the presented PhD research, is given in the following:

Conference Papers

1. I. Kovačević, A. Müsing, T. Friedli, J. W. Kolar, *Electromagnetic Modeling of EMI Input Filters*, Proc. of the International Confer-

ence of Integrated Power Electronics Systems (CIPS), Nuremberg, Germany, March 6-8, 2012.

2. I. Kovačević, T. Friedli, A. Müsing, J. W. Kolar, *PEEC-based Virtual Design of EMI Input Filters*, Proc. of the 3rd IEEE Energy Conversion Congress & Exposition (ECCE USA), Phoenix, USA, September 17-22, 2011.

3. I. Kovačević, T. Friedli, A. Müsing, J. W. Kolar, *A Full PEEC Modeling of EMI Filter Inductors in Frequency Domain*, Proc. of the 18th International Conference on The Computation of Electromagnetic Field (COMPUMAG), Sydney, Australia, July 12-15, 2011.

4. I. Kovačević, A. Müsing, J. W. Kolar, *PEEC Modeling of Toroidal Magnetic Inductor in Frequency Domain*, Proc. of the International Power Electronic Conference (ECCE Asia), Sapporo, Japan, June 21-24, 2010.

5. I. Kovačević, A. Müsing, J. W. Kolar, *An Extension of PEEC Method for Magnetic Materials Modeling in Frequency Domain*, Proc. of the 14th Biennial IEEE Conference on Electromagnetic Field Computation (CEFC), Chicago IL, USA, May 10-12, 2010.

Journal Papers

1. I. Kovačević, A. Müsing, J. W. Kolar, *An Extension of PEEC Method for Magnetic Materials Modeling in Frequency Domain*, IEEE Trans. Magn., Vol. 47, No. 5, pp. 910-913, May 2011.

2. I. Kovačević, T. Friedli, A. Müsing, J. W. Kolar, *3D Electromagnetic Modeling of Parasitics and Mutual Coupling in EMI Filters*, IEEE Trans. Power Electron., accepted for publication, published on IEEE Xplore Mar. 22, 2013.

3. I. Kovačević, T. Friedli, A. Müsing, J. W. Kolar, *3D Electromagnetic Modeling of EMI Input Filters*, IEEE Trans. Ind. Electron., accepted for publication, published on IEEE Xplore Jan. 24, 2013.

4. I. Kovačević, T. Friedli, A. Müsing, J. W. Kolar, *Full PEEC Modeling of EMI Filter Inductors in the Frequency Domain*, IEEE Trans. Magn., accepted for publication, published on IEEE Xplore Apr. 26, 2013.