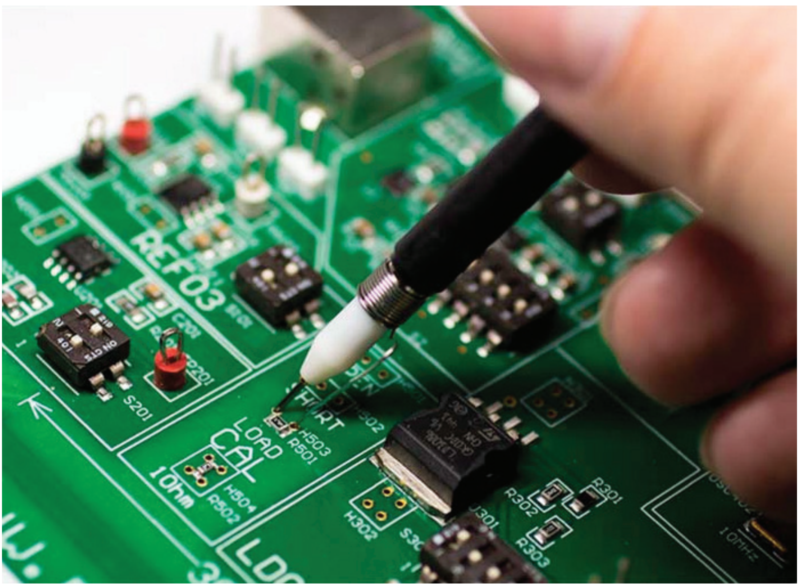
Power Integrity

Measuring, Optimizing and Troubleshooting Power-Related Parameters in Electronics Systems



The Faraday Press Edition

Steven M. Sandler

Power Integrity: Measuring, Optimizing and Troubleshooting Power-Related Parameters in Electronics Systems

Other books by Steven M. Sandler

Switched-Mode Power Supply Design with SPICE
Power Integrity Using ADS (with Anto K. Davis)
SPICE Circuit Handbook
Measuring Power: Application Notebook

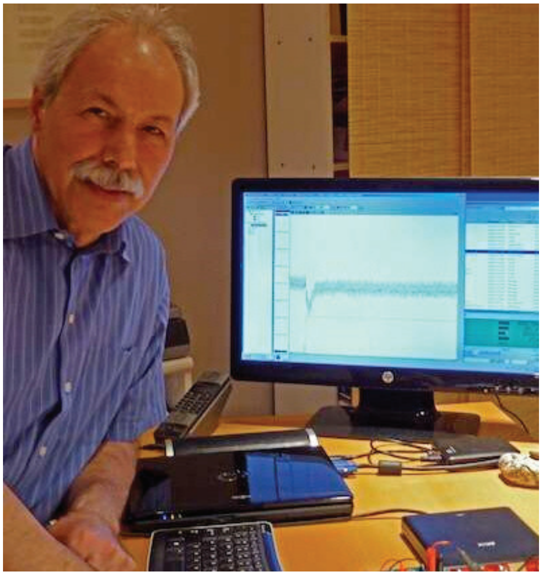
Print ISBN 978-1-960405-06-7

Cover Design by Guy D. Corp, www.GrafixCorp.com

www.FaradayPress.com
1000 West Apache Trail—Suite 126
Apache Junction, AZ 85120 USA

Dedication

THIS BOOK IS dedicated to my wife, Susan. She had the very difficult job of keeping my stress level down and my outlook up. She sacrificed the many hours I spent in my "man cave" making measurements rather than spending time with her. When I (frequently) whined about how much work writing this book was, she never said "I told you so", but gave me the pep talk I needed to keep me motivated. Sweetheart, I love you.



Foreword

WHEN I HEAR the name of Steve Sandler, the first thing that comes to my mind is his long list of excellent publications and books about power converter circuits that go back decades. Second, in most recent years, the impressive range of power integrity test accessories envisioned and made reality for all of us in the industry. Not only do I value and trust Steve as an excellent engineer, I also count him among my friends. For both reasons I am truly honored to write this foreword for his new edition of his book *Power Integrity*.

This book is a very valuable summary of power integrity measurement and test principles and can serve as a useful reference book for all practicing technicians and engineers, who need to decide what should and can be measured—with what—in today's electronic circuits.

What significantly increases the value of the book is the collaborative effort of major players in the test and measurement industry so different test and measurement approaches can be compared as implemented by different companies using different instruments. This fact is also underlined by the long list of people in the Acknowledgement section.

When people want to do careful and thorough designs, the result has to be validated. Before the circuit or system is built, it can be simulated, but the real test is when we have the hardware built and measure it.

Today we have a large choice of software for power integrity purposes, ranging from the simple and free to the complicated and expensive. Also, software changes fast; bug fixes, feature updates and full revisions come to market regularly, sometime two or three times a year. Unfortunately, often they become obsolete or incompatible equally quickly. As opposed to software tools, hardware equipment, especially professional test equipments, tend to have longer design cycles, but they also stay relevant and useful much longer. This is true also for instruments used for power-integrity measurements.

What usually lags is the development of smaller accessories that may serve specialized purposes and make general-purpose test instruments suitable for the various power integrity tests. As the power integrity discipline gradually became relevant for more and more users in the 1990s, existing instruments, like some low-frequency network analyzers, quickly became the preferred choice to measure the frequency domain behavior of the power delivery network, but for years I had to create my own home-made probes, common-mode transformers, injectors, just to name a few, to do the necessary measurements.

It was a very welcome change when Picotest entered the market and started to make such accessories in high quality and professional form. I have always been happy to take a look at the new accessories before they got finalized, try them out and share my comments, suggestions and feedback. These accessories are essential in power integrity labs, regardless of the manufacturer of the instrument we use them with.

There are many things I like about this book.

For one, the many illustrations. I am a visual type of person, so, for me, seeing what we are talking about is important. As the saying goes "a picture is worth of thousand words." Good pictures like the setup photos in this book, are worth millions of words. They show a lot of additional details that the figure captions and the text going with the figures can not capture.

The illustration photos and resultant screen captures are masterfully arranged to summarize each particular message in a clear way. What makes these illustrations even more valuable is the fact that Steve is a practicing engineer himself, so he understands what is important for fellow engineers to observe.

The Tricks and Tips at the end of each chapter are based on decades of Steve's experience and should serve as important guidance for anyone entering the field of power integrity. So many times we have seen results presented based on measurement-only or simulation-only, lacking any checks and tests of the process used to generate the data. Though we cannot (and should not) always aim for perfection, many times we consciously settle for a 'good enough' result, but the conclusions still have to be based on solid and trusted measurements or simulation data, or, even better, correlated data, data sufficiently above the noise floor that does not include masking noise picked up from the surroundings or are based on invalid calibration or wrong simulation settings, just to name a few of the common pitfalls that are hard to recognize without careful cross checking—even for a trained set of eyes.

And last, but not least, I like the fact that the book brings together the different domains (time, frequency, impedance) and the three major disciplines (power integrity, signal integrity and electromagnetic compatibility) that are all important for us practicing engineers to create successful designs and perform proper measurements and simulations.

When I completed my first book, *Frequency-Domain Characterization of Power Distribution Networks*, none of the great accessories described in this book were available. As a welcome change, now, many years later, there is an ever-growing list of probes, active and passive devices, software, device models and tutorial videos are readily available to support our power integrity work.

Finally, I want to thank Steve for putting in the time and effort to create this book; I am sure it will serve as a valuable reference for many of us for years to come.

—Istvan Novak

Istvan can be found on LinkedIn
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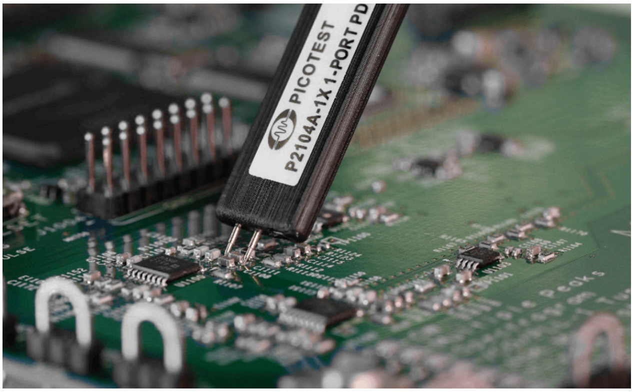

Acknowledgments

WRITING THIS BOOK was a major undertaking. Of course writing any book is a lot of work, but the vast range of instruments necessary to perform the measurements and finding ideal examples to measure stepped it up a bit. Many of the concepts in this book may be new and so the information had to be presented very clearly and concisely. This effort required a lot of support from many individuals and companies. Without this support, I would never have been able to complete this book. I also had a record number of peer reviewers for this book. I am forever grateful to the following individuals and companies and apologize profusely in the event I left anyone out.

I want to thank my editor, Michael McCabe, Kritika Kaushik and all of the folks at McGraw-Hill for their work in creating the first edition of this book.

Thanks to my long term friend and business partner, Charles Hymowitz, Vice President of Sales and Marketing for Picotest, and CEO of AEi Systems. He read every page, edited, commented, and offered many helpful suggestions to make this a better book. Thank you does not seem to cover it, but thanks.

Bernhard Baumgartner, Florian Hämmerle, and Wolfgang Schenk of OMICRON Lab for their constant support, for including the noninvasive measurement in their instrument and for being great friends in addition to sales partners. Thanks for the support and the many helpful comments and suggestions.

Mark Roberts, Stacy Hoffacker, Mike Mende, Amy Higgins, and Tom Lenihan from Tektronix were always ready and willing to help, whether it was to discuss equipment, answer questions, or arrange the shipment of loaner instruments to and from my lab. They also offered some comments and suggestions.

David Tanaka, Yasuhiro Mori, Eileen Meenan, and Hiroshi Kanda from Agilent Technologies for the tremendous knowledge they possess regarding their instruments and their willingness to share some of it with me. I also thank them for arranging the shipment of loaner instruments in and out of my lab.

Dan Burtraw, David Rishavy, and Mike Schnecker from Rohde-Schwarz for arranging the loan of their RTO1044 oscilloscope, for answering the many questions I asked, and for providing helpful comments and suggestions helping to make this a better book.

Bob Hahnke, Steve Murphy, Stephen Mueller, and Kathleen Woods from Teledyne Lecroy for their support of demo equipment and for the helpful comments they provided.

Hawk Shang of PICOTEST Corp for his generous support of our projects, for making excellent general purpose test equipment, and for manufacturing the Picotest signal injectors. Hawk, thank you for all that you do.

Chris Hewson of Power Electronic Measurement for providing the CWT015 probe used in this book as well as answering my questions about Rogowski current probes in general.

Paul Ho, Nazila Arefazar, Cesar Redon, Gordon Leverich, Michael Lui, Shivam Patel, Sahar Sadeghi, Josh Behdad, John Aschennbrenner and Tom Boehler of AEi Systems, and Dave Morrison of How2Power.com for all of your comments and suggestions to make this a better book. Thanks to Tim Guzman, also of AEi Systems, for his photography and image contributions.

Shawn Winchester and Artescapes for enhancing many of the oscilloscope and spectrum analyzer images to make them clearer and easier to see. Shawn also managed daily operations at Picotest, allowing me to focus on writing this book.

To all of you, "thanks" doesn't say enough, but I could not have finished this book without you.

The index was created and revised by Robert Swanson and Zurain Shahzad. Zurain can be found on LinkedIn at: https://www.linkedin.com/in/zurain-shahzad-3a367a204/

During a May 2013 visit to Austria, while having dinner in a medieval castle with Bernhard Baumgartner, my daughter Rachel Sandler and a few others, we discussed what makes books popular in this generation. The final conclusion was that to be successful, the book must include dragons.

Not just any dragons, but medieval dragons.

I am not superstitious, but just to be safe I have included the following image and hope it will help make this book a best seller.

Image credit: Elena Schweitzer/123RF.com

What has changed since this Book was originally Published?

Part 1

Everything!

What has changed since this Book was originally Published?

Part 2

WOULD YOU LIKE a less frivolous answer? Among the many things which have changed:

- Impedances got lower. What was once measured in milliohms is now measured in micro-ohms.
- Accurately measuring lower impedances requires better common-mode isolators.
- Probing became much more difficult and a focus of interest.
- The Non-Invasive Stability Margin (NISM) calculation is becoming more mainstream and is now supported by modern software tools and equipment.
- Most oscilloscopes can now directly do impedance and PSRR measurements…and very soon will also directly measure NISM.

About the Author

STEVEN M. SANDLER has been in the power conversion business since 1976. He has worked for companies such as Acme Electric, Lambda Electronics, Venus Scientific, Transistor Devices, Keltec-Florida and Signal Technology. The majority of his work has been involved with the development of power conversion products for commercial, military and space platforms. He was the founder of AEi, a company specializing in the computer simulation and worst case analysis of power electronics. AEi performed a great deal of the computer simulation of the power electronics used on the International Space Station as well as many other platforms.

In 2010, Steve founded Picotest, a company dedicated to providing instruments, accessories and training to support electronic test and measurements, with an emphasis on power integrity solutions. Picotest is headquartered in Phoenix, AZ.

For more information on Picotest, please contact the company at 1-877-914-PICO or visit www.Picotest.com.

Steve can be found on LinkedIn
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PICOTEST

Publisher's Note

THIS BOOK IS an updated reprint of Steve's historic *Power Integrity*. One of the benefits of working with power supplies is that the underlying physics are timeless and eternal. Magnetics, capacitance, Ohm's Law (this should really be called Ohm's relation…a useful relation between voltage and current we call ohms), frequency effects and control loops are not subjective.

The ways applied physics works today is the way it will work forever. What a luxury compared to other technical fields where information and strategies have a half-life measured in years—often just a few years. By half-life, I mean that period when half what the engineer knows becomes obsolete.

Thus, a book like this will always contain useful information. Forever. Maybe this is as close to immortality as we can achieve.

All that said, many things change and will continue to change. In fact, the evolution of our trade is accelerating at a breathtaking pace.

I'm halfway kidding, but it seems like modern loads evolve to maximize the difficulty of creating a robust design. Core voltages are headed toward zero. It's conceivable a future power supply design will require tight tolerance around 0.3V. ±3% would require a total tolerance window of 18mV and that includes initial setpoint, ripple and transient response.

Load currents are increasing. Perhaps this imaginary power supply will have to deliver 2,000W. That's 6667A @ 0.3V.

The frequency content of load transients is increasing. Perhaps this imaginary power supply will need a flat impedance at very high frequency, like 30Ghz.

Power densities are increasing. Remember the good old days when 100W per cubic inch was state-of-the art?

All this reminds me of a question I recently asked Steve…

Ken: Let's say present trends continue and in 10 years we're asked to deliver 0.1 V at 10 kW to serve some monster ASIC. How in the world are we going to do it?

Steve: That's the fun part—we have no idea, yet. When there is a void, rest assured that engineers will find a way to fill it! There are sub-threshold devices now operating at several hundred millivolts. Devices are slow there, and so the current isn't high.

But who knows what the future will bring?

Today there is an explosion of immersive devices running in liquid to keep them cool. That's inefficient, so we push for smaller geometries to reduce the current. But then the devices are faster, so we run them at higher rates and the current climbs back up.

It's a never ending cycle and I love it!

Bring it on.

Steve condensed a lifetime of knowledge and experience into this book. It will, as much as anything can, prepare you for the future.

What's left? To get out there and get it done.

Keep your impedances flat and no higher (or lower) than necessary, my friends.

—Ken Coffman

Ken can be found on LinkedIn
https://www.linkedin.com/in/kencoffman/

Chapter One

Introduction

I CHOSE TO write this book because it has become increasingly clear that much of the data that we need to do our jobs as electronics engineers is lacking. Either the data we need is missing entirely or when we do have data—that we created or received from others—it frequently lacks completeness, fidelity and/or accuracy.

There are a variety of reasons for these shortcomings, and it is my hope that this book will provide useful information and direction to several different audiences.

One goal for this book is to show component and device manufacturers the breadth and fidelity of the data end-users really do need to do their jobs, as well as to help them improve their datasheets accordingly.

Another goal is to provide design and test engineers with methods that enable them to generate higher fidelity measurements with less effort by using appropriate techniques and equipment. It is also my hope that test instrument manufacturers will gain insight into the issues engineers face, as well as how they can improve their equipment capabilities, operating systems, software, and documentation.

Lastly, and maybe most importantly, this book also illustrates the impact power supply performance has on the systems they serve.

What You Will Learn

This book provides useful insights into all aspects of making high fidelity measurements, including power, high-speed, and low-power analog and instrumentation circuits.

Technology continuously, consistently, and rapidly advances. A few new technologies, such as eGaN, GaN, SiC and GaAs, will present new measurement challenges due to the combination of high voltage and ultra-high speed switching. Switching frequencies and edge speeds are increasing, while devices are becoming more highly integrated.

For example, many Point of Load (POLs) switching regulators now include the switching MOSFETs internally. Some devices include the output inductor internally as well. These advances in technology make measurement more difficult and demand a better understanding of measurement fundamentals in order to obtain accurate results. The evolution of high speed FPGAs and CPUs have propelled the measurement of Power Distribution Networks (PDNs) to magnitudes below 1 milliohm and to frequencies above 10 GHz.

Once the need for a measurement is established, there are several important decisions that need to be made. These decisions relate to the measurement domain, the selection of appropriate test equipment, the impact of the connection of the equipment to the device being tested and the interpretation of the acquired data. This book provides the necessary information to evaluate the needs of the measurement and make the best decisions to achieve high fidelity results.

I highly recommend reading the first section of the book

(Chapters One through Six) prior to making any of the measurements discussed. This material provides all of the background information related to equipment selection and fidelity, as well as how test equipment should be interfaced to the device being tested. The relative significance of each type of test at the system level is also discussed.

Once you have reviewed the introductory material, the remainder (Chapters 7 through 15) can be used as reference allowing you the freedom to refer to the material on each type of measurement as needed.

Who Will Benefit from This Book?

This book is written for engineers and technicians of all levels of experience, including those working in field support, design and test engineering disciplines. It is also appropriate for engineering managers, as well as those that are responsible for the leasing or purchasing of test equipment.

In most instances, engineers are underequipped for the measurements they need to perform. More often than not this is due to a lack of understanding of what minimum set of capabilities are actually required to make measurements needed for the particular application. For engineers and management alike it should be noted that there are substantial costs for bad or misleading data.

This book addresses these issues for both the test engineer and the purchaser trying to secure the least expensive solution.

The General Format of This Book

As noted above, this book is written in two sections. The first section is dedicated to the available types of test equipment, measurement fundamentals and interfacing or connecting the test equipment to the Device-Under-Test (DUT).

The second section of the book addresses the specifics of making particular measurements. Each chapter discusses one or more specific measurement methods. Each measurement method includes a brief discussion of the measurement including why it's important.

Additionally, each measurement method includes setup pictures, pros and cons of the measurement method, tips and/or hints, and example measurements.

Why Measure?

It seems appropriate to start a book about measurement fundamentals by considering the goals we hope to achieve. To that end, this book takes the viewpoint that the end goal of the learning process is to enable the reader to acquire better (as in more-precise, higher-fidelity) data. There are four major reasons for testing:

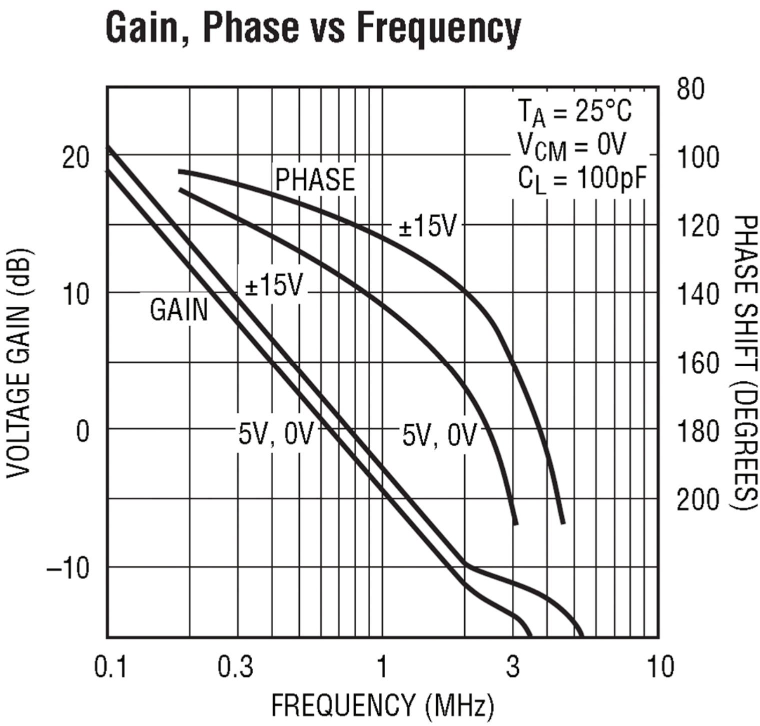
1. To obtain data that is not available or published or validate data that is.
2. To compare possible devices or circuit topologies for use in a design.
3. To troubleshoot.
4. To validate or verify design performance.

Obtain or Validate Data

In many cases, the manufacturer provides very limited data or data that is not at the operating points that we are interested in. As is often the case, data sheets are more of a marketing tool than technical documents.

Some of the more common examples of this are evident in operational amplifier (op-amps), voltage reference and regulator data sheets. In the case of op-amps, the open-loop gain and phase response curves may not be at the operational voltage we plan to use. The open loop gain and phase curve in Figure 1-1 shows the performance a single 5V power supply and also for a ±15V supply. The phase is shifted significantly between these two voltages. How would the performance differ if our circuit operates with ±5V or a single +12V supply?

Likewise, this figure shows a load capacitance of 100pF. If our circuit does not include a 100pF load capacitance, how do we determine the impact of the load capacitance?

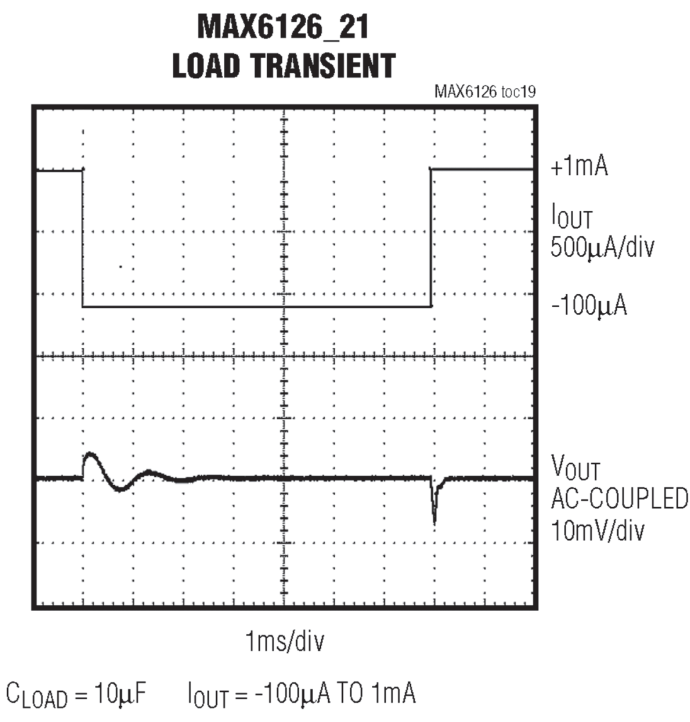


Op-amp Gain and Phase versus Frequency for the LT1014 Op-amp

Figure 1-1

In the cases of voltage references and linear regulators, stability information is generally not provided at all. The load transient of a voltage reference is shown in Figure 1-2. The datasheet does not include a stability plot, but does include the statement that the device is stable with a load capacitance in the range of 0.1-10µF. The step load response shows three rings, indicating less than 'ideal' stability. We'll talk more about this in Chapter 8.

While this reference may not break into a full-blown oscillation under these conditions, it will not perform optimally in terms of regulation, PSRR, or noise. This is a good example of the need to interpret the manufacturer's data. As designers, we have a different idea than the component manufacturers about what constitutes "stable" performance.



Step Load Response of a Voltage Reference

Figure 1-2

Design, Selection and Optimization

We may need to test in order to obtain missing information, as in the case of the op-amp above—or possibly to compare devices from different manufacturers to see which one performs better in the circuit.

An example of this is seen in Figure 1-3 which compares the PSRR of two linear regulators under the same conditions.

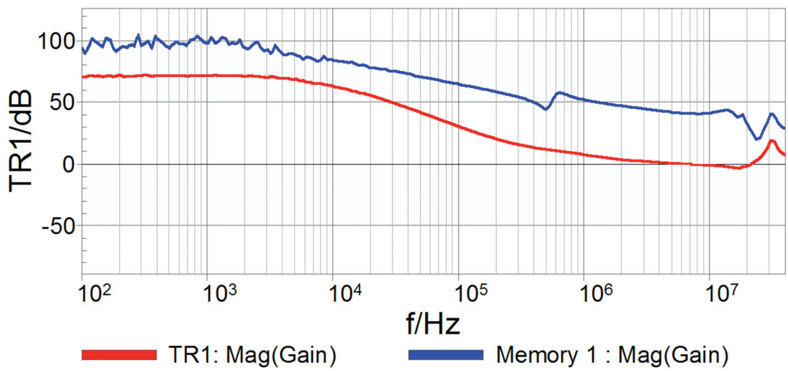
If PSRR is the only concern, it is clear that one of these regulators outperforms the other by a large margin. In fact, the better of the two reveals the noise floor of the measurement to be 100dB.

Finally, we might use measurements to optimize component values for a new design.

In some cases, this optimization is performed in production, where adjustments are made either by discrete component value selection or by the adjustment of trimmers in order to more precisely set a particular parameter.

In the semiconductor industry, devices such as voltage references and voltage regulators are routinely laser trimmed during manufacturing to improve their performance.

While this optimization process may or may not be automated, the selection is performed in conjunction with a measurement.



PSRR of Two Linear Regulators under the Same Operating Conditions

Figure 1-3

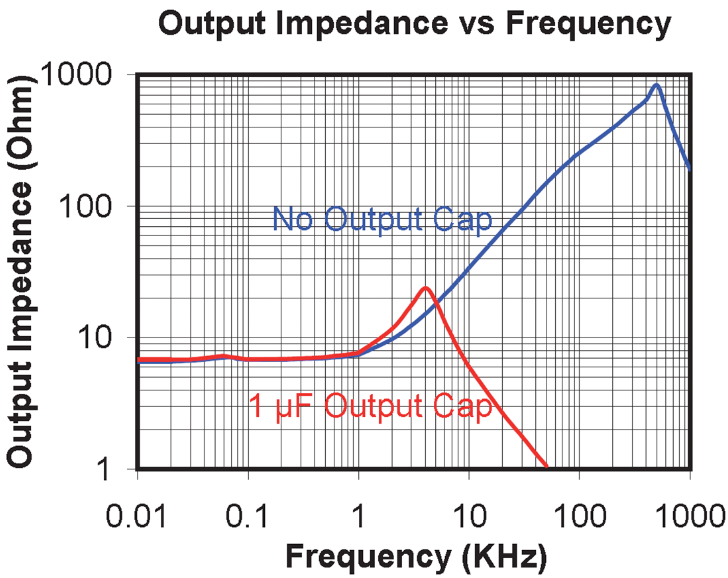
Troubleshooting

As much as we would like to see all of our designs work perfectly the first time we power them up, it rarely works out that way.

In some cases, there may be an interaction between different devices or subsystems, while in other cases there may be a bad component. Yet in other cases, the design may not perform properly because of printed circuit board influences.

The process of troubleshooting is generally dependent on a series of measurements that finally lead us to the culprit. This is one area where an understanding of high fidelity measurement is crucial as the sources of the problems are generally very good at hiding and the quality of the data can be critical to the search. Generally, it falls to the engineers to find these root causes.

Usually the engineer is expected to do so very quickly and under great pressure. In some cases, the underlying problem is simply that the manufacturer provided incorrect or misleading data.



Manufacturer's Datasheet for a Voltage Reference with and without an Output Load Capacitor

Figure 1-4

In the case of Figure 1-4, the manufacturer shows the output impedance of their voltage reference with and without the addition of a 1µF capacitor.

From the 1Ω impedance measurement at 50kHz we can easily calculate the capacitance as:

$$C = \frac{1}{2\pi \cdot (50kHz \cdot 1\Omega)} = 3.2\mu F \qquad 1.1$$

The output capacitor is actually a 3.3µF capacitor and not a 1µF capacitor as stated. These incorrect results are not intentional, nor are they uncommon, offering further evidence for the need to make your own measurements.

In the case of Figure 1-5, we can see that the reference is specified to have an output noise of 9.6PPM or 24µVrms in the bandwidth from 10Hz to 1kHz. Looking at the output impedance plot the device presents a resonant peak at 2kHz to 3kHz, depending on the output capacitor, which is outside of the specified 1kHz bandwidth.

At the peak of the resonance, the output impedance is approximately 600Ω. Simple math tells us that if a noise current of 40nArms is presented to the voltage reference at the resonant frequency, the induced noise equals the specified device noise (i.e. 24µVrms).

This is a simple example of how the interaction between a device and the system in which it resides can present unexpected behavior.

Output Voltage Noise	0.1Hz ≤ f ≤ 10Hz	8	PPM_{p-p}
	10Hz ≤ f ≤ 1kHz	9.6	PPM_{RMS}

Voltage Reference Output Impedance and Noise Specification

Figure 1-5

Validation or Verification

In many instances, engineers verify the performance compliance of their design by comparing measurements of the circuit with a specification or other requirements document.

Once the design is approved, and in production, the performance is generally assured by testing every product manufactured for various performance characteristics. Often a separate, and more comprehensive test set is also performed on a representative sample from a given production lot. Each of these test processes has a different specific goal, though they are all necessary to verify the quality of the product being manufactured. We might also be interested in validating the computer simulation models we are (hopefully) using to analyze performance. It is essential that we validate the accuracy and fidelity of these models before using them.

This validation process is a check and balance that helps to verify that both the design is built as intended and that the model is correlated. In the case where the measurements and simulations do not agree it can be either because the design is not what we modeled, that the model is not correct, or both.

The process of correlating your models with the test measurements helps to resolve such errors.

Terminology

Before taking the discussion further, let's define some basic terms that are used throughout the book.

Measurement

The result of a test. This can be in the form of a number, a curve, or a dataset. The dataset can be amplitude and time, amplitude and phase, amplitude and frequency or a set of singular numbers, such as 5V, 100kHz, i.e. any data that accurately quantifies a performance characteristic.

High Fidelity

Dictionaries generally relate this term to the reproduction of an audio signal along the lines of a reproduction of an electronic signal that is faithful to the original without any added distortion.

For our purposes, we use it to describe a test or simulation result that presents a faithful reproduction of the signal being measured while presenting sufficient detail and clarity to allow precise values to be determined and precise conclusions related to the outcome to be made.

Precise

A measurement that provides a result without uncertainty or ambiguity. The measurement would generally not be subject to different interpretation by different observers.

For example, if we measure the rise time of a MOSFET, the measurement should be *precise* enough that a selection of engineers would all obtain the same value from the measurement.

Non-Invasive

One of our fundamental goals in making high-fidelity, precise measurements is to observe the measurement without impacting or influencing its result.

We take that to mean two different things. First, the connection of the equipment should not in any way impact the measurement. The impact of the equipment connection is one of the more common sources of measurement error.

A simple example is the measurement of a Pulse Width Modulator (PWM) switching frequency.

Many engineers use a passive scope probe to see the timing ramp on an oscilloscope. The oscilloscope probe capacitance is often large enough to change the frequency. This is an *invasive* measurement. Often the connection of test equipment to the device being tested is a limitation of the fidelity and precision of the measurement.

The second interpretation of non-invasive measurement is that the measurement does not require traces to be cut, lifted, unsoldered or otherwise manipulated.

This is a common issue for high-reliability systems, such as aerospace programs, where such invasive measures are not allowed due to risk, cost and manufacturing constraints.

Indirect Measurement

In some cases, it is desirable to measure performance indirectly, meaning that our measurement is not made on the circuit providing the signal, but on the circuit receiving the signal.

For instance, in high-performance clock oscillators, power supply noise is a major contributor to jitter. Power supply noise can degrade the performance of the clock and the circuit using the clock, such as an ADC.

In such cases, we can often measure the power supply noise more accurately by measuring its effect on the clock than we could by measuring the power supply directly.

In-Situ or In-Circuit

This refers to circumstances surrounding the device under test (DUT) and its interconnections to the circuit driving and loading it.

For instance, the power supply source and load connections influence the performance. On the input side, the input filter interacts with the switching power supply. This is one particular circuit example where the interaction between the wiring to the power supply and the power supply itself interact with one another.

There are many other such examples.

As we saw in Figure 1-4, the addition of the external load capacitor *increased* the output impedance of the voltage reference at 4kHz. This is an example of an interaction on the load side of the voltage reference. Such degradation would also be noted in other aspects of performance, such as PSRR.

For these reasons it is often best to make measurements or with the power supply integrated into the system or in-situ.