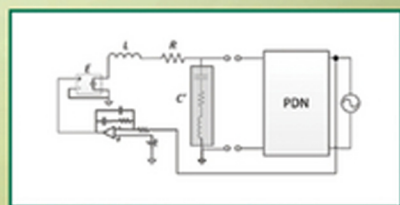
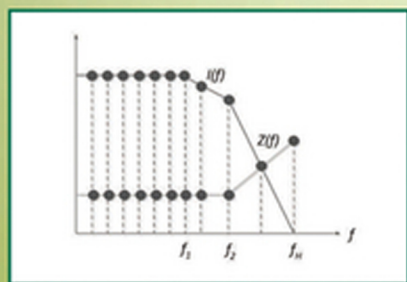
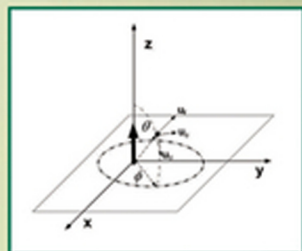
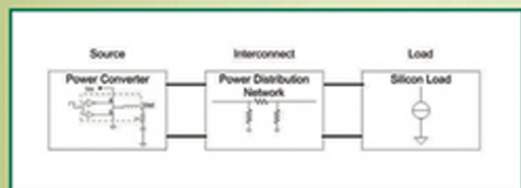


# Fundamentals of Power Integrity for Computer Platforms and Systems



J. TED DiBENE II

WILEY



**FUNDAMENTALS  
OF POWER INTEGRITY  
FOR COMPUTER  
PLATFORMS  
AND SYSTEMS**



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**J. TED DIBENE II**

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



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# 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.

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# 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



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# 1

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## 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

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.

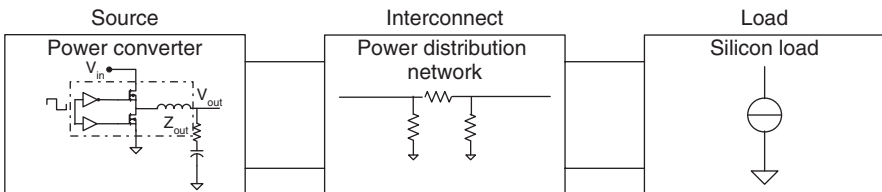
## 1.1 DEFINITION FOR POWER INTEGRITY

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.

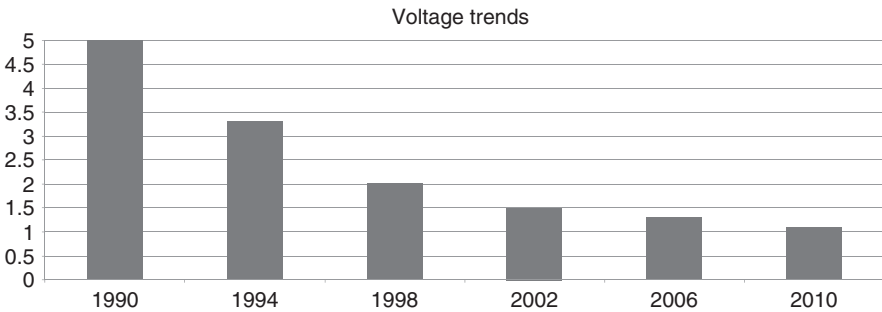
## 1.2 HISTORICAL PERSPECTIVE ON POWER INTEGRITY DRIVERS

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

and the migration toward a deeper understanding of the state of the art is clearly needed today.

One very dramatic change that has occurred over the past two decades is in silicon power requirements. The relatively fast decline in source voltages and the sudden increase in currents delivered to silicon over this time has necessitated a stringent examination of the power delivery path—particularly for complex devices, such as microprocessors [3].<sup>1</sup> Figure 1.2 shows the voltage decline over time for microprocessor devices for the past 20 years. The changes in supply voltage have come about for a number of reasons. First, as complexity and transistor density has increased, so has the power required for the device. This has necessitated that the voltage be dropped to help reduce the overall power to the device. Second, as the silicon process geometries have shrunk, so has the requirement to reduce the voltages to the devices to prevent their damage. Thus manufacturing constraints and device physics have also driven the need to reduce the voltage to these devices as much as any factor. This has in turn driven the power converter industry to follow suit to supply suitable power to these complex devices [2]. The simple graph in Figure 1.2, however, may be a bit misleading. The voltages to these devices have *indeed* been reduced over the past decade. However, today, many high performance silicon devices and the *system on a chip* (SoC) devices are highly integrated, meaning they have other functional units in them besides the processing units. Thus this graph represents—for the silicon parts in more recent years—merely the voltage trends for the processing *elements*. For example, many processors have multiple processing *cores*, IO, memory, graphics, and power management units in them as well. The implication here is that most high-performance silicon chips now require *more* than one supply voltage to power these different units, and most of the supply rails for these units require *different* voltages.

The other important development to note is the *lower* core voltages in use today compared to just a mere 20 years ago. This change alone has led the rise toward power integrity analysis. Today, most core voltages are at or below one volt.



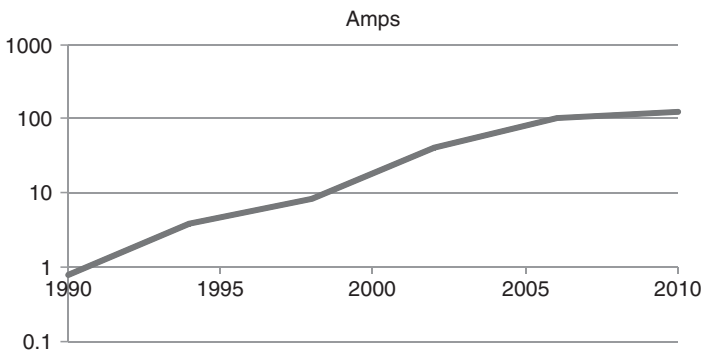
**Figure 1.2** Microprocessor voltage trends over the past 20-year period

<sup>1</sup>The trend is not limited to microprocessors. Many other high-performance devices had also been operating at these voltage levels at this time.

This means that even the smallest noise voltage on the power bus may influence functional operation and cause data corruption. In 1990, the 5-V power rail to the processor (or the high-performance computing device) was typically specified at  $\pm 5\%$ , or  $\pm 250$  mV. Over time the tolerance for this power source has decreased to a voltage setpoint of only  $\pm 1\%$  today. Most complex devices require this tight regulation to ensure proper frequency and efficacy of operation. If a supply voltage were varied over the 500-mV range ( $\pm 250$  mV), for a 1V rail the voltage tolerance would be today  $\pm 25\%$ ! Clearly, it is highly unlikely that the device would even function under such conditions. Thus, the noise margins (by necessity) have been required to shrink along with the voltage source to ensure the correct operation of the processor. This has made the job of the power integrity engineer that much more important.

An interesting change was also made in *current* over this same period; see Figure 1.3. The increase in current is graphed in a *log scale* to show the progression of growth. Notice that the *peak currents*<sup>2</sup> have increased by more than *two orders of magnitude* over just one decade.<sup>3</sup> So dynamic was this change that independent groups and even whole *companies* were created to help with the high current distribution problems that affected the motherboards and processing systems.<sup>4</sup> This change *alone* has necessitated the need for more expertise in power system and power integrity analysis.

Figure 1.4 gives a pictorial representation of this evolution. In 1990, the typical personal computer had noncolor screen (though color screens were coming into use at that time), a large ATX box that sat under the desk, and a large dot-matrix printer. Wireless communications in the office were either not available or

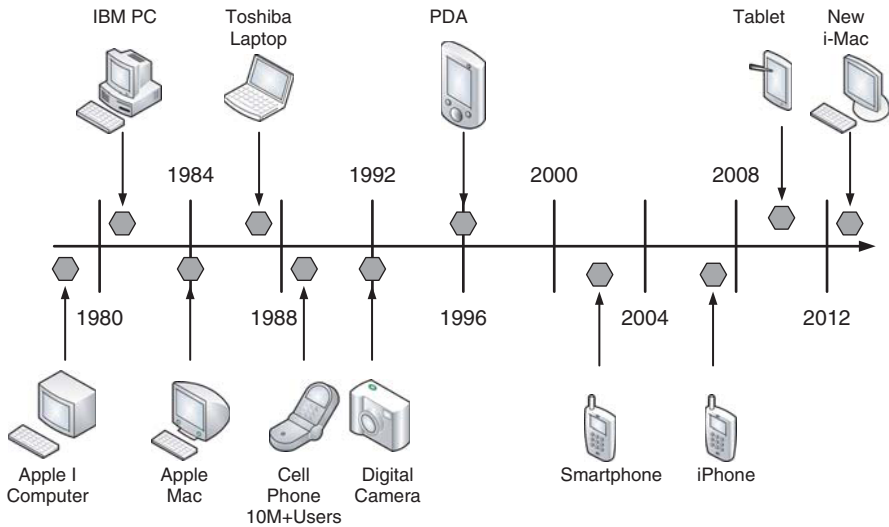


**Figure 1.3** Peak current trends for high-performance silicon over the past 20-year period

<sup>2</sup>This trend does not represent the continuous, or steady-state current changes. These are typically lower than the peak currents.

<sup>3</sup>The current trend data are highly dependent on specific devices and are not representative of every device. The trends are also independent of manufacturer and considered generic.

<sup>4</sup>Many of the companies are focused on delivering CAD software for analysis purpose. A simple search on the internet on the subject of Power Integrity reveals a number of these.



**Figure 1.4** Evolution of modern computers

just starting. Today, many people use a tablet or smartphone to communicate in their personal and professional lives. The Internet has also revolutionized the way people use electronic systems.

What is *not* shown in the Figure 1.4 is the evolution of the *silicon* over the same period of time. *Moore's Law* has continued to hold true over this time window as well, as the number of transistors has doubled in computing hardware every 18 months. No doubt, as transistor density increases, so will the need to power these transistors with high-quality power.

The merge of communications and computers that has occurred over the past 20 years has changed the way people live their daily lives. This change has also motivated the development of power integrity as a separate field of study. While, in many ways, the field of power integrity is very new, it is expected to grow rigorously in the coming years to meet advances in silicon and platform power delivery. And, as technology progresses, so will the demand for well-trained power integrity engineers.

### 1.3 FIRST PRINCIPLES ANALYSIS

As computers have evolved, so has the software that runs on computer systems. For the developer or engineer, the modeling requirements have become ever more sophisticated with more options and methods to analyze complex problems. CAD tools that utilize SPICE or numerical solvers with advanced models to solve for electromagnetic fields have grown substantially over the past two decades. In fact,

today, more engineers have become heavily reliant upon these tools to resolve PI problems.

Moreover, in today's fast-paced world of research and development, engineers are faced with solving complex circuit problems that require a strong background in other fields. That is to say, despite the fact that more sophisticated tools are now at their disposal, engineers cannot bypass this deeper learning and dive headlong into a simulation effort with the goal, inevitably, to deliver a solution that is satisfactory and meets the required deadline. The result is often error in the analytical process—or a less than optimal solution—and more lost time in the end to find a more adequate solution based on the first simulation. Those engineers coming out of school who lean too heavily upon the available tools and less upon the basics to solve difficult problems soon become frustrated.

However, the blame is not with the CAD companies and the ease in which their tools generate data. It is that professional engineers often lack preparation in analytical skills.

Not surprisingly, there is a good solution to this problem. In most cases, seemingly overly complex problems can be solved by understanding the *first principles* behind such problems before embarking on a detailed model and simulation effort. This does not mean that the final solution to the problem will be any simpler than the numerical modeling effort; it just means that the *estimates* and *boundaries* placed upon the problem (initially) will lead to a deeper understanding of the problem and thus a more efficient path to the solution.

### 1.3.1 Steps to Solve Power Distribution Problems

The *first principles analysis* is simply a way of using basic equations and physics (tools engineers have encountered in their education) to describe a problem, and then using those tools to solve the problem. Usually the mathematical representations used to describe the problem are close *approximations* to the exact equations. For this reason, it is important to have the understanding that comes with the mathematics. Indeed, many complex problems can be solved quickly, using pen and paper, a simple spreadsheet, or a math program, and thus give the engineer quick insight into the boundaries of the solution. *First principles* will allow engineers to solve a related problem in order to gain insight into the solution of the problem of interest. While the results are typically an approximation to the actual solution, they are satisfactory for the initial analysis.

Invariably, the key for gaining a reasonable result to a complex problem is twofold: first, the assumptions must be within the bounds of physical behavior, and second, the limitations of the physical and mathematical models must be understood up front. The steps in solving a problem using the *first principles method* are straightforward and have been used by engineers in schools and in their professions for many years, though perhaps not known by this term. The steps outlined below are for solving a simple AC, or frequency-dependent, power integrity distribution problem. However, the same method could be used for any engineering problem.

1. Determine the result you expect to achieve, (Is this an impedance profile? Filter analysis? What is the output you expect to have?) Here, the objective is to capture the AC impedance across a given bandwidth.
2. Determine the relative positions of the components involved in the distribution and their dimensions relative to each other. Typically, this means sketching a plan and/or a cross-sectional view of the problem. For this problem, a cross-section of the various distribution networks may be drawn with placement of the components in the “plan view” of the networks.
3. Create a simple schematic of the problem. If the problem is too cumbersome or large, break it into subsections and analyze each subsection one at a time. Confine them into larger sections and re-analyze. Here again, draw the network components (R, L, and C’s).
4. Fill in the values for the schematic, starting with the known quantities (e.g., the capacitors).
5. Extract the interconnecting values from the basic equations and add these to the schematic to complete it. Here, one would use the tools of the later chapters of this book to extract these values, which are typically approximations to the exact values. Check to determine if each approximation is satisfactory for the desired estimation.
6. Determine, using simple hand calculations, a math program or, using SPICE, the solution, then examine the results.
7. Check the data against the simplifications. Typically, this means shorting or opening parts of the circuit to see if the results make sense. This does not always guarantee the assumptions or analysis is correct, but it is a good first check on the data.

This *first principles* method will work for most problems, such as time-domain analyses, with minimal modifications. It is also possible to combine it with numerical results obtained from data of other programs, published papers, and so forth. In any case, some simplifications will need to be made to link data to the simple model obtained by these from first-principles steps.

These seven steps are essentially a variant on the *scientific method*. So the process is clearly not new. These steps will always cut down the number of simulations and modeling iterations used because they provide the engineer with a strong foundation on where to start in the analysis process and give some insights that can improve on the early assumptions. Later in this book, some further tools that support this procedure will be discussed, along with some illustrative examples. It is, however, assumed that the reader has basic knowledge of the equations used in solving the type of power integrity problems illustrated previously. The rest of this section sets the *foundation* for the analyses used throughout this text.

It should be noted that it is not the intention here to replace detailed numerical modeling with the *first principles* method. The main purpose is to show how a strong analytical foundation can help the power integrity engineer solve problems more efficiently using these additional skill sets.