# Switching and Linear Power Supply, Power Converter Design

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HAYDEN BOOK COMPANY, INC.
Rochelle Park, New Jersey

To
ANNE
Norman, Daniel, Eric, Dotty
Jeremy and Julie

*Library of Congress Cataloging in Publication Data*

Pressman, Abraham I
Switching and linear power supply, power converter design.

Includes index.
1. Electronic apparatus and appliances—Power supply. 2. Voltage regulators. 3 Electric current converters. I. Title.
TK7868.P6P74 621.3815'37 77-14639
ISBN 0-8104-5847-0

*Printed in the United States of America*

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | PRINTING |
|---|---|---|---|---|---|---|---|---|---|
| 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | YEAR |

# Preface

It is widely experienced throughout the electronics/aerospace industry that power supplies give rise to more problems in design and reliability than the complex systems which they power. This book seeks to remedy that situation. It deals with all aspects of power supply design—from the initial block diagram systems alternatives to the detailed circuit design of all the electronics within the blocks. Written for both design engineer and undergraduate with little or no knowledge of the power supply field and the available design alternatives, this text should enable them first to make the best decision on a system block diagram concept and then to implement it with detailed circuits, magnetics, and a safe thermal design.

Switching regulators—which are in the process of revolutionizing the power supply industry because of their low internal losses, small size, and weight and costs competitive with conventional series-pass or linear power supplies—are covered fully. Half-cycle width-modulated dc/dc converters, dc/dc voltage down chopping, voltage up chopping, and transformer-coupled flyback regulators are detailed. Design equations for critical components are derived and typical designs presented. The dc/dc square-wave converters, used so frequently with switching regulators in modern power supply systems, are treated in depth.

For the present, series-pass regulators remain the major design approach in the industry; these are discussed at length along with their fields of application, advantages, capabilities, and disadvantages. Logical, step-by-step design procedures are offered, and combinations of series-pass and -switching regulators that retain the best capabilities of each type in a complex system are demonstrated. Efficiencies of various combinations are calculated.

Extensive discussion is devoted to magnetics—transformer and inductor design for high-frequency switching regulators. Design equations for transformer core selection for a given power level, frequency, and magnetic flux density are derived and typical designs shown. Design of inductors with air gaps or molypermalloy powder cores to avoid saturation in usual switching regulator usages is also presented.

Elements of thermal design and heat-sink performance are evaluated, with design equations and graphs showing temperature rise as a function of power level, area, and air flow. Feedback loop stability is treated in detail. Throughout, graphs are presented which permit gain and phase-shift calculations in the usual switching regulator elements—the LC filter and operational amplifiers with RC feedback. Tailoring the gain-phase characteristic to achieve loop stability is also discussed, along with commonly occurring problems in circuits and subtle failure modes in switching and series-pass power supplies.

The electronics industry has long had a vital need for a textbook on the reliable design of all the complex electronics in a modern society—computers, communications equipment, weapons systems and satellites, industrial control, and consumer electronic equipment. It is hoped that this book will fulfill the need for a comprehensive treatment of this significant element in our modern electronic world.

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*Waban, Massachusetts*

# Contents

# 1

# Basic Voltage Regulators, Power Converters

## 1.0 Introduction

The voltage regulators considered herein generate single or multiple output dc voltages whose magnitudes are substantially constant for any value of static or dynamic load currents or input voltage within their specified limits.

Input voltages can be dc or single- or multiple-phase ac at any of the usual power line frequencies, generally ranging between 50 and 800 Hz. Magnitudes of the dc or rms ac input voltages can be higher or lower than the desired output voltages. Output voltages must remain constant to the specified accuracy with input voltages generally varying from ±5 to ±15% around their nominal values and load currents varying from 0 to 100% of maximum at each output. Often, the supplies must cope with transient input voltage changes in excess of the ±5 to ±15% steady-state variations. Duration of such transients may range from less than one to several hundred milliseconds.

Supplies are often required to have protective features such as the ability to survive short-circuited outputs or output voltage limiting above specified values. Limits on power supply efficiency, weight, size, cost, and audio and rfi noise outputs are almost always specified.

The various ways to design power supplies to meet such specifications will be dealt with in this book. In this chapter, the basic regulating and power-converting techniques available to the designer will be presented in general terms without going into detailed circuit designs. In the following chapter, systems combinations of these individual regulating schemes will be taken up in block diagram form. Finally, subsequent chapters will go into detailed circuit designs of individual regulators and combinations of regulator types comprising whole power supply systems.

## 1.1 DC Voltage Regulators

### 1.1.1 Series-Pass Regulators

The series-pass regulator is the simplest, most frequently used but least efficient regulating technique. Until the appearance of high-current, low-forward-drop transistors, usable as high-frequency single-pole switches, it was the main

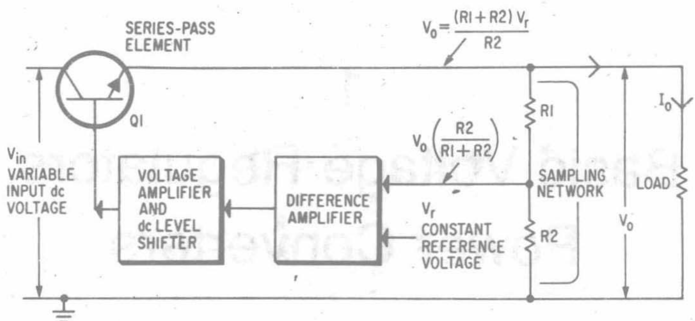


**Fig. 1-1.** Basic series-pass voltage regulator. Q1 is an electronically controlled variable resistance in series with the load.

and practically the only voltage-regulating technique up to power levels of 1,000 W. Techniques using constant voltage transformers and phase-controlled silicon-controlled rectifiers (SCR) have certain fields of application but are slow in response to line and load changes and will not be considered herein.

The basic series-pass regulator is shown in Fig. 1-1. It converts a variable higher voltage dc to a constant lower voltage dc. Input is dc—either from a battery source, which decreases in output as it discharges, or from a rectifier directly off an ac line source or from a rectifier following a step-up or step-down transformer.

In either of the latter cases, the rectified dc output is proportional to ac line input and will thus vary by the same ±5 to ±15% usually specified for ac line sources. Further, usual rectifier outputs will have a large-amplitude ripple voltage at some harmonic of the line frequency superimposed on the rectified dc. The series-pass regulator will eliminate both the line harmonic ripple and the slower dc variations proportional to line changes, yielding a constant output voltage. Output voltage can be made as constant as desired, limited only by the stability of the reference sources, drift in the difference amplifier, and gain in the feedback loop.

In Fig. 1-1, the output is kept constant by using the series-pass element consisting of one or a number of paralleled transistors as a variable resistance device. As the input rises or falls, the effective resistance of the series element is increased or decreased so that it, rather than the output load, absorbs the input voltage change. The series element is controlled to give a constant output voltage by the negative-feedback loop composed of the resistor sampling chain, the difference amplifier, and voltage amplifier-level shifter element.

A fraction of the output voltage, $[R2/(R1 + R2)]\,V_o$, is sampled and compared to a constant reference voltage, $V_r$. The difference amplifier yields a voltage proportional to the difference between $V_r$ and the output sample. The amplified difference voltage is further amplified and the dc level shifted to drive the input terminal of the series element. Voltage polarities are such that a small increase or decrease in output voltage resulting from line or load changes causes the correct increase or decrease, respectively, in series element impedance to keep the output constant. The output adjusts itself so that the sampled fraction $V_o R2/(R1 + R2)$ is very closely equal to the reference voltage.

It is obvious from Fig. 1–1 that all of the output load current must flow through the series-pass element at a dc voltage drop of $V_{in} - V_o$. The minimum efficiency occurs at maximum input voltage and is equal to $P_o/P_{in} = V_oI_o \div V_{in(\max)}I_o = V_o/V_{in(\max)}$. The larger the difference between input and output voltage, the larger the internal dissipation for a given load current. Any dc voltage can be dropped down and regulated to any lower voltage, but the series-pass element must be capable of absorbing the maximum dissipation at its maximum voltage drop.

Thus, the series-pass regulator of Fig. 1–1 is seen to be simple, comprised only of a series voltage dropping element, resistor voltage sampling chain, difference amplifier, and voltage amplifier-level shifting device. But the relatively high dissipation across the series element at the maximum input voltage results in low output–input power efficiency.

### 1.1.2 Series-Pass Regulator Efficiency

In the usual power supply, whose prime input is ac line power, efficiency calculations must consider rectifier drop, ripple, transformer regulation, and transformer losses. But here, to start with, maximum attainable efficiencies will be calculated for sources with totally ripple-free dc output voltage whose magnitude can be set at any desired value to maximize regulator efficiency.

Such efficiencies will be the highest achievable for a given output voltage. Practical efficiencies for regulators with optimum ac inputs and realistic ripple voltage at regulator input terminal will be calculated in Chap. 6.

The usual series-pass element, npn or pnp power transistor, has a knee in its $I_c$–$V_c$ curve at about 2.0 V (Fig. 1–2A). Although operation below the knee is possible, gain is low and a larger fraction of input changes would be transmitted to the output if operation below the knee were permitted.

Thus, in Fig. 1–1 with output taken from the emitter, the minimum input voltage permissible at the collector when the input is at its low tolerance limit is $(V_o + 2)$ volts. For a nominal input voltage of $V_n$ and tolerances of ±T percent, minimum and maximum input voltages are then $(1 - 0.01T)V_n$ and $(1 + 0.01T)V_n$. Since the minimum input voltage must be no less than $V_o + 2$, then

$$(1 - 0.01T)V_n = V_o + 2$$

and maximum input voltage is

$$(1 + 0.01T)V_n = \left(\frac{1 + 0.01T}{1 - 0.01T}\right)(V_o + 2)$$

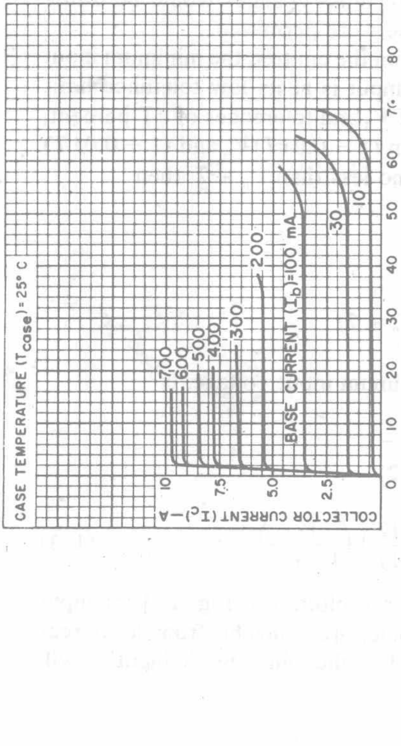
And minimum efficiency, which occurs at maximum input voltage, is

$$V_o/V_{in(\max)} = \frac{V_o}{\left(\dfrac{1 + 0.01T}{1 - 0.01T}\right)(V_o + 2)}$$

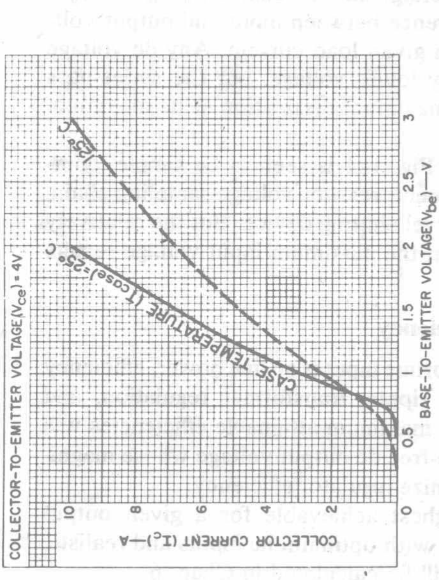
or

$$\text{Minimum efficiency} = \left(\frac{1 - 0.01T}{1 + 0.01T}\right)\left(\frac{V_o}{V_o + 2}\right) \qquad (1\text{–}1)$$

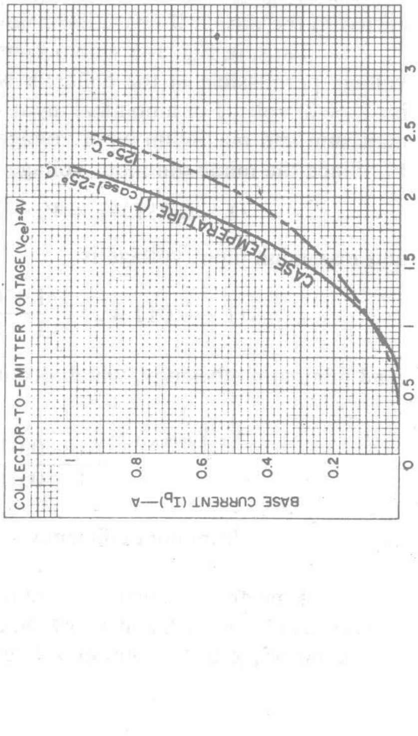
Efficiencies calculated from Eq. 1–1 are plotted in Fig. 1–3 for input tolerances of ±5, ±10, and ±15%. Such efficiencies are realizable from dc sources having no ripple and at output voltages 2 V below the minimum dc input. It will



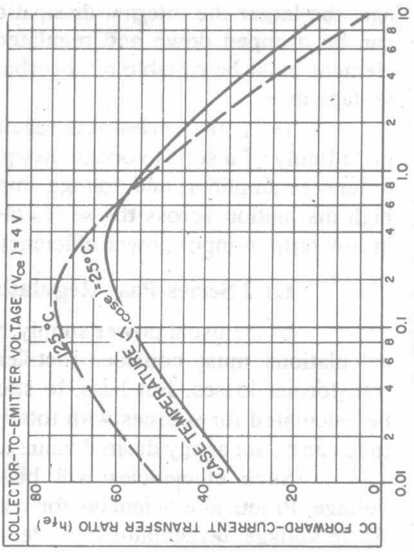
(A) -Typical output characteristics for type 2N3055.



(B) -Typical transfer characteristics for types 2N6253 and 2N3055.



(C) -Typical input characteristics for type 2N3055.



(D) -Typical dc-beta characteristics for type 2N3055.

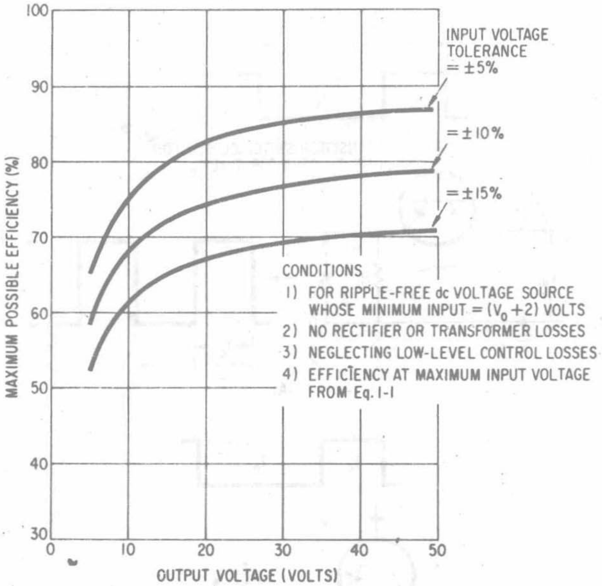


**Fig. 1-3.** Maximum possible efficiency versus output voltage for a series-pass voltage regulator.

be seen in Chap. 6 that when the input source is the rectified output of a transformer and when the effect of transformer losses, rectifier output ripple, and rectifier losses are considered, efficiencies considerably less than shown in Fig. 1-3 result.

## 1.2 Pulse-Width-Modulated Series-Switch Step-Down Converter

Figure 1-4 shows a far superior way of obtaining a lower voltage from a higher one. Instead of absorbing the difference between the input and desired output with a power-dissipating element, a low-impedance transistor switch is made to open and close periodically between input and output. If the switch S1 has zero voltage drop in its closed position, the output shown in Fig. 1-4A varies periodically between zero volts and the input voltage. The average or dc value of this waveform is $V_o = V_{in}T_c/T$, where $T_c$ is the switch-closed time and $T$ is the switching period. This is the voltage that would be read with a dc voltmeter at the output terminals. The ripple component has a peak-to-peak value of $V_{in}$ volts and would, of course, not be observed by a dc voltmeter.

By adding the L1-C1 filter as shown in Fig. 1-4B, the ripple component can be reduced to any desired value, yielding a clean dc voltage of magnitude $V_o = V_{in}(T_c/T)$. By going to high switching rates permitted by transistor switches (5-50 kHz), the filter components L1 and C1 become quite small.

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**Fig. 1-2.** Characteristics of an often-used series-pass transistor. (*Courtesy* RCA)

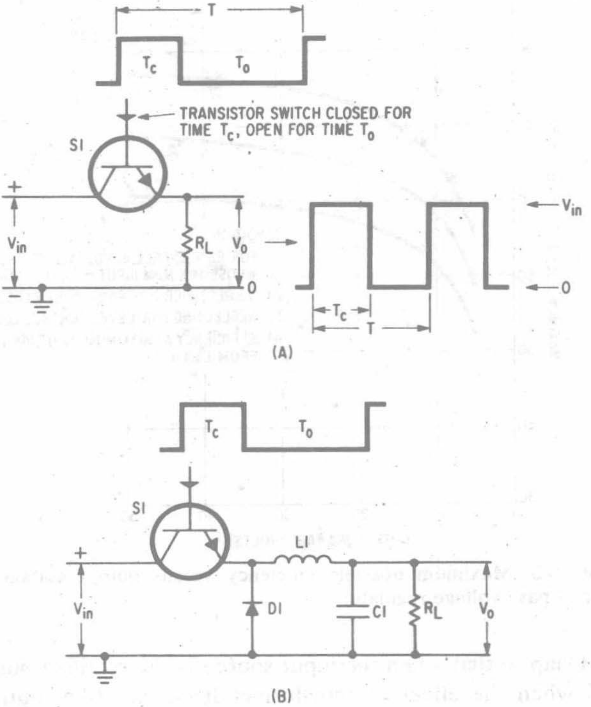

**Fig. 1–4.** (A) Switching voltage converter average output voltage at $V_o = V_{in}(T_c/T)$. (B) Switching voltage converter with LC filter and diode for eliminating ripple.

Any desired output voltage lower than the input can be obtained by varying the width of the "on" time $T_c$ or the ratio $T_c/T$. Such a voltage stepdown is achieved at very high efficiency, since the only losses in such a stepdown are those primarily in the switch S1 when it is closed. Using a transistor switch, the voltage drop with the switch in the closed position can be as low as 1 V. During the time the switch is open, the full input voltage is absorbed, but since no current flows in it, there is no power dissipation.

During the transition between open-switch and closed-switch times or vice versa, there is a momentary overlap of high voltage and current, which does yield some losses. Even with such switching losses, efficiencies of 95% are achievable.

### 1.2.1 Pulse-Width-Modulated Voltage Converter Efficiency

The circuit has the interesting properties of a step-down transformer. With a relatively large inductance for L1, the current in L1 remains constant during the switch-open time. As the switch opens, there is an inductive "kick" across L1 with its input end going negative, since current in an inductor cannot change instantaneously. It goes negative until diode D1 (often referred to as a "free-wheeling" diode) latches on and starts conducting with its cathode one