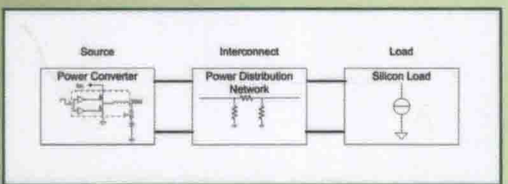
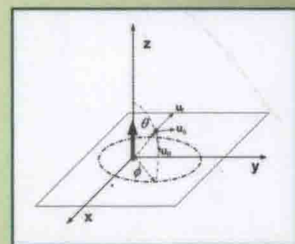
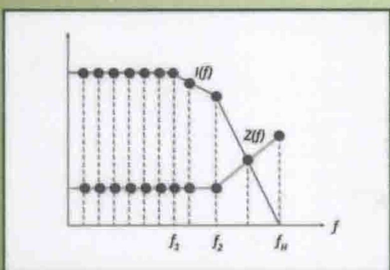
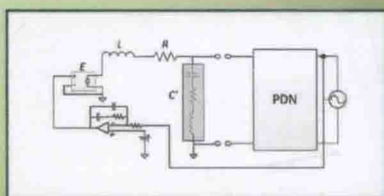
Fundamentals of Power Integrity for Computer Platforms and Systems









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FUNDAMENTALS OF POWER INTEGRITY FOR COMPUTER PLATFORMS AND SYSTEMS

To my wife,
for her strength, love,
and courage

FOREWORD

The development of computing hardware operating at increasingly higher speeds and requiring more power continues at an inexorable pace. Successful development of computing systems requires careful design of hardware so that unintentional analog effects do not seriously compromise or degrade digital performance. This is particularly true with systems operating at high clock speeds and having high power requirements. There are three design arenas that are crucial to successful digital operation of hardware: signal integrity (designing to ensure sufficient integrity of the signal waveform) power integrity (designing to maintain sufficient quality of the power supplied to active devices), and electromagnetic interference/compatibility (EMI/EMC) where the design is tailored to ensure that radio frequency emissions from the digital system do not violate international regulatory limits that are in place to protect the public airwaves. Typically, there are substantial areas of overlap in these design disciplines and in the specific design of any digital hardware system. Each discipline has been studied at length, but the push of faster and higher power hardware requires continued development of the design technologies and techniques embodied in each arena.

This book primarily addresses power integrity and offers an introductory-to-intermediate view of the requirements and design ramifications based on physics fundamentals, rather than on detailed mathematical modeling. A value in this book is that it provides the basic information to allow a problem to be defined without the need for creating a complex mathematical model and also provide means of checking the reasonableness of results obtained from complex models. Power integrity has typically been addressed in the literature as a subtopic of signal integrity at the printed circuit board level, so the author's system view and the consideration of the power integrity of both the integrated circuit package and the integrated circuit die is a valuable contribution to this field and should provide interesting reading for those pursuing this topic. The author has considerable practical experience in power and signal integrity design in the semiconductor industry, which lends credence to this book. I recommend this book to the reader and wish the author much success with its publication.

James L. Knighten, PhD

Hardware Engineer at Teradata Corporation
IEEE Fellow
San Diego, CA
July 25, 2013

PREFACE

This book is an introductory text on power integrity. It is intended for students at the college under graduate level and for engineers who are new to the area of power integrity. It is assumed that the reader has some background in electromagnetics and basic power conversion. However, it has been written with an understanding that many concepts may be foreign even to engineers and thus the basics are covered first. It is also assumed that the reader has a working knowledge of how to use various tools, such as SPICE and math programs, for analysis. This text is *not* intended to teach modeling methods and how to use various field solvers—there are many good texts on these subjects that can be easily found through a search on the Internet or in a college library. The purpose of this book is to focus on some of the fundamentals that are key toward enabling the reader to build a foundation in understanding how to solve a basic power integrity problem without having to resort to modeling in a CAD tool—before that basic understanding ever takes place. Thus, the objective here was to focus on the tools and the methods of the problem—rather than on the *tuning* of the solution to the problem—which is where many good CAD programs excel.

Thus, in that spirit, I set about crafting this book with a few basic goals in mind; first, introduce the concepts of power integrity by utilizing basic analytical tools. Second, structure each chapter so that the complexity increases (for the most part) as one progresses further into the text. Third, emphasize the ability to set up problems—without the use of advanced software programs—enabling the reader to grasp the concepts first before embarking on a complex modeling exercise. Finally, fourth, introduce power integrity from a *systems* perspective rather than focusing on just the network analysis—which appears to be where many texts on power integrity tend to start, and sometimes stop, their learning paths. I hope that the reader will find that I satisfactorily accomplished these goals and that the information within the text is useful.

ACKNOWLEDGMENTS

There were many people who have guided me over the years, and I wish I could thank them all explicitly here. To those who are not mentioned below, my gratitude is given nonetheless.

To my editors at Wiley, for their patience through my wife's illness. To my two long time mentors and friends David H. Hartke and Dr. James L. Knighten for their tremendous faith and guidance throughout the years—and thanks again Jim for the Foreword and edit suggestions as well! To Dr. Keith Muller—words would not suffice here to express my thanks. To the late, great, Dr. Clayton R. Paul for his faith in me and support. To my friend Joseph S. Riel for his brilliance and insights in so many ways. To Dr. Jack Shemer for his incredible business teachings and leadership. To Dr. David Hochanson, for those long deep talks. To Dr. James L. Drewniak for his help and insights thoughout the years—and, of course, to the UMR team. To Dr. Kevin Quest, my friend and advisor. To Dr. Henry Koertzen for his depth of knowledge in power technologies and edit suggestions. To my father and sister for our talks. To my friends Bob Fite and Ed Stanford at Intel. To my team at Intel—you know who you are. To my son for his patience—especially all those nights we had to miss. And finally, to my wife, to whom this book is dedicated, and who has graciously stood by throughout while remaining so amazingly strong under some very tough circumstances. I thank you all.

ACRONYMS

PI power integrity
PDN power distribution network
VR voltage regulator
TD time-domain
FD frequency-domain
AVP adaptive voltage positioning
VID voltage identification
DAC digital to analog converter
RSS root sum of squares
PCB printed circuit board
MOSFET metal oxide semiconductor field effect transistor
SSN simultaneous switching noise
FCC federal communication commission
OATS open area test site
RF radio frequency
DUT device under test
SA spectrum analyzer
FFT fast fourier transform
SoC system on a chip
MD mask designer
PMIC power management integrated circuit

CONTENTS

1

INTRODUCTION TO POWER INTEGRITY

This book examines the design concepts of power delivery to modern microprocessors and other related high-speed silicon devices. Today this field is termed power integrity. This chapter provides the background information on what has driven the need for platform power integrity analysis in this relatively new field. The platform is essentially the computer board with its multiple silicon devices, in addition to the power sources, or *converters*, that power them. The subject of power conversion will be examined, in particular as it applies to areas relevant to power integrity engineering. For computer systems the power conversion is mainly in the DC–DC conversion area. The chapters that follow will discuss areas relevant to power integrity analysis—circuit and field theory, modeling, the power delivery network (PDN) and boundary analysis, and other system considerations—and end with an examination of system noise, loadline, and measurement techniques. The last chapter will introduce silicon power integrity, along with some advanced interrelated topics, because of the increasing interest now being given to silicon-level power and the problems associated with on-silicon and on-package power delivery.

In the present chapter, power integrity is defined in terms of the paths that make up the PDN. The paths and all their components comprise the PI (power integrity) domain. A historical review of the voltage and current changes over time (using the microprocessor as an example) is provided to show how silicon has been one of the driving forces behind the need for such fundamental power integrity analyses today. The concept of *first principles* is discussed, because utilizing known equations and

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circuit analysis helps one gain insight into complex problems prior to embarking on sophisticated modeling with numerical tools. A discussion of the limitations and boundaries in power distribution analysis follows covering the circuit limitations (noise sensitivity and silicon process technology) of many advanced devices today that can compromise the accuracy of results.

1.1 DEFINITION FOR POWER INTEGRITY

Power integrity as a field of study includes *power conversion*, *power distribution analysis*, *circuit analysis*, and often the *package/board/silicon system analysis*. But PI is not limited to these subjects. The PI engineer should also be versed in thermal and mechanical basics because some problems needing to be solved may include these and components of other disciplines that impact the system under study. A simple, but somewhat limiting definition is:

Power Integrity *The study of the efficacy of the power delivered from the source to the load within an electronic system.*

Today, power integrity engineers versed in other disciplines may need to consider in their analyses the *system's source*, *load*, and *path*. In the past power integrity engineers often excluded the source and load parts of a system. This is understandable because many power integrity problems focused only on the power distribution path. However, today, having knowledge of both the silicon load *and* the power source allows PI engineers to comprehend fully the complexities of the problems that they face. Conversely, many power conversion engineers are required to cross over into the power integrity domain in order to solve their domain's problems. It is therefore reasonable for engineers from both disciplines to move regularly into each other's domains in order to solve their problems satisfactorily.

As Figure 1.1 shows, the primary power source is the power converter. This is a type of DC–DC converter at the motherboard of the server, forming an inter computer platform. The power source to this converter is typically neglected in an analysis. The power converter includes a certain amount of *decoupling* for filtering and charge storage. In the middle of the figure is the PDN, or *power distribution*

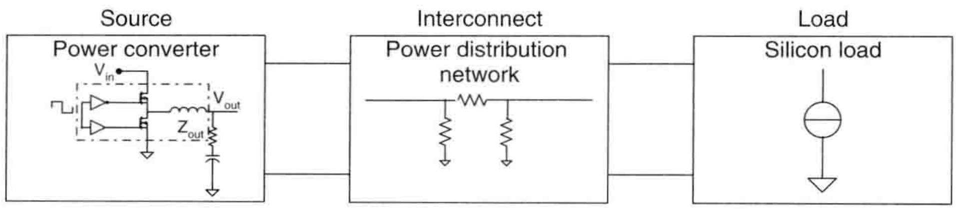

Figure 1.1 Power integrity domain and Scope of influence

network. The PDN typically comprises passive elements from the printed circuit board all the way to the level of the silicon. All of the decoupling and interconnections are included, from the output of the voltage regulator to the load. The printed circuit board and/or design package was where the PI engineer focused in the past. With the more complex recent systems, the PI engineer must often optimize the performance of the *silicon*-level passive and active components, so the circuit load must be considered as well. Note that Figure 1.1 gives a schematic representation of circuit load behavior. This is because modeling the actual behavior of load transistors under all possible conditions is virtually impossible. Nonetheless, knowledge of load behavior is required for PI engineers to do their jobs, and PI engineers must work closely with silicon development teams to gather the data necessary to perform their analyses.

For the PI engineer, at the start of a study, there are many complementary components to consider. Often these are thermal and even mechanical issues that contribute to delivery problems. It is then up to the PI engineer to rework the filter structures in the PDN and, together with the board and silicon teams, to ensure that the power delivery path is performing efficiently. Such analysis requires knowledge of the board's layout, its components, the power source, the load characteristics, the design package, noise coupling to other planes, EMI (electromagnetic interference) issues, and other items that may contribute (potentially) to the results of PI modeling. The assumptions that go into the analysis are a critical part of a PI engineer's responsibilities and the next chapters will explore in detail these assumptions.

1.2 HISTORICAL PERSPECTIVE ON POWER INTEGRITY DRIVERS

The idea of analyzing the power distribution path is not novel. Engineers have been working with the concept of measuring voltages and currents on power lines since the 1920s [1]. However, the need for advanced power integrity techniques in the computer was not realized until recently. The transition from virtually *no* power integrity analysis needed to its being *required* on virtually every platform developed today has been more dramatic than many technologists could have realized. Though noise, EMI, and signal fidelity have traditionally been areas of focus for the system designer, the need for advanced power integrity analysis, relative to the advent of the microprocessor, is still a recent event. Many conferences today are dedicating significant blocks of time to the multitude of papers written on the subject in just the past few years. The main factors behind this trend are a culmination of system metrics: the need for more stringent voltage and current requirements, the increase in voltage rail proliferation (internal and external to the silicon), a dramatic increase in platform and silicon signal densities, and device and platform cost pressures, to name just a few. As evidenced by the previous issues, many of these developments are clearly platform dependent. The issues though vary across each platform type. For example, voltage proliferation and current and voltage requirements may be the main issue on a server platform, whereas cost will typically dominate in a desktop, laptop, or tablet today. Nonetheless, the problems are very similar between them