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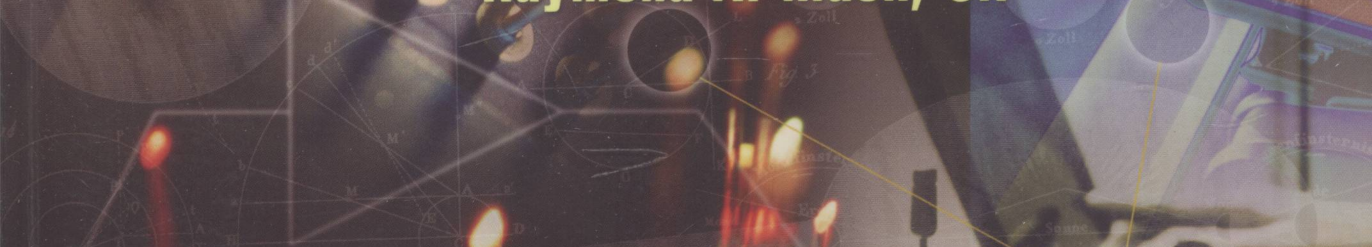
Demystifying Switching Power Supplies

Raymond A. Mack, Jr.



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Preface

This book is intended for those who need to understand how a switching power supply works. I intend to provide enough information so you can intelligently specify a custom off-line supply from a power supply manufacturer. You should also gain enough information to be able to design a DC–DC converter. I have included basic analog design information for those whose primary electronics background is not analog circuits. Then I build on that basic information to show how to design and analyze practical switching power supplies. Those with a strong background in analog circuitry may want to skim over the preliminary data.

In numerous places I skip over the details of derivations and transformations of equations. The details of those transformations are left as an exercise for the reader.

There are two broad classes of power supplies: linear and switching. Linear supplies use time continuous control of the output. Switching supplies are time-sampled systems that use rectangular samples to control the output. This book explores each of the variations of switching power supplies.

Acknowledgments

Like most work, this book is built on the efforts of many others. I wish to acknowledge the large contribution to my understanding of switching power supplies by the authors of the Motorola application book *Linear/Switchmode Voltage Regulator Handbook*, the International Rectifier *HDB-3 Power MOSFET HEXFET Databook*, and the Philips *Switch Mode Power Supply* Semiconductor application book (an excellent book but available only on their website).

I also wish to acknowledge the gracious contributions by Linear Technology Corporation. Linear Technology gives away their program SwitcherCAD III. It is intended for use by their customers, but it is free to all who want to use it. Most of the schematics in this book were initially prepared using the drafting functions of SwitcherCAD III.

Introduction

The principles of switching power supplies have been used for over 100 years (though people didn't know that's what they were). The ignition system used in a gasoline engine was the earliest version of a flyback switching power supply. The next general use of switching supplies was in the high voltage section of televisions. Again, this is an example of a rudimentary flyback supply. The flyback name comes from the short time period where the spot on the television CRT is moved from the right side of the screen back to the left side of the screen (it would "fly back"). The rapid change in current in the deflection coil causes a very large voltage to be generated. This was used to advantage in televisions to create the large acceleration potential necessary for the CRT.

Widespread switching supply use was limited to television high voltage service until the late 1960s because of limited capabilities of the three major components in a switching supply: the magnetics, the switch, and the rectifier. Components were available for switching supply use in the early 1960s with the advent of high voltage bipolar transistors, but they weren't economically feasible for low wattage uses until the price of semiconductors became reasonable. Since 1970, advances in all component categories have changed the power supply market to the point where linear power supplies are almost nonexistent above the level provided by three terminal linear regulators. Advances in semiconductors allow single package switching power supplies with multi-watt capability. These designs use the IC, an inductor, and a couple of capacitors to produce a complete voltage regulator in a volume smaller than a single TO-3 switching transistor from the 1960s.

The price per watt of AC line operated power supplies has dropped to the point that it is not cost effective to design and build such a supply in-house unless extremely large quantities are involved. Many companies market lines of standard output voltage supplies. Most of these companies can also supply nonstandard voltages based on standard designs for nominal design fees.

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Most of the major linear IC manufacturers (Linear Technology, Maxim, TI, National Semiconductor, Analog Devices, etc.) provide a line of switching regulator circuits suitable for local voltage regulation or voltage conversion. Modern devices from these manufacturers are extremely small and efficient. This is true especially of devices intended for battery-operated equipment where maximum operation between charging is important. Modern devices frequently integrate the control circuit, the switch, and the required rectifiers in the same package.

The passive component manufacturers have been busy improving components as well. The magnetic materials companies (Ferroxcube, Siemens, Micrometals, Magnetics division of Spang & Co., etc.) have extended the useful range of transformers and chokes from the low kHz range (10–50 kHz) in the 60s to well above 1 MHz today. This improvement has allowed much smaller filter capacitors and magnetic cores in modern designs. Capacitor manufacturers have also improved filter capacitors for use in switchers. Ordinary electrolytic capacitors have a very large equivalent series resistance that causes them to dissipate power when a rapidly varying DC voltage is applied. If this equivalent AC current is too high, these electrolytics will heat to the point of explosion. All electrolytic capacitor manufacturers now make lines of capacitors that are designed to limit this equivalent series resistance.

Comparison of Linear and Switching Supplies

A comparison of representative linear and switching power supplies shows why we would want to use a switching supply in most applications.

A linear power supply can only produce a voltage lower than the input voltage. All linear regulators require the input voltage to be at least a minimum amount above the output voltage. This is called the drop-out voltage. The drop-out voltage is the parameter that drives the calculations for efficiency and worst-case power dissipation.

Let's look at the operation of a device that operates at 6.0 V and has a maximum current draw of 2 A. A representative linear regulator will have a drop-out voltage of 2 V. If we choose to use a lead acid battery, the battery will be discharged when the voltage reaches around 1.9 V per cell. Since we require a minimum of 8 V

(6 V for the load plus the 2 V drop-out voltage) for proper operation, we will require a minimum of 5 cells to provide the necessary voltage. This yields a minimum input voltage of 9.9 V when the battery is discharged. The power in the load is 12 W with 2 A supplied, and the regulator must dissipate 7.8 W when the battery is discharged. This yields an efficiency of 60%. When the battery is fully charged, the cell voltage is 2.26 V and the battery supplies 11.3 V. The load power is still 12 W. The regulator must now dissipate 10.6 W, which yields an efficiency of 53%.

The situation is better if we decide to draw less from each cell. We can increase the efficiency and decrease the cost of the battery (at the cost of more frequent recharge cycles) if we stop operation at a cell voltage of 2.0 V. Now we only require 4 cells for operation. The regulator dissipates 4 W at end of charge so the efficiency increases to 75%. At full charge the efficiency has only improved to 67%.

In the first example, 2 of the 5 cells contribute all of their energy to heat. In the second example, 1 of the 4 cells is used entirely for heat. You can see that linear regulation is a very expensive way to provide a constant voltage in a battery-operated system.

A simple switching power supply can be built for the application described above with FET switches that have an on resistance on the order of 0.008 Ohm. The commutating diode can be a Schottky diode with an on voltage of only 0.5 V. As a first approximation, the power dissipated in the switch is a maximum of 0.032 W, and the power dissipated by the diode is 1.0 W. The efficiency at full charge is 92 % and the efficiency at discharge is close to 99%. What is even better is that these relative efficiencies will hold for a 4-cell battery, a 6-cell battery, or a 12-cell battery.

There is another advantage of switching power supplies over a linear supply. With the linear supply, we were restricted to a battery of 4 cells or more for proper operation. A switching power supply can be built to provide the necessary power from 1 to 3 cells that will still have better efficiency than the linear supplies.

The situation is similar for line operated power supplies. A line operated linear supply requires a transformer. A linear supply that delivers 1000 W of power requires a transformer weighing approximately 100 pounds (and heavier if both 50 Hz and 60 Hz operation is required), requires massive heat sinks for the semiconductors and blowers for the heat sinks, and occupies more than a cubic foot of volume. If 110 V or 220 V operation is required, a linear supply will need manual or complicated electronic switching to handle both line voltages. By contrast, a switching supply can be designed that handles 110 or 220 and 50 Hz or 60 Hz without selection circuitry, weighs less than 50 pounds, and occupies one-quarter the volume of the linear supply. The switching power supply also costs a fraction of the linear supply.

Switching supplies are not always the best solution. High frequency noise is an inherent part of the output of a switching power supply. Linear supplies can be 100 to 1000 times quieter than a switching supply. A linear supply is usually a requirement for very noise sensitive analog circuits. Where maximum efficiency is required, modern systems will frequently pre-regulate a voltage with a switching supply to a value just above the drop-out voltage and use a linear supply to provide the low noise power to the analog circuits. Another disadvantage of switching supplies is that there is typically a longer recovery time from a large step change in load current or a step change in input voltage when compared with linear supplies.

Linear supplies are usually a better solution for very low power applications. In the example above, we approximated the loss in the switch as the I^2R power. A better analysis will include losses in the switch during the turn on and turn off times as well as the power needed to drive the switch. Additionally, there are special purpose linear regulators that have very low drop-out voltages for use in low power applications. Both of these factors can tip the balance toward linear regulators in some low power applications.

Contents

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CHAPTER 1

Basic Switching Circuits

- Energy Storage Basics
- Buck Converter
- Boost Converter
- Inverting Boost Converter
- Buck-Boost Converter
- Transformer Isolated Converters
- Synchronous Rectification
- Charge Pumps

CHAPTER 1

Basic Switching Circuits

In this chapter, we will look at the time domain description of ideal inductors and capacitors and review ideal versions of each type of switching supply. In later chapters, we will look at the magnetic, electrical, and parasitic properties of inductors and capacitors and their effect on the design of individual components.

Energy Storage Basics

Equation (1-1) contains the definition of inductance. An inductor has an inductance of one henry if a change of current of one ampere/second produces one volt across the inductor.

$$V = L\, di/dt \tag{1-1}$$

This is *Lenz's law*. The first consequence of Eq. (1-1) is that the current through an inductor cannot change instantaneously. To do so would generate an infinite voltage across the inductor. In the real world, things such as an arc across switch contacts will limit the voltage to very high, but not infinite, values. The other consequence of Eq. (1-1) is that the voltage across an inductor changes instantaneously from positive to negative when we switch from storing energy in the inductor (*di/dt* is positive) to removing energy from it (*di/dt* is negative). Equation (1-2) is the converse of Eq. (1-1) and is used to determine the current in the inductor when the voltage is known.

$$I = 1/L \int V\, dt + I_{initial} \tag{1-2}$$

Equation (1-3) contains the definition of a capacitor. It states that a capacitor is one farad if storing one coulomb of charge creates one volt.

$$Q = CV \tag{1-3}$$

Equations (1-4) and (1-5) describe a capacitor in terms of voltage and current (where charge is the integral of current and current is *dq/dt*).

$$V = 1/C \int i\, dt + V_{initial} \tag{1-4}$$

$$I = C\, dv/dt \tag{1-5}$$

The current waveform of the filter capacitor of a switching power supply is typically a sawtooth waveform. The goal of the capacitor is to limit the change in voltage (ripple voltage). There are two variables in Eq. (1-4) that can control the change in output voltage. We can either make the capacitance large or make *dt* small to control the voltage ripple. One of the major advantages of switching power supplies is that we can make *dt* very small (a high switching frequency) which allows the value of C to also be very small.

Buck Converter

Figure (1-1) shows an ideal buck converter regulator made of an ideal voltage source, an ideal voltage controlled switch, an ideal diode, an ideal inductor, an ideal capacitor, and a load resistor. It is called a buck converter because the voltage across the inductor "bucks" or opposes the supply voltage. The output voltage of a buck converter is always less than the input voltage. This ideal regulator is designed to use a 20 V source and provide 5 V to the 10 ohm load. The switch is opened and closed once every 10 μs.The switch produces a pulse width modulated waveform to the passive components. When the regulator is at steady state, the output voltage is:

$$V_{out} = V_{in} * \text{Duty Cycle} \tag{1-6}$$

This equation is independent of the value of the inductor, the load current, and the output capacitor as long as the inductor current flows continuously. This equation assumes that the inductor voltage has a rectangular shape.

The diode acts as a voltage controlled switch. It provides a path for the inductor current once the switch is opened. No current flows through the diode while the inductor is charging because it is reverse biased. When the control switch opens, the inductor current flows through the diode.

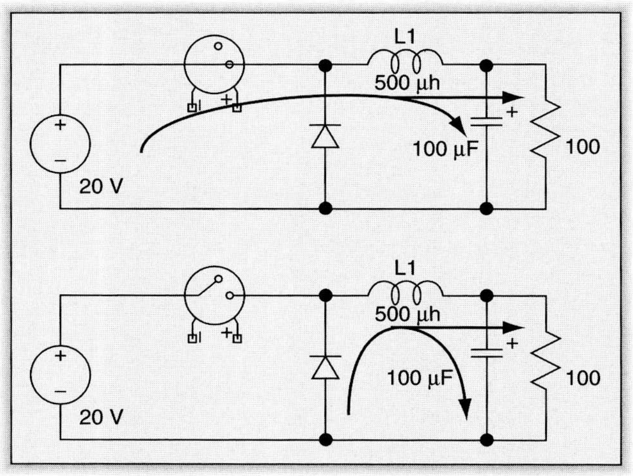

Figure 1-1: Idealized buck converter regulator

We design switching supplies with the simplifying assumption that the applied voltage to the inductor during charging is a perfect rectangular wave. Our example power supply has voltage output ripple of 20 mV. The perfect rectangle is a good approximation since the change in inductor voltage during charging is 0.02/15 or 0.13% and the variation on discharge is 0.02/5 or 0.4%. The constant voltage of the rectangular pulse causes *di/dt* in Eq. (1-1) to be a constant.

Figure 1-2 shows a plot of the output voltage (lower trace) and inductor current (upper trace) after the system is at steady-state providing 5 V and 500 mA to the load resistor.

Note that the change in output current is relatively small compared to the DC value of current in the inductor. In this case, the ripple current is 75 mA P-P. Another important point is that the ripple current is independent of load current when the system is steady-state. This is a consequence of the current through the inductor being controlled by the voltage across the inductor. The slope and duration of charging is controlled entirely by the difference ($V_{in} - V_{out}$). The average inductor current is equal to the output current.

It is also possible for the buck converter to work in discontinuous mode, which means the inductor current goes to zero during part of the switching period.

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