ELECTRONIC ENGINEERING

ANALOG IC DESIGN with LOW-DROPOUT REGULATORS

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Analog IC Design with Low-Dropout Regulators

To my parents Gladys Maria Mora de Rincón and
Gilberto Rincón Belzares and my brother
Gilberto Alexei Rincón Mora, without whom *I* would not be

About the Author

Gabriel Alfonso Rincón-Mora (B.S., M.S., Ph.D.) worked for Texas Instruments from 1994 to 2003, was appointed an adjunct professor at Georgia Tech in 1999, and became a full-time faculty member in 2001. His scholarly products include five books and one book chapter, 26 patents, over 100 scientific publications, and 26 commercial power management chip designs. He is a Distinguished Lecturer for IEEE CASS, an Associate Editor for IEEE TCAS II, Chair of IEEE's SSCS-CASS chapter, and the recipient of several awards.

Preface

My objective with this book is to introduce, discuss, and illustrate how to design, simulate, build, and test linear low-dropout (LDO) regulator integrated circuits (ICs). The driving inspiration for this effort is the increasingly important role LDO regulator ICs play in modern-day and emerging state-of-the-art applications, as the demand and promise of system-on-chip (SoC) integration continues to drive old and create new markets. The fact is the ubiquity of noisy and unpredictable input sources and loads demands point-of-load (PoL) regulators that draw little to no power yet generate increasingly accurate and fast-responding supply voltages. As a result, mixed-signal ICs that traditionally excluded power-conditioning features must now embed system and PoL power supplies, of which linear regulators comprise a large fraction because their switching counterparts alone generate outputs with unacceptably high noise content.

A pedagogical presentation of linear regulators, however, must invariably include analog IC theory and design because linear regulator ICs are, as much as operational amplifiers (op amps) are, intrinsically analog. As a result, this book, in setting a foundation for linear regulators, also reviews analog theory, as some popular books in the industry also do, but from an intuitive, design-oriented perspective, one that I have found useful and necessary when designing ICs. The idea is to understand devices, circuits, and systems well enough at the physical level to predict their individual and combined characteristics without resorting to equations or books, the by-product of which is also being able to reproduce and verify the equations and theory already found in textbooks. As such, this book presents solid-state semiconductor theory, circuit design and analysis of basic analog building blocks, and feedback concepts, and shows how to apply them to the ac and IC design of an analog system: a linear regulator. In other words, this book includes a fairly comprehensive treatment of analog IC design.

I wrote the book with the intention of introducing and leading a novice microelectronic engineer through the entire analog IC design process, through the eyes of a linear regulator, which embodies numerous aspects of the art. Notwithstanding, the book also aims to enlighten practiced analog IC designers with little experience in the field of regulator ICs. The book also targets experienced regulator IC engineers who wish to not only review some analog and linear regulator principles from an intuitive yet still academic perspective but also ascertain and expand their understanding of the state of the art in the field of linear regulator ICs.

The tone, format, and thought process presented in the book embodies my combined experience in industry as an analog IC designer and academia as professor and researcher. From industry, for instance, I discovered the art of design and the value of product development, so the book places emphasis on intuitive insight, overall system objectives, IC development process, and circuit reliability. As professor and researcher, I continue to learn the art of a pedagogical presentation and the value of technical depth and outside-the-box thinking. What the reader sees in this book is therefore my attempt at drafting a practical yet academically valuable treatment of analog IC design and linear regulator ICs. I must confess, however, I still have much to learn, so I hope my devotion to the book and the field at large ultimately wins enough of the reader's favor to pardon any deficiencies, inconsistencies, and inaccuracies the reader may find in the book.

With respect to organization, I divided the book into eight chapters. The first chapter is analogous to the product-definition phase (but with an academic undertone), when a semiconductor company justifies a design effort by defining the role and operational objectives of the proposed system. Before attempting to undertake the design, however, a novice engineer must first train in the art of analog IC design, which is why the second, third, and fourth chapters discuss solid-state theory and devices, circuit building blocks, and feedback, respectively. The fifth chapter focuses on ac system-design issues and corresponds to the second step in a prototype-development effort; here the designer applies the circuit and feedback principles discussed in the previous two chapters. The next two chapters apply and combine the device know-how presented in the second chapter with the teachings of the next few chapters to design the actual IC, first at the component level (sixth chapter) and then at the system level (seventh chapter). The development process, from an IC designer's perspective, culminates in these two chapters because all analog training converges here, with IC design. Finally, the eighth chapter incorporates protection and discusses characterization, the final two steps in a product-development cycle. As a whole, the book is an example of a top-down-top design approach because it starts with an abstract view of the system for context, then dives down to devices for training, slowly rising through circuits, until finally reaching the system again, but now the final design, at the transistor level.

Novice engineers may use this book to learn about analog IC design by reviewing the entire design process by traversing through all eight chapters sequentially. They may also seek to enhance their understanding of specific analog design principles, in which case they might target specific chapters such as Chaps. 2 to 4 for devices, circuits, and feedback and Chap. 5 for important ac design and stability considerations. Trained analog designers with little regulator experience who do not wish to review basic analog principles but wish to design linear regulator ICs may target Chap. 1 for system perspective and Chaps. 5 to 8 for regulator-specific issues. Experienced regulator IC designers, on the other hand, may pinpoint specific sections in Chaps. 1 and 5 to 8 to enhance their understanding of the state of the art. With all this in mind, I divided each chapter into self-inclusive sections and sections into what I thought were relevant and subject-specific subsections, assigning titles I thought were meaningful, so I hope the Contents facilitates the process of targeting chapters, sections, and subsections.

Gabriel Alfonso Rincón-Mora, Ph.D.

Contents

CHAPTER 1

System Considerations

1.1 Regulators in Power Management

Supplying and conditioning power are the most fundamental functions of an electrical system. A loading application, be it a cellular phone, pager, or wireless sensor node, cannot sustain itself without energy, and cannot fully perform its functions without a stable supply. The fact is transformers, generators, batteries, and other off-line supplies incur substantial voltage and current variations across time and over a wide range of operating conditions. They are normally noisy and jittery not only because of their inherent nature but also because high-power switching circuits like central-processing units (CPUs) and digital signal-processing (DSP) circuits usually load it. These rapidly changing loads cause transient excursions in the supposedly noise-free supply, the end results of which are undesired voltage droops and frequency spurs where only a dc component should exist. The role of the voltage regulator is to convert these unpredictable and noisy supplies to stable, constant, accurate, and load-independent voltages, attenuating these ill-fated fluctuations to lower and more acceptable levels.

The regulation function is especially important in high-performance applications where systems are increasingly more integrated and complex. A system-on-chip (SoC) solution, for instance, incorporates numerous functions, many of which switch simultaneously with the clock, demanding both high-power and fast-response times in short consecutive bursts. Not responding quickly to one of these load-current transitions (i.e., load dumps) forces storage capacitors to supply the full load and subsequently suffer considerable transient fluctuations in the supply. The bandwidth performance of the regulator, that is, its ability to respond quickly, determines the magnitude and extent of these transient variations.

Regulators also protect and filter integrated circuits (ICs) from exposure to voltages exceeding junction-breakdown levels. The requirement is more stringent and acute in emergent state-of-the-art technologies whose susceptibility to breakdown voltages can be less than 2 V. The growing demand for space-efficient, single-chip solutions, which include SoC, system-in-package (SiP), and system-on-package (SoP) implementations, drives process technologies to finer photolithographic and metal-pitch dimensions. Unfortunately, the maximum voltage an IC can sustain before the onset of a breakdown failure declines with decreasing dimensions and pitch because as the component density increases, isolation barriers deteriorate.

References, like regulators, generate and regulate accurate and stable output voltages that are impervious to variations in the input supply, loading environment, and various operating conditions. Unlike regulators, however, references do not supply substantial dc currents. Although a good reference may shunt positive and negative noise currents, its total load-current reach is still relatively low. In practice, references supply up to 1 mA and regulators from 5 mA to several amps.

1.2 Linear versus Switching Regulators

A voltage regulator is normally a buffered reference: a bias voltage cascaded with a noninverting op-amp capable of driving large load currents in shunt-feedback configuration. Bearing in mind the broad range of load currents possible, regulators are, on a basic level, generally classified as *linear* or *switching*. Linear regulators, also called *series* regulators, linearly modulate the conductance of a series pass switch connected between an input dc supply and the regulated output to ensure the output voltage is a predetermined ratio of its bias reference voltage, as illustrated in Fig. 1.1*a*. The term "series" refers to the pass element (or switch device) that is in series with the unregulated supply and the load. Since the current flow and its control are

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Note on text: To complement and augment the verbal explanations presented in this book, an effort has been made to conform variable names to standard small-signal and steady-state naming conventions. Signals embodying both small-signal and dc components use a smaller-case name with uppercase subscripts, like for instance output voltage v_{OUT}. When referring only to the dc component, all capitals are used, as in V_{OUT}, and similarly, when only referring to small-signal values, the entire name, including subscripts, is in lower case, as in v_{OUT}. As also illustrated by the previous example, the variables adopt functionally intuitive names. The first letter usually describes the signal type and its dimensional units such as v for voltage, i for current, A or G for amplifying gain, p for power, and so on. The subscript tends to describe the function or node to which the variable is attached, such as "out" for the output of the regulator, "reg" for a regulated parameter, and so on.

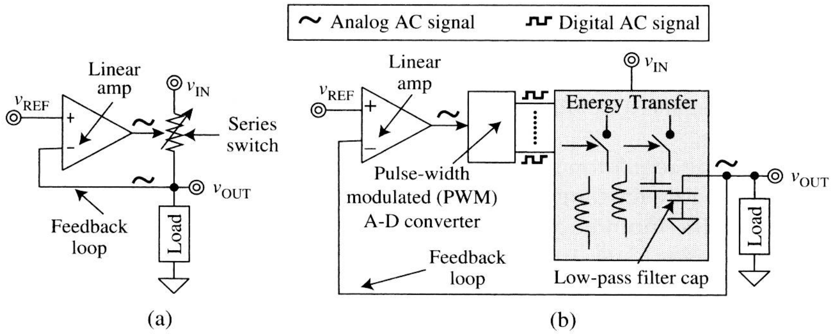

FIGURE 1.1 (*a*) Basic linear and (*b*) switching regulator circuits.

continuous in time, the circuit is linear and analog in nature, and because it can only supply power through a linearly controlled series switch, its output voltage cannot exceed its unregulated input supply (i.e., $V_{OUT} < V_{IN}$).

A switching regulator is the counterpart to the linear solution, and because of its switching nature, it can accommodate both alternating-current (ac) and direct-current (dc) input and output voltages, which is why it can support ac-ac, ac-dc, dc-ac, and dc-dc converter functions. Within the context of ICs, however, dc-dc converters predominate because the ICs derive power from available dc batteries and off-line ac-dc converters, and most loading applications in the IC and outside of it demand dc supplies to operate. Nevertheless, given its ac-dc converting capabilities, switching regulators are also termed *switching converters*, even if only dc-dc functions are performed.

From a circuit perspective, the driving difference between linear and switching regulators is that the latter is mixed-mode with both analog and digital components in the feedback loop (Fig. 1.1*b*). The basic idea in the switching converter is to alternately energize inductors and/or capacitors from the supply and de-energize them into the load, transferring energy via quasi-lossless energy-storage devices. To control the network, the circuit feeds back and converts an analog error signal into a pulse-width-modulated (PWM) digital-pulse train whose on-off states determine the connectivity of the aforementioned switching network. From a signal-processing perspective, the function of the switching network is to low-pass-filter the supply-level swings of the digital train down to a millivolt analog signal, the average of which is the regulated output.

The blocks that normally comprise a dc-dc converter include a PWM controller, which is the combination of an analog linear amplifier and a pulse-width-modulated analog-digital converter, as shown in Fig. 1.1*b*, synchronous and/or asynchronous switches (i.e., transistors and/or diodes), capacitors, and, in many cases, inductors. Many switched-capacitor implementations do not require power inductors, sometimes making total chip integration possible. These integrated, inductorless converters, however, cannot typically supply the high-current levels the discrete power inductors can, which is why they normally satisfy a relatively smaller market niche in low-power applications.

Switching regulators, unlike their linear counterparts, are capable of generating a wide range of output voltages, including values below and above the input supply. *Buck* converters, for instance, generate output voltages lower than the input supply (i.e., $V_{OUT} < V_{IN}$) while *boost* converters deliver the opposite (i.e., $V_{OUT} > V_{IN}$)—*charge pump* is the name normally applied to an inductorless buck or boost converter. Buck-boost converters, as the name implies, are a combination of both buck and boost circuits and they are consequently capable of regulating output voltages both above and below the input supply. In spite of the apparent flexibility and advantages of switching supplies, however, linear regulators remain popular in consumer and high-performance electronics, as the next subsection will illustrate.

1.2.1 Speed Tradeoffs

Linear regulators tend to be simpler and faster than switching converters. As Fig. 1.1 illustrates, there are fewer components in a linear regulator, which imply two things: simplicity and less delay through the feedback loop, in other words, higher bandwidth and therefore faster response. The PWM controller, and more specifically, the pulse-width-modulated analog-to-digital converter, is generally a relatively laborious block to design, often requiring a clock, comparators, non-overlapping digital drivers, and a saw-tooth triangular-wave generator. For a stable switching converter in negative feedback, the switching frequency is often a decade above the bandwidth of the loop, further limiting its response time to orders of magnitude below the transitional frequency (f_t) of the transistors available in a given process technology. Because of this, and the fact they are relatively complex circuits (i.e., more delays across the loop), dc-dc converters require more time to respond than linear regulators, 2–8 μs versus 0.25–1 μs. The switching frequencies of these devices are between 20 kHz and 10 MHz. Although higher switching frequencies can reduce the ripple content of the output voltage and/or relax the LC-filter requirements, they are often prohibitive because they increase the switching power losses of the converter beyond acceptable limits—increasing power losses demands more energy from the battery and therefore reduces its runtime.

1.2.2 Noise

Switching regulators are noisier than their linear counterparts are, and Fig. 1.1 illustrates this by the presence of digital signals in the ac-feedback path of the circuit. Power switches, which are large devices conducting