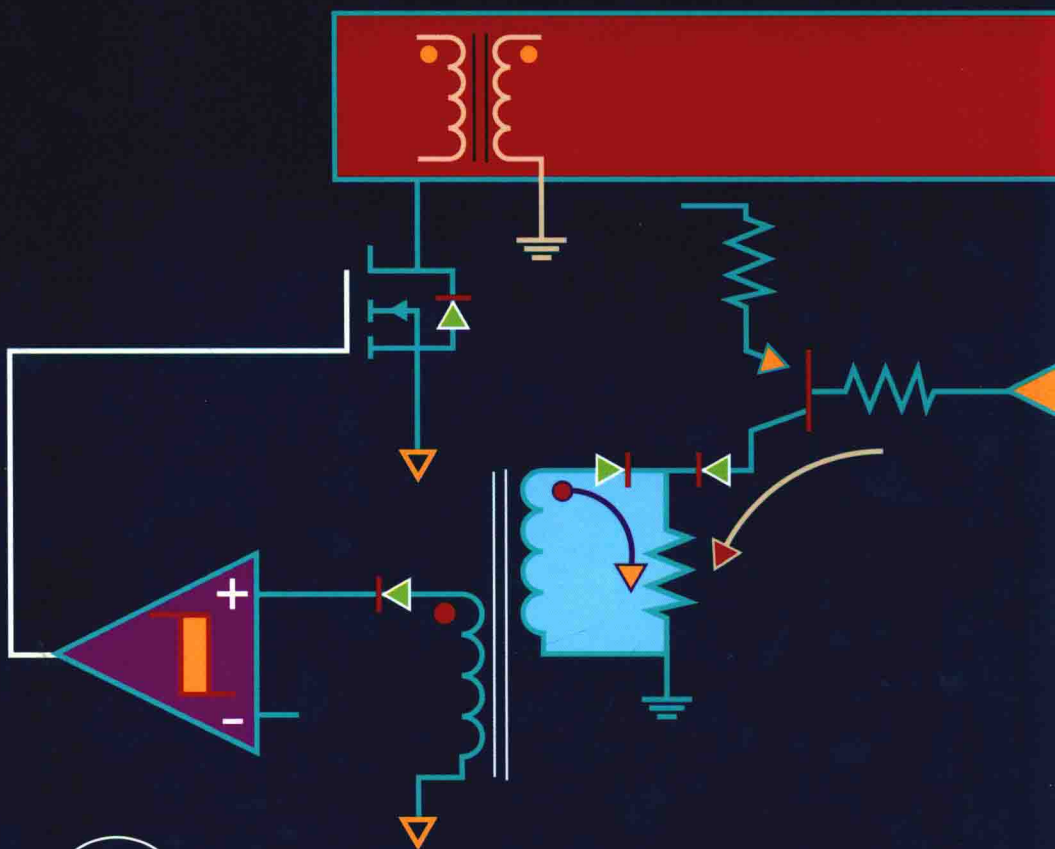


SWITCH-MODE POWER *Design and Analysis* CONVERTERS



KENG WU

Switch-Mode Power Converters

Design and Analysis

Keng C. Wu



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Switch-Mode Power Converters

To
My wife, Shwu
My daughter, Stephanie
My mother, Tai

Preface

This is not a cookbook, for switch-mode power converter design is a serious topic that must be treated with the utmost care. Therefore, the book makes a major departure from most existing texts covering the same subjects. It uses mathematics extensively, employing, for example, symbolic closed-form solutions for conduction times of a loaded full-wave-rectifier with a capacitor filter. At the first sight, readers may feel discouraged, but there is no shortcut. I sincerely urge readers to be patient, for the reward is profound.

The book covers in depth the three basic topologies: step-down (buck, forward), step-up (boost), step-down/up (flyback); push-pull; current-fed; resonant converters and their derivatives; AC-DC power factor correction. Depending on the operating conditions, switch-mode power converters may operate either in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). Under transient conditions, the operation of power converters may slide in and out of both modes. For closed-loop control of converters, two fundamental mechanisms, voltage-mode control or current-mode control, are generally employed. Current-mode control has been understood to offer superior performance. Current mode control is further subdivided into average-current control and peak-current control. While most switch-mode converters utilize pulse-width modulation, resonant converters use frequency modulation. In addition to the main operation mechanism, many supporting circuits are also needed to make power converters viable. These include switch drivers, error amplifiers, and feedback isolators.

The presentation follows a fairly consistent pattern. The relationship between steady-state output and control variables (duty cycle, in the case of PWM, or frequency, in the case of resonance) is established first for both the CCM and the DCM operation. By examining the cyclical current waveforms of CCM, geometrical properties of the waveforms

are extracted. These lead to the identification of critical inductance, which marks the boundary distinguishing CCM and DCM operation.

Under each operation mode and given a selected control mechanism, steady-state closed-loop output formulation that includes feedback ration, error amplifier, PWM gain (or frequency-modulation gain), and power stage is then established. In some simplified cases that exclude losses, the output formulation may be placed in the explicit form. When losses are included, the desire to obtain an explicit form is prohibitively impractical and abandoned. Instead, implicit functions and Jacobian determinants are employed to study output sensitivity and regulation.

With the steady state firmly established, the small-signal AC stability issues are examined for both control modes. Loop stability with voltage-mode control based on the average model (Dr. R. Middlebrook) is formulated and validated. Current-mode control necessitates the addition of current-loop gains surrounding the original average mode. In effect, the Middlebrook average model is extended to current-mode control and remains as valid.

This book also introduces accelerated steady-state analysis in the time domain. The technique connects the concept of the continuity of state and the periodic, steady-state output of converters. The analysis uses two approaches: Laplace transformation and state transitions. The latter calls on eigenvalues, eigenvectors, and matrix exponentials, the core of matrix theory associated with system theory.

Nowadays, simulations always play some role in almost all fields of studies. For power converters, there is no exception. This book, however, approaches it from a more fundamental way, which is quite distinctive from the graphic-based simulations available commercially. The latter suffers convergence issues frequently. Our approach avoids such nagging difficulties.

The book is written for those already exposed to the basics of switch-mode power converters and seek higher dimensions. It is suitable for graduate students and professionals majoring in electrical engineering. In particular, readers with training in linear algebra will find the techniques of state transition being applied very inspiring.

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Finally and most importantly, profound gratitude is extended to Charles B. Glaser, senior acquisition editor and his staff at Elsevier Inc., Burlington, MA ; Annie Martin, production director, Elsevier Ltd., England; and Sheryl Avruch, copyeditors, typesetters, and staff at SPI Publisher Services.

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Chapter 1

Isolated Step-Down (Buck) Converter

The power stage of an isolated buck converter in its simplest form is presented in Figure 1.1. Depending on the output loading and the value of filter inductor L , the power stage can be operated in two distinctive modes: continuous conduction mode (CCM) and discontinuous conduction mode (DCM). In the CCM, the inductor current, i , always stays above zero. In the DCM, the current, for a certain duration, stays at zero. It is also understood that, in the CCM, the power stage alternates between two topologies while, on the contrary, it experiences three in the DCM.

1.1 CCM Open-Loop Output and Duty Cycle Determination

If ideal rectifiers are assumed and series losses are ignored, the requirement of flux conservation, that is, the volt-second balance, across the inductor gives

$$\left(\frac{N_s}{N_p} V_{in} - V_o \right) D \cdot T_s + (-V_o)(1 - D)T_s = 0 \quad (1.1)$$

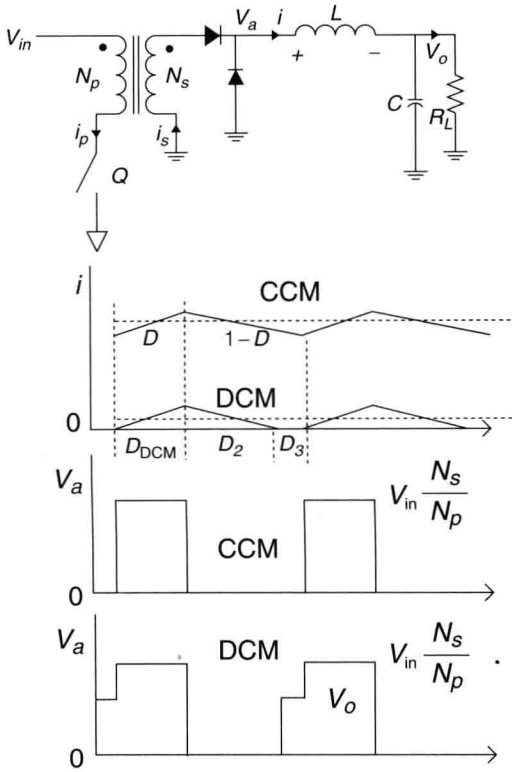


Figure 1.1: Power stage of an ideal forward converter

when the circuit alternates between two topologies under the steady state with a defined switch(Q)-on duty cycle, D , and a given clock rate T_s . Obviously, (1.1) results in

$$D = \frac{V_o}{\frac{N_s}{N_p} V_{in}} \quad (1.2)$$

As a matter of fact, (1.2) can also be given a different interpretation. That is, the rectangular wave, V_a , driving the loaded LC filter contains a DC component:

$$V_o = \frac{N_s}{N_p} V_{in} \cdot D \quad (1.3)$$

This latter view aligns well with the ultimate goal of the converter operation, extracting the average voltage embedded in the transformed input drive and regulating the output voltage by fine-tuning the turn ratio with variable duty cycle, D .

However, in reaching (1.1)–(1.3), we made an expedient, but unrealistic, assumption, which is the zero forward voltage a rectifier diode offers when it is conducting. We shall make the necessary corrections by first forgoing the assumption of the ideal diode. Rather, the rectifier's forward voltage is given a nonzero value, V_D . With it, and referring to Figure 1.2, (1.1)–(1.3) are modified and become

$$\left(\frac{N_s}{N_p} V_{in} - V_D - V_o \right) D \cdot T_s + (-V_D - V_o)(1 - D)T_s = 0 \quad (1.4)$$

$$D = \frac{V_o + V_D}{\frac{N_s}{N_p} V_{in}} \quad (1.5)$$

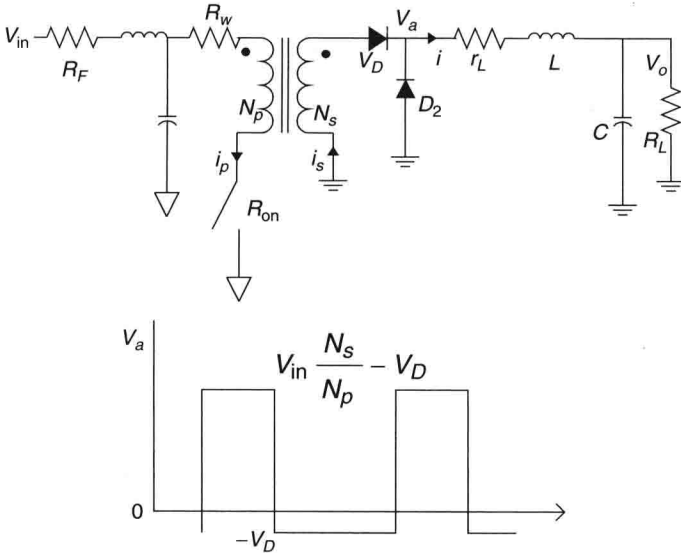


Figure 1.2: Nonideal power stage

$$V_o = \frac{N_s}{N_p} V_{in} \cdot D - V_D \quad (1.6)$$

Next, we consider series losses—first the secondary side losses then the primary side losses. We include the secondary side losses by examining (1.6). What (1.6) offers is the voltage presented by an ideal source that has zero source resistance. If a nonzero source resistance, r_L , exists, (1.6) evolves into

$$V_o = \frac{N_s}{N_p} V_{in} \cdot D - V_D - r_L \cdot \frac{V_o}{R_L} \quad (1.7)$$

or

$$V_o = \frac{\frac{N_s}{N_p} V_{in} \cdot D - V_D}{1 + \frac{r_L}{R_L}} \quad (1.8)$$

We also note the presence of primary side resistance, including the input filter series resistance, the transformer primary winding resistance, and the switch-on resistance. It is also understood that the input filter resistance experiences a DC current while the transformer's primary winding resistance registers a pulsating current. In other words, (1.8) is modified as

$$V_o = \frac{\frac{N_s}{N_p} \left[V_{in} - \frac{N_s}{N_p} \cdot \frac{V_o}{R_L} (R_w + R_{on}) - \frac{N_s}{N_p} \cdot \frac{V_o}{R_L} \cdot D \cdot R_F \right]}{1 + \frac{r_L}{R_L}} D - V_D \quad (1.9)$$

Readers are cautioned in applying (1.9), for it is an implicit function in V_o and a quadratic equation for D . With a little patience, (1.9) yields

$$V_o = \frac{(n \cdot D \cdot V_{in} - V_D) R_L}{[D^2 \cdot R_F + (R_w + R_{on}) D] n^2 + R_L + r_L}, \quad n = \frac{N_s}{N_p} \quad (1.10)$$