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Power Sources and Supplies

World Class Designs

Marty Brown

with

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Preface

This book is an assemblage of four books from different authors on topics from linear and switching power supply design. The book covers a wide range of different aspects of power supply design with differing perspectives from these authors; all this combines to provide a more rounded view of the power field.

There are many different stories as to how the designers in the field came to be "power supply engineers." For me it was quite by accident. I had been an engineer for 5 years, using nothing more than 780X linear regulators. I was working on an avionics product designing the digital sections. I went to my manager when I had finished and said, "We need to fly this product, and we cannot take these bench supplies along with us. We need some power supplies designed."

He responded, "I was just waiting to see who finished first." One year and four different versions later, the unit flew.

And that was the start of my involvement in switching power supplies. In 1974, there were no PWM controller ICs, so by providing positive feedback around a linear regulator or by using a 556, one could generate the needed function. Discrete bipolar transistors and fast-recovery diodes were the only power semiconductor devices of the day.

The technology has come a long way since then. Semiconductor suppliers are providing virtually "plug and play" solutions such as National Semiconductor's Simple Switcher™. The added help of the many online design and simulation tools makes the design task seemingly quick and painless. Other suppliers too, such as the magnetic component suppliers, have made it easier than ever to produce a switching power supply design. They produce many families of standard shapes and values of inductors and transformers.

However, once you go beyond the simple printed circuit board level switching power supply, the online tools quickly lose their usefulness. The majority of graduating engineers today are in the digital hardware and software fields, where only their basic electronics courses involved physical electronics. So when a power supply needs to be designed, it becomes a matter of who can run the fastest! Of course, the job usually falls to the most junior engineer and it then becomes his or her next assignment.

The power supply design then usually follows that engineer throughout their employment with that company because of the "millstone effect." For me, this turned out to be fortunate. I had always been intrigued by the unknown and loved the field's curious combination of RF, digital, analog and power. My reward is in realizing that I intuitively understand an area that few engineers do, and my power supply designs are in many of the products in use today.

The contributing authors of this book are very respected engineers coming from very different experiential backgrounds. Their differing perspectives should provide a good appreciation of the power supply field.

So, good learning and good designs.

Marty Brown
September 2007

About the Editor

Marty Brown (Chapters 1, 9, and 12) is the author of the *Power Supply Cookbook* and *Practical Switching Power Supply Design*. He earned his amateur radio license at the age of 11 and has had electronics as a hobby throughout his life. He graduated cum laude from Drexel University in 1974. His electronic design history includes underwater acoustics with the department of the Navy, airborne weather radar design (digital and SMPS), a satellite CODEC, and process control equipment. He was previously with Motorola Semiconductor as a principal application engineer, where he defined more than eight semiconductor products in the power conversion market and received two patents. He later started his own electronics consulting firm where he designed products from satellite power systems to power-related integrated circuits for many semiconductor companies. He is presently working in the field of digitally controlled power supplies with Microchip Technologies. He has eight children, five of whom are adopted. His wife is an internationally known writer and speaker in the area of inter racial adoption and related issues. He presently lives in Scottsdale, Arizona.

About the Contributors

Nihal Kularatna (Chapter 7) is the author of *Power Electronics Design Handbook.* He is an electronics engineer with over 30 years of experience in professional and research environments. He is a Fellow of the IEE (London), a Senior Member of IEEE (USA) and an honors graduate from University of Peradeniya, Sri Lanka. Presently, he is a Senior Lecturer in the Department of Engineering, the University of Waikato, New Zealand. He worked at the Arthur C. Clarke Institute for Modern Technologies (ACCIMT) in Sri Lanka as a Research and Development Engineer until 1990 when he reached Principal Researcher Engineer status. He was then appointed as CEO of ACCIMT in 2000. From 2002 to 2005 he was a Senior Lecturer at the Department of Electrical and Electronic Engineering, University of Auckland. He is currently active in research in transient propagation and power conditioning in power electronics, embedded processing applications for power electronics, and smart sensor systems. He has authored five books and is currently working on his sixth. His hobby is gardening cacti and succulents.

Raymond A. Mack, Jr. (Chapters 2, 4, 5, 6, and 11) is the author of *Demystifying Switching Power Supplies.*

Sanjaya Maniktala (Chapters 3, 8, and 10) is the author of *Switching Power Supplies A to Z.* He is a Senior Applications manager and Systems Architect at Fairchild Semiconductor. A post graduate in Physics from the Indian Institute of Technology, Bombay, and Northwestern University in Evanston, Illinois, he has worked on several continents, holding lead engineering positions in companies such as Artesyn Technologies (now part of Emerson Electric), Siemens AG, Freescale Semiconductor, and Power Integrations. More recently, he was the most prolific author/writer at National Semiconductor for five years in a row, during which time he wrote what are considered by many to be their most widely consulted and popular reference, Application Notes. In his spare time, he also wrote several articles for major electronics publications such as *EDN, Electronic Design, Power Electronics Technology*, and *Planet Analog*. He holds several patents in the area of power conversion and control, including the "Floating Buck Regulator Topology."

Contents

An Introduction to the Linear Regulator

Marty Brown

Linear power supplies are the simplest of the DC/DC converters, but don't be fooled by the apparent simplicity of them. There are several factors in every application of linear supplies that are important for their reliable operation. These are thermal design, output regulation, stability considerations and its transient response, any of which could cause the system to behave badly.

Linear regulators are used much more often than switching regulators. One finds them distributed throughout products as POL (point of load) supplies, where local circuit regulation is needed, voltage bus quieting for noise sensitive circuits, and inexpensive voltage bus generation.

If you have done a design completely using linear regulators, you may technically call yourself a "power supply designer," but you will not fully appreciate the complexities of the field until you have experienced a switching power supply design. You have only reached the "tenderfoot" level of experience.

I've attempted to cover the material in a succinct and intuitive manner showing how flexible the humble linear regulator can be. The design examples can be scaled and adapted to many other applications. Related topics such as thermal design can be found in chapter 12.

—Marty Brown

The linear regulator is the original form of the regulating power supply. It relies upon the variable conductivity of an active electronic device to drop voltage from an input voltage to a regulated output voltage. In accomplishing this, the linear regulator wastes a lot of power in the form of heat, and therefore gets hot. It is, though, a very electrically "quiet" power supply.

The linear power supply finds a very strong niche within applications where its inefficiency is not important. These include wall-powered, ground-base equipment where forced air cooling is not a problem; and also those applications in which the instrument is so sensitive to electrical noise that it requires an electrically "quiet" power supply—these products might include audio and video amplifiers, RF receivers, and so forth. Linear regulators are also popular as local, board-level regulators. Here only a few watts are needed by the board, so the few watts of loss can be accommodated by a simple heatsink. If dielectric isolation is desired from an AC input power source, it is provided by an AC transformer or bulk power supply.

In general, the linear regulator is quite useful for those power supply applications requiring less than 10 W of output power. Above 10 W, the heatsink required becomes so large and expensive that a switching power supply becomes more attractive.

1.1 Basic Linear Regulator Operation

All power supplies work under the same basic principle, whether the supply is a linear or a more complicated switching supply. All power supplies have at their heart a closed negative feedback loop. This feedback loop does nothing more than hold the output voltage at a constant value. Figure 1.1 shows the major parts of a series-pass linear regulator.

Linear regulators are step-down regulators only; that is, the input voltage source must be higher than the desired output voltage. There are two types of linear regulators: the *shunt regulator* and the *series-pass regulator*. The shunt regulator is a voltage regulator that is placed in parallel with the load. An unregulated current source is connected to a higher voltage source; the shunt regulator draws output current to maintain a constant voltage across the load given a variable input voltage and load current. A common example of this is a Zener diode regulator. The series-pass linear regulator is more efficient than the shunt regulator and uses an active semiconductor as the series-pass unit, between the input source and the load.

The series-pass unit operates in the linear mode, which means that the unit is not designed to operate in the full on or off mode but instead operates in a degree of "partially

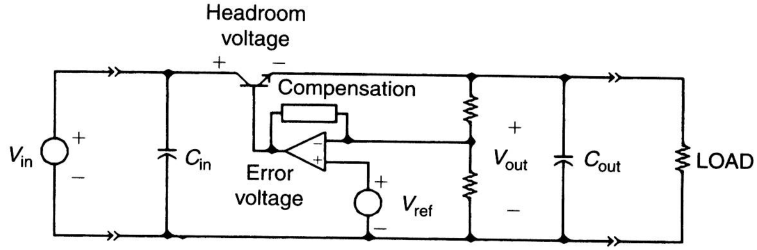

Figure 1.1: The basic linear regulator

on." The negative feedback loop determines the degree of conductivity the pass unit should assume to maintain the output voltage.

The heart of the negative feedback loop is a high-gain operational amplifier called a *voltage error amplifier.* Its purpose is to continuously compare the difference between a very stable voltage reference and the output voltage. If the output differs by mere millivolts, then a correction to the pass unit's conductivity is made. A stable voltage reference is placed on the noninverting input and is usually lower than the output voltage. The output voltage is divided down to the level of the voltage reference. This divided output voltage is placed into the inverting input of the operational amplifier. So at the rated output voltage, the center node of the output voltage divider is identical to the reference voltage.

The gain of the error amplifier produces a voltage that represents the greatly amplified difference between the reference and the output voltage (error voltage). The error voltage directly controls the conductivity of the pass unit thus maintaining the rated output voltage. If the load increases, the output voltage will fall. This will then increase the amplifier's output, thus providing more current to the load. Similarly, if the load decreases, the output voltage will rise, thus making the error amplifier respond by decreasing pass unit current to the load.

The speed by which the error amplifier responds to any changes on the output and how accurately the output voltage is maintained depends on the error amplifier's *feedback loop compensation*. The feedback compensation is controlled by the placement of elements within the voltage divider and between the negative input and the output of the error amplifier. Its design dictates how much gain at DC is exhibited, which dictates how accurate output voltage will be. It also dictates how much gain at a higher frequency and bandwidth the amplifier exhibits, which dictates the time it takes to respond to output load changes or *transient response time.*

The operation of a linear regulator is very simple. The very same circuitry exists in the heart of all regulators, including the more complicated switching regulators. The voltage feedback loop performs the ultimate function of the power supply—the maintaining of the output voltage.

1.2 General Linear Regulator Considerations

The majority of linear regulator applications today are board-level, low-power applications that are easily satisfied through the use of highly integrated three-terminal regulator integrated circuits. Occasionally, though, the application calls for either a higher output current or greater functionality than the three-terminal regulators can provide.

There are design considerations that are common to both approaches and those that are only applicable to the nonintegrated, custom designs. These considerations define the operating boundary conditions that the final design will meet, and the relevant ones must be calculated for each design. Unfortunately, many engineers neglect them and have trouble over the entire specified operating range of the product after production.

The first consideration is the *headroom voltage*. The headroom voltage is the actual voltage drop between the input voltage and the output voltage during operation. This enters predominantly into the later design process, but it should be considered first, just to see whether the linear supply is appropriate for the needs of the system. First, more than 95 percent of all the power lost within the linear regulator is lost across this voltage drop. This headroom loss is found by

$$P_{HR} = (V_{in(max)} - V_{out})I_{load(rated)} \tag{1-1}$$

If the system cannot handle the heat dissipated by this loss at its maximum specified ambient operating temperature, then another design approach should be taken. This loss determines how large a heatsink the linear regulator must have on the pass unit.

A quick estimated thermal analysis will reveal to the designer whether the linear regulator will have enough thermal margin to meet the needs of the product at its highest specified operating ambient temperature. One can find such a thermal analysis in Chapter 12.

The second major consideration is the minimum *dropout voltage* of a particular topology of linear regulator. This voltage is the minimum headroom voltage that can be experienced by the linear regulator, below which it falls out of regulation. This is predicated only by how the pass transistors derive their drive bias current and voltage. The common positive linear regulator utilizes an NPN bipolar power transistor (see Figure 1.2a). To generate the needed base-emitter voltage for the pass transistor's operation, this voltage must be derived from its own collector-emitter voltage. For the NPN pass units, this is the actual minimum headroom voltage. This dictates that the headroom voltage cannot get any lower than the base-emitter voltage (~0.65 VDC) of the NPN pass unit plus the drop across any base drive devices

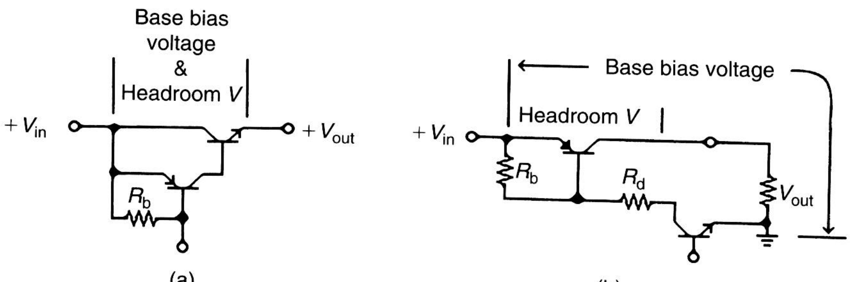

Figure 1.2: The pass unit's influence on the dropout voltage: (a) NPN pass unit; (b) PNP pass unit (low dropout)