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Power Supply Cookbook

Second Edition

Marty Brown

Newnes

Boston Oxford Johannesburg Melbourne New Delhi

Newnes is an imprint of Butterworth–Heinemann.

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Library of Congress Cataloging-in-Publication Data

Brown, Marty.
Power supply cookbook / Marty Brown.—2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-7506-7329-X
1. Electric power supplies to apparatus—Design and construction.
2. Power electronics. 3. Electronic apparatus and appliances—power supply. I. Title.
TK7868.P6 B76 2001
621.381′044—dc21
00-050054

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

The publisher offers special discounts on bulk orders of this book.
For information, please contact:
Manager of Special Sales
Butterworth–Heinemann
225 Wildwood Avenue
Woburn, MA 01801-2041
Tel: 781-904-2500
Fax: 781-904-2620

For information on all Newnes publications available, contact our World Wide Web home page at: http://www.newnespress.com

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

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Preface

Power Supply Cookbook was written by a practicing design engineer for practicing design engineers. Through designing power supplies for many years, along with a variety of electronic products ranging from industrial control to satellite systems, I have acquired a great appreciation for the "systems-level" development process and the trade-offs associated with them. Many of the approaches I use involve issues outside the immediate design of the power supply and their impact on the design.

Power Supply Cookbook, Second Edition has been updated with the latest advances in the field of efficient power conversion. Efficiencies of between 80 to 95 percent are now possible using these new techniques. The major losses within the switching power supply and the modern techniques to reduce them are discussed at length. These include: synchronous rectification, lossless snubbers, and active clamps. The information on methods of control, noise control, and optimum printed circuit board layout has also been updated.

As with the previous edition, the "cookbook" approach taken in *Power Supply Cookbook, Second Edition* facilitates information finding for both the novice and seasoned engineer. The information is organized so that the reader need only read the material for the degree of in-depth knowledge he or she wishes to acquire. Because of the enclosed design flow, the typical power supply can be designed schematically in less than 8 hours, which can cut weeks from the expected design period.

The purpose of this book is not to advance the bastions of academia, but to offer the tried and true design approaches implemented by many engineers in the power field. It offers advice and examples which can be immediately applied to the reader's own designs.

Introduction

This book is an invaluable adjunct to those engineers wanting to better understand power supply operation in order to effectively implement the computer-aided design (CAD) tools available. The broad implementation and success of CAD tools, along with the internationalization of the world's design resources, has led to competition that has shortened the typical product design cycle from more than a year to a matter of months. As a result, it is important for design engineers to locate and apply just the right amount of information without a long learning period.

Power Supply Cookbook, Second Edition is organized in a rather unique manner and, if followed correctly, can greatly shorten the amount of time needed to design a power supply. By presenting intuitive descriptions of the power supply system's operation along with commonly used circuit approaches, it is designed to help anyone with a working electronics knowledge to design a very complex switching power supply quickly.

I developed the concept for *Power Supply Cookbook* after having spent many hours working with design engineers on their power supply designs and, subsequently, my own designs.

The "Cookbook" Method of Organization

Power Supply Cookbook, Second Edition follows the same tried and true "cookbook" organization as its predecessor. This easy-to-use format helps readers quickly locate the power supply design sections they need without reading the book from start to finish. Additionally, the text follows the design flow that a seasoned power supply designer would follow. Circuit sections are designed in a way that provides information needed by subsequent circuit sections. Coverage of more complicated design areas, such as magnetics and feedback loops, is presented in a step-by-step format to help designers reduce the opportunity for mistakes.

The results of the calculations in this book lead to a conservative ("middle of the road") design. The results are "calculated estimates" that can be adjusted one way or another to enhance a performance or a physical property of the power supply. These compromises are discussed in the appropriate sections of the text.

For best results, the new reader should follow this flow:

A. Read Chapter 1 on the role of the power supply within the system and design program. This chapter provides the reader with insight as to the role of the power supply within the overall system, and develops the power supply design specification.
B. Read the introduction sections for the type of power supply you wish to develop (linear, pulsewidth modulated [PWM] switching, or high-efficiency).
C. Follow the order of the design "flowchart" and refer to the appropriate section within the book. Within each section, read the basic operation of that subcircuit. Then choose a design implementation that would best

fit your requirements from the selection of common industry design approaches.

D. Calculate the component values and ratings from the design equations using your particular set of operating conditions.
E. “Paste” the resulting subcircuit into the main schematic and proceed to the next subcircuit to be designed.
F. At the end of the “paper design” (estimated 8 to 12 hours), read the section on PCB layout and begin building the first prototype.
G. Debug and test the prototype.
H. Finalize the physical and electrical design in preparation for production release.

The appendices are provided for those technical areas that are common among the various power supply technologies. They also present more detail for those designers who wish a deeper understanding of the subjects. The material on the design of basic PWM switching power supplies should be followed for all switching power supply designs. Chapter 4 describes how one can further enhance the overall efficiency of the power supply being designed.

In short, this book is written for working engineers by a working engineer. I hope you find it infinitely useful.

1. The Role of the Power Supply within the System and Design Program

The power supply assumes a very unique role within a typical system. In many respects, it is the mother of the system. It gives the system life by providing consistent and repeatable power to its circuits. It defends the system against the harsh world outside the confines of the enclosure and protects its wards by not letting them do harm to themselves. If the supply experiences a failure within itself, it must fail gracefully and not allow the failure to reach the system.

Alas, mothers are taken for granted, and their important functions are not appreciated. The power system is routinely left until late in the design program for two main reasons. First, nobody wants to touch it because everybody wants to design more exciting circuits and rarely do engineers have a background in power systems. Secondly, bench supplies provide all the necessary power during the system debugging stage and it is not until the product is at the integration stage that one says "Oops, we forgot to design the power supply!" All too frequently, the designer assigned to the power supply has very little experience in power supply design and has very little time to learn before the product is scheduled to enter production.

This type of situation can lead to the "millstone effect" which in simple terms means "You designed it, you fix it (*forever*)." No wonder no one wants to touch it and, when asked, disavows any knowledge of having ever designed a power supply.

1.1 Getting Started. This Journey Starts with the First Question

In order to produce a good design, many questions must be asked prior to the beginning of the design process. The earlier they are asked the better off you are. These questions also avoid many problems later in the design program due to lack of communication and forethought. The basic questions to be asked include the following.

From the marketing department

1. From what power source must the system draw its power? There are different design approaches for each power system and one can also get information as to what adverse operating conditions are experienced for each.

2. What safety and radio frequency interference and electromagnetic interference (RFI/EMI) regulations must the system meet to be able to be sold into the target market? This would affect not only the electrical design but also the physical design.
3. What is the maintenance philosophy of the system? This dictates what sort of protection schemes and physical design would match the application.
4. What are the environmental conditions in which the product must operate? These are temperature range, ambient RF levels, dust, dirt, shock, vibration, and any other physical considerations.
5. What type of graceful degradation of product performance is desired when portions of the product fail? This would determine the type of power busing scheme and power sequencing that may be necessary within the system.

From the designers of the other areas of the product

1. What are the technologies of the integrated circuits that are being used within the design of the system? One cannot protect something, if one doesn't know how it breaks.
2. What are the "best guess" maximum and minimum limits of the load current and are there any intermittent characteristics in its current demand such as those presented by motors, video monitors, pulsed loads, and so forth? Always add 50 percent more to what is told to you since these estimates always turn out to be low. Also what are the maximum excursions in supply voltage that the designer feels that the circuit can withstand. This dictates the design approaches of the cross-regulation of the outputs, and feedback compensation in order to provide the needs of the loads.
3. Are there any circuits that are particularly noise-sensitive? These include analog-to-digital and digital-to-analog converters, video monitors, etc. This may dictate that the supply has additional filtering or may need to be synchronized to the sensitive circuit.
4. Are there any special requirements of power sequencing that are necessary for each respective circuit to operate reliably?
5. How much physical space and what shape is allocated for the power supply within the enclosure? It is always too small, so start negotiating for your fair share.
6. Are there any special interfaces required of the power supply? This would be any power-down interrupts, etc., that may be required by any of the product's circuits.

This inquisitiveness also sets the stage for the beginning of the design by defining the environment in which the power supply must operate. This then forms the basis of the design specification of the power supply.

1.2 Power System Organization

The organization of the power system within the final product should complement the product philosophy. The goal of the power system is to distribute power effectively to each section of the entire product and to do it in a fashion that meets the needs of each subsection within the product. To accomplish this, one or more power system organization can be used within the product.

For products that are composed of one functional "module" that is inseparable during the product's life, such as a cellular telephone, CRT monitor, RF receiver, etc., an integrated power system is the traditional system organization. Here, the product has one main power supply which is completely self-contained and outputs directly to the product's circuits. An *integrated power system* may actually have more than one power supply within it if one of the load circuits has power demand or sequencing requirements which cannot be accommodated by the main power supply without compromising its operation.

For those products that have many diverse modules that can be reconfigured over the life of the product, such as PCB card cage systems and cellular telephone ground stations, etc., then the *distributed power system* is more appropriate. This type of system typically has one main "bulk" power supply that provides power to a bus which is distributed throughout the entire product. The power needs of any one module within the system are provided by smaller, *board-level* regulators. Here, voltage drops experienced across connectors and wiring within the system do not bother the circuits.

The integrated power system is inherently more efficient (less losses). The distributed system has two or more power supplies in series, where the overall power system efficiency is the product of the efficiencies of the two power supplies. So, for example, two 80 percent efficient power supplies in series produces an overall system efficiency of 64 percent.

The typical power system can usually end up being a combination of the two systems and can use switching and linear power supplies.

The engineer's motto to life is "Life is a tradeoff" and it comes into play here. It is impossible to design a power supply system that meets *all* the requirements that are initially set out by the other engineers and management and keep it within cost, space, and weight limits. The typical initial requirement of a power supply is to provide infinitely adaptable functions, deliver kilowatts within zero space, and cost no money. Obviously, some compromise is in order.

1.3 Selecting the Appropriate Power Supply Technology

Once the power supply system organization has been established, the designer then needs to select the technology of each of the power supplies within the system. At the early stage of the design program, this process may be iterative between reorganizing the system and the choice of power supply technologies. The important issues that influence this stage of the design are:

1. Cost.
2. Weight and space.
3. How much heat can be generated within the product.
4. The input power source(s).
5. The noise tolerance of the load circuits.
6. Battery life (if the product is to be portable).
7. The number of output voltages required and their particular characteristics.
8. The time to market the product.

The three major power supply technologies that can be considered within a power supply system are:

1. Linear regulators.
2. Pulsewidth modulated (PWM) switching power supplies.
3. High efficiency resonant technology switching power supplies.

Each of these technologies excels in one or more of the system considerations mentioned above and must be weighed against the other considerations to determine the optimum mixture of technologies that meet the needs of the final product. The power supply industry has chosen to utilize each of the technologies within certain areas of product applications as detailed in the following.

Linear

Linear regulators are used predominantly in ground-based equipments where the generation of heat and low efficiency are not of major concern and also where low cost and a short design period are desired. They are very popular as board-level regulators in distributed power systems where the distributed voltage is less than 40 VDC. For off-line (plug into the wall) products, a power supply stage ahead of the linear regulator must be provided for safety in order to produce dielectric isolation from the ac power line. Linear regulators can only produce output voltages lower than their input voltages and each linear regulator can produce only one output voltage. Each linear regulator has an average efficiency of between 35 and 50 percent. The losses are dissipated as heat.

PWM switching power supplies

PWM switching power supplies are much more efficient and flexible in their use than linear regulators. One commonly finds them used within portable products, aircraft and automotive products, small instruments, off-line applications, and generally those applications where high efficiency and multiple output voltages are required. Their weight is much less than that of linear regulators since they require less heatsinking for the same output ratings. They do, however, cost more to produce and require more engineering development time.

High efficiency resonant technology switching power supplies

This variation on the basic PWM switching power supply finds its place in applications where still lighter weight and smaller size are desired, and most importantly, where a reduced amount of radiated noise (interference) is desired. The common products where these power supplies are utilized are aircraft avionics, spacecraft electronics, and lightweight portable equipment and modules. The drawbacks are that this power supply technology requires the greatest amount of engineering design time and usually costs more than the other two technologies.

The trends within the industry are away from linear regulators (except for board-level regulators) towards PWM switching power supplies. Resonant and quasi-resonant switching power supplies are emerging slowly as the technology matures and their designs are made easier. To help in the selection, Table 1–1 summarizes some of the trade-offs made during the selection process.

Table 1–1 Comparison of the Four Power Supply Technologies

	Linear Regulator	PWM Switching Regulator	Resonant Transition Switching Regulator	Quasi-Resonant Switching Regulator
Cost	Low	High	High	Highest
Mass	High	Low-medium	Low-medium	Low-medium
RF Noise	None	High	Medium	Medium
Efficiency	35–50%	70–85%	78–92%	78–92%
Multiple outputs	No	Yes	Yes	Yes
Development time to production	1 week	8 person-months[a]	10 person-months[a]	10 person-months[a]
		5 person-months[b]	8 person-months	8 person-months[b]

[a] Based upon a reasonable level of experience and facilities.

[b] With the use of this book.

1.4 Developing the Power System Design Specification

Before actually designing the power system, the designer should develop the power system design specification. The design specification acts as the performance goal that the ultimate power supply must meet in order for the entire product to meet its overall performance specification. Once developed, it should be viewed as a semi-firm document and should only be changed after the needs of the product formally change.

When developing the design specification, the power supply designer must keep in mind what is a reasonable requirement and what is an idealistic requirement. Engineers not experienced in power supply design often will produce requirements on the power supply that either will cost an unnecessary fortune and take up too much space or will be impossible to meet with the present state of the technology. Here the power supply designer should press the other engineers, managers, and marketers for compromises that will prompt them to review their requirements to decide what they can actually live with.

The power system specification will be based upon the questions that should previously have been asked of the other departments involved in defining and designing the product. Some of the requirements can be anticipated to grow, such as the current needed by various subsystems within the product. Always add 25 to 50 percent to the output current capabilities of the power supply during the design process to accommodate this inevitable event. Also, the space allocated to the power system and its cost will almost always be less than what will be finally required. Some negotiations will be in order. Since the power system is a support function within the product, its design will always be modified in reaction to design issues within the other sections of the product. This will always make the power supply design the last circuit to be released for production. Recognizing and addressing these potential trouble areas early in the design period will help avoid delays later in the program.

To develop a good design specification, the designer should understand the meaning of the terms used within the power supply field. These are measurable power supply parameters with a common set of test conditions that the actual design affects. These parameters are the following.

Input voltage

$V_{in(nom)}$	The input voltage at which the product expects to operate for >99 percent of its life.
$V_{in(low)}$	The lowest anticipated operational input voltage (brown-out).
$V_{in(hi)}$	The highest anticipated operational average input voltage.
Line Frequency(s)	dc, 50, 60, or 400 Hz, etc.

Include any adverse operating conditions that may require the supply to operate outside the conventional specifications such as:

Dropout	A period of time over which the input line voltage completely disappears (the specification is typically 8 mS for 60 Hz ac off-line applications).
Surge	A defined period of time where the input voltage will exceed the $V_{in(hi)}$ specification that the unit must survive and during which it may need to operate.
Transients	These are very high voltage “spikes” (+/–) that are characteristic of the input power system.
Emergency operation	Any operation required of the product during any adverse operating periods. This may be because the product’s function is so critical for the survival of the operator of the unit, that it must operate to just short of its own destruction.

Input current

$I_{in(max)}$	This is the maximum average input current. Its maximum limit may be specified by a safety regulatory agency.

Output voltage(s)

$V_{out(rated)}$	The nominal output voltage (ideal).
$V_{out(min)}$	The output voltage below which the load should be inhibited or turned off.
$V_{out(max)}$	The maximum output voltage under which normal operation of the load circuits can operate.
$V_{out(abs)}$	The voltage at which the loads reach their destructive limits.

Ripple voltage (switching power supplies) This is measured in peak-to-peak volts, and its frequency and level should be acceptable to the load circuits.

Output current

$I_{out(rated)}$	The maximum average current that will be drawn from an output.
$I_{out(min)}$	The minimum current that will be drawn from the output during normal operation.
I_{sc}	The maximum current limit that should be delivered into a short-circuited load.

Describe any unusual load demand characteristics related to any output. These consist of intermittent loads such as motors, CRTs, etc., and also any loads that may be removed from or added to the system as part of an overall system architecture, such as probes, handsets, and the like.

Dynamic load response time: This is the amount of time it requires the power supply to recover to within load regulation limits in response to a step change in the load.

Line regulation: Percentage change in the output voltage(s) in response to a change in the input voltage.

$$\text{Line Reg.} = \frac{V_{o(\text{hi-in})} - V_{o(\text{lo-in})}}{V_{o(\text{nom-in})}} \cdot 100(\%) \tag{1.0}$$

Load regulation: Percentage change in the output voltage(s) in response to a change in load current from one-half rated to rated load current.

$$\text{Load Reg.} = \frac{V_{o(\text{full-load})} - V_{o(\text{half-load})}}{V_{o(\text{rated-load})}} \cdot 100(\%) \tag{1.1}$$

Overall efficiency: This will determine how much heat will be generated within the product and whether any heatsinking will be needed in the physical design.

$$\text{Effic.} = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100(\%) \tag{1.3}$$

Protections

- Input fusing limits.
- Overcurrent foldback on the outputs.
- Overvoltage trip protection limits.
- Undervoltage lockout on the input power line.
- Any graceful degradation features and repair philosophy after system failure.

Operating and Storage Ambient Temperature Ranges Outside the Product

Safety regulatory agency issues

- Dielectric withstanding voltage (hipot).
- Insulation resistance.
- Enclosure considerations (interlocks, insulation class, shock, marking, etc.).

RFI/EMI (Radiofrequency and electromagnetic interference) which regulatory agency specifications the product must meet.

- Conducted EMI: line filtering.
- Radiated RFI: physical layout and enclosures.

Special functionalities required of the power supply. These include any power-on resets and power-fail signals needed by any microcomputers in the system, remote turn-off, output voltage or current programming, power sequencing, status signals, etc.

This now forms a very good basis from which to begin a power supply design. This specification is now at a point that it can dictate which design paths must be pursued in order to meet the above specifications and will help to guide the designer during the design process.

1.5 A Generalized Design Approach to Power Supplies: Introducing the Building-block Approach to Power Supply Design

All power supply engineers follow a general pattern of steps in the design of power supplies. If the pattern is followed, each step actually sets the foundation for subsequent design steps and will guide the designer through a path of least resistance to the desired result. This text presents an approach that consists of two facets: first it breaks the power supply into distinct blocks that can be designed in a modular fashion; secondly, it prescribes the order in which the blocks are to be designed in order to ease their "pasting" together. The reader is further helped by the inclusion of typical industry design approaches for each block of various applications used by power supply designers in the field. Each block includes the associated design equations from which the component values can be quickly calculated. The result is a coherent, logical design flow in which the unknowns are minimized. The approach is organized such that the typical inexperienced designer can produce a "professional" grade power supply schematic in under 8 working hours, which is about 40 percent of the entire design process. The physical design, such as breadboarding techniques, low-noise printed circuit board (PCB) layouts, transformer winding techniques, etc., are shown through example. The physical factors always present a problem, not only to the inexperienced designer, but to the experienced designer as well. It is hoped that these practical examples will keep the problems to a minimum. All power supplies, regardless of whether they are linear or switching, follow a general design flow. The linear power supplies, though, because of the maturity of the technology and the level of integration offered by the semiconductor manufacturers, will be presented mainly via examples. The design flow of the switching power supplies, which are much more complicated, will be covered in more detail in the respective chapters dealing with the selected power supply technology. The generalized approach is as follows.

1. Select the appropriate technology and topology for your application.
2. Perform "black box" approximations knowing only the design specification requirements. This results in estimates of semiconductor power losses, peak currents and voltages. It may also indicate to the designer that the chosen topology is inappropriate and a different choice is necessary. It also allows the designer to order any semiconductor samples that may be required during the breadboarding phase of the program.
3. Design the power supply schematically, guided by the design flowcharts.
4. Build the breadboard using the techniques outlined in the physical layout and construction sections in the text.
5. TEST, TEST, TEST! Test the power supply against the requirements stated in the design specification. If they do not meet the requirements, some design modifications may be necessary. Make "baseline" measurements so

that you can measure any subsequent changes in the power supply's performance. Conduct tests with the final product connected to the supply to check for unwanted interactions. And by all means, begin to measure items related to safety and RFI/EMI prior to submitting the final product to the approval bodies.

6. Finalize the physical design. This would include physical packaging within the product, heatsink design, and the PCB design.
7. Submit the final product for approval body safety and RFI/EMI testing and approval. Some modifications are usually required, but if you have done your homework in the previous design stages, these can be minor.
8. Production Release!

It all sounds simple, but the legendary and cursed philosopher, Murphy, runs wild through the field of power supply design, so expect many a visit from this unwelcome guest.

1.6 A Comment about Power Supply Design Software

There is an abundance of software-based power supply design tools, particularly for PWM switching power supply designs. Many of these software packages were written by the semiconductor manufacturers for their own highly integrated switching power supply integrated circuits (ICs). Many of these ICs include the power devices as well as the control circuitry. These types of software packages should only be used with the targeted products and not for general power supply designs. The designs presented by these manufacturers are optimized for minimum cost, weight, and design time, and the arrangements of any external components are unique to that IC.

There are several generalized switching power supply design software packages available primarily from circuit simulator companies. Caution should be practiced in reviewing all software-based switching power supply design tools. Designers should compare the results from the software to those obtained manually by executing the appropriate design equations. Such a comparison will enable designers to determine whether the programmer and his or her company really understands the issues surrounding switching power supply design. Remember, most of the digital world thinks that designing switching power supplies is just a matter of copying schematics.

The software packages may also obscure the amount of latitude a designer has during a power supply design. By making the program as broad in its application as possible, the results may be very conservative. To the seasoned designer, this is only a first step. He or she knows how to "push" the result to enhance the power supply's performance in a certain area. All generally applied equations and software results should be viewed as calculated estimates. In short, the software may then lead the designer to a result that works but is not optimum for the system.

1.7 Basic Test Equipment Needed

Power supplies, especially switching power supplies, require the designer to view parameters not commonly encountered in the other fields of electronics. Aside