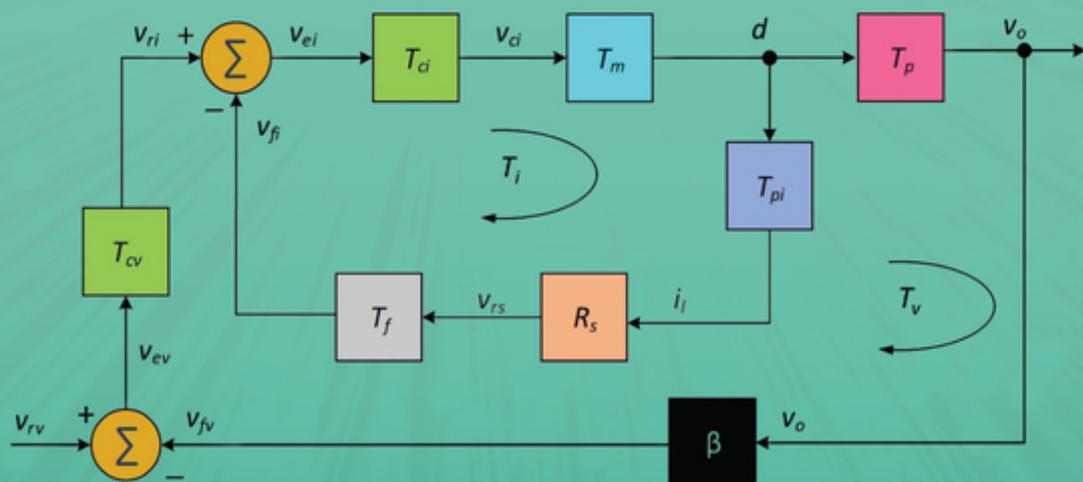


MARIAN K. KAZIMIERCZUK
DALVIR K. SAINI
AGASTHYA AYACHIT

AVERAGE CURRENT-MODE CONTROL OF DC-DC POWER CONVERTERS



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Average Current-Mode Control of DC-DC Power Converters

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Marian K. Kazimierczuk, Dalvir K. Saini, and Agasthya Ayachit

*Department of Electrical Engineering, Wright State University,
Dayton, Ohio, USA*

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List of Symbols

A_i	load current-to-inductor current transfer function
A_{io}	DC gain of load current-to-inductor current transfer function
BW	bandwidth
C	filter capacitance
C_o	transistor output capacitance
D	DC component of on-switch duty cycle
D_{cr}	critical duty cycle of switch
d	AC component of on-switch duty cycle
d_T	large-signal on-switch duty cycle
f_c	gain crossover frequency
f_z	frequency of zero of transfer function
f_o	corner frequency or natural frequency
f_p	frequency of pole of transfer function
f_s	switching frequency
I_D	average or DC component of diode current
i_d	small-signal AC component of diode current
i_D	large-signal diode current
I_I	average or DC component of input current
i_i	small-signal AC component of input current
i_I	large-signal component of input current
I_L	average or DC component of inductor current
i_l	small-signal AC component of inductor current
i_L	large-signal inductor current
I_O	DC component of load current
i_o	small-signal AC component of load current
i_O	large-signal load current
I_S	DC component of switch current
i_s	small-signal AC component of switch current
i_S	large-signal switch current
i_C	large-signal filter capacitor current
L	inductor or inductance
M_{di}	input voltage to duty-cycle transfer function relevant to inner-current loop

M_{dv}	input voltage to duty-cycle transfer function relevant to outer-voltage loop
M_{IDC}	DC current transfer function of converter
M_{icl}	input voltage-to-inductor current transfer function
M_v	open-loop input-to-output voltage transfer function
M_{VDC}	DC voltage transfer function of a converter
M_{vcl}	input-to-output voltage transfer function relevant to outer-voltage loop
M_{vi}	open-loop input voltage-to-inductor current transfer function
M_{vicl}	input-to-output voltage transfer function relevant to inner-current loop
M_{vio}	open-loop input voltage-to-inductor current transfer function at DC
M_{vo}	open-loop input-to-output voltage function at DC
PM	phase margin
P_I	converter DC input power
P_{LS}	converter power loss
P_O	converter DC output power
P_{RF}	conduction loss in diode forward resistance R_F
P_{rC}	conduction loss in equivalent series resistance of the filter capacitor
P_{VF}	conduction loss in diode forward voltage V_F
r	equivalent averaged resistance
R_{iicl}	real component of input impedance relevant to inner-current loop
R_{oicl}	real component of output impedance relevant to inner-current loop
R_{ivcl}	real component of input impedance relevant to outer-voltage loop
R_{ovcl}	real component of output impedance relevant to outer-voltage loop
R_F	diode forward resistance
R_L	load resistance
r_C	equivalent series resistance (ESR) of filter capacitor
r_L	equivalent series resistance (ESR) of inductor
r_{DS}	ON resistance of switch
R_s	sense resistance
T	switching period, Loop gain
T_{ci}	voltage transfer function of controller relevant to inner-current loop
T_{cv}	voltage transfer function of controller relevant to outer-voltage loop
T_f	low-pass filter transfer function
T_i	loop gain of inner-current loop
T_v	loop gain of outer-voltage loop in the presence of inner-current loop
T_{ki}	uncompensated loop gain of inner-current loop
T_{kv}	uncompensated loop gain of outer-voltage loop in the presence of inner-current loop
T_m	transfer function of pulse-width modulator
T_p	open-loop duty cycle-to-output transfer function
T_{pi}	open-loop duty cycle-to-inductor current transfer function
T_{po}	open-loop control-to-output transfer function at DC
T_{pio}	open-loop control-to-inductor current transfer function at DC
T_{icl}	reference voltage-to-inductor current transfer function

T_{pcl}	reference voltage-to-output voltage transfer function relevant to outer-voltage loop
T_{picl}	reference voltage-to-output voltage transfer function relevant to inner-current loop
T_v	loop gain of outer-voltage loop
V_C	DC component of control voltage
v_C	total control voltage
v_c	AC component of control voltage
V_{CI}	DC component of control voltage relevant to inner-current loop
$V_{C_{pp}}$	peak-to-peak ripple voltage of the filter capacitor
V_D	DC component of diode voltage
v_D	large-signal component of diode voltage
V_{EI}	DC component of error voltage relevant to inner-current loop
v_{EI}	total error voltage relevant to inner-current loop
v_{ei}	AC component of error voltage relevant to inner-current loop
V_{EV}	DC component of error voltage relevant to outer-voltage loop
v_{ev}	AC component of error voltage relevant to outer-voltage loop
v_{EV}	total error voltage relevant to outer-voltage loop
V_F	diode forward voltage
V_{FI}	DC component of feedback voltage relevant to inner-current loop
v_{FI}	total feedback voltage relevant to inner-current loop
v_{fi}	AC component of feedback voltage relevant to inner-current loop
V_{FV}	DC component of feedback voltage relevant to outer-voltage loop
v_{FV}	total feedback voltage relevant to outer-voltage loop
v_{fv}	AC component of feedback voltage relevant to outer-voltage loop
V_I	DC component of input voltage
v_i	small-signal AC component of input voltage
v_I	large-signal component of input voltage
V_O	DC component of output voltage
v_o	AC component of output voltage
v_O	large-signal component of output voltage
V_{RI}	reference voltage relevant to inner-current loop
v_{ri}	AC component of reference voltage relevant to inner-current loop
V_{RS}	DC voltage across sense resistor
V_{RV}	reference voltage relevant to outer-voltage loop
v_{rv}	AC component of reference voltage relevant to outer-voltage loop
v_{rc}	voltage across ESR of filter capacitor
V_r	peak-to-peak value of ripple component of the output voltage
V_{Tm}	peak ramp voltage of pulse-width modulator
v_L	voltage across inductor
X_{iicl}	imaginary component of input impedance relevant to inner-current loop
X_{oicl}	imaginary component of output impedance relevant to inner-current loop
X_{ivcl}	imaginary component of input impedance relevant to outer-voltage loop

X_{ovcl}	imaginary component of output impedance relevant to outer-voltage loop
Z_i	open-loop input impedance
Z_{io}	open-loop input impedance at DC (R_i)
Z_{iicl}	input impedance relevant to inner-current loop
Z_{ivcl}	input impedance relevant to outer-voltage loop
Z_o	open-loop output impedance
Z_{oo}	open-loop output impedance at DC (R_o)
Z_{oicl}	closed-loop output impedance relevant to inner-current loop
Z_{ovcl}	closed-loop output impedance relevant to outer-voltage current
β	transfer function of feedback network
η	efficiency of converter
ξ	damping ratio
σ	real component of complex-conjugate poles
ω	angular frequency
ω_c	unity-gain angular crossover frequency
ω_o	corner frequency or angular frequency
ω_p	angular frequency of simple pole
ω_z	angular frequency of simple zero

About the Authors

Marian K. Kazimierczuk, PhD, Professor of Electrical Engineering, Wright State University, Dayton, Ohio, USA. He has taught undergraduate electronics courses and graduate courses in the area of high-frequency power electronics for more than 35 years. Professor Kazimierczuk has done an extensive research on power converters and has published over 500 hundred papers in *IEEE Transactions* and IEEE international conferences, has written eight textbooks, and holds 7 patents. He is the Life Fellow of the IEEE.

Dalvir K. Saini, PhD, Research Engineer, Failure Analysis Lab, University of Dayton Research Institute, Wright Patterson Air Force Base, Dayton, Ohio, USA. She has been pursuing the area of failure analysis of electrical systems and components related to aircraft safety. She has published several journal and conference publications in the field of analysis, design, and modeling of switched-mode power converters, radio-frequency power amplifiers, and magnetic component design.

Agasthya Ayachit, PhD, Senior Systems Engineer, Mercedes-Benz Research & Development North America, Redford, Michigan, USA. He has been actively contributing to the design and development of power conversion stages in electric vehicle charging and e-drive systems. He has published several journal papers in *IEEE Transactions* and *IET* and in various IEEE conferences and has co-authored a laboratory manual on pulse-width-modulated DC–DC power converters. His research interests are in the field of circuit topologies, modeling and design of power converters, wireless charging, and wide-bandgap semiconductor devices (GaN/SiC).

Preface

The demand for power converters is growing by the day and is applicable in almost every field of engineering – automotive, consumer applications, datacenters and Internet of things, healthcare, aerospace, and telecommunications. Characterization of the properties of power converters is essential to achieve high efficiency, high power density, and high reliability of power-electronic systems. While circuit topologies and their design, analysis, and performance optimization form one aspect, circuit modeling, closed-loop control design, and converter stability form the other important part of power circuit development.

This textbook *Average Current-Mode Control of DC–DC Power Converters* aims to make the link between the classical circuit theory, circuit modeling, and control of pulse-width-modulated (PWM) DC–DC power converters. The book is envisioned to aid undergraduate and graduate students of electrical engineering, practicing engineers, scientists, and circuit designers to gain an in-depth understanding of modeling and control of PWM DC–DC power converters. One critical development in the field of power electronics has been current-mode control. This book exploits the average current-mode control “for” the classical buck, boost, buck–boost, and flyback PWM DC–DC converters. By developing a small-signal circuit model using the circuit-averaging technique and deriving the related converter power-stage transfer functions, design of higher-order control circuits, and current-mode and voltage-mode schemes, the book characterizes a complete closed-loop converter system. The book also supplies its readers with a comprehensive appendix to get accustomed to different simulation tools such as MATLAB®, Synopsys SABER®, LTSpice®, or any other Spice-based circuit simulation platforms, provides component datasheet parameters for a quick reference, and hosts a set of basic design equations for common DC–DC converters.

This book features the following attributes:

- i. Unique in the market of power electronic textbooks.
- ii. Ability to adopt as a supplementary material for any commercially available textbooks on power electronics and class notes.
- iii. Possible usage for distance-learning power electronic course or e-learning.
- iv. Simple and easy-to-understand theoretical framework procedure-sets.
- v. Providing quick overview of various power converters and components.

The topics presented in this book have been thoughtfully considered, keeping in mind the benefits it offers to the readers. The primary author of this book has been teaching specialized graduate-level courses in power electronics for more than 35 years and has made significant contributions in the field of modeling of power converters, including circuit-averaging technique, principle of energy conservation, modeling of converters with disjoint switches, and many more. Since then, consistent efforts have been put into developing this material for students and engineers practicing power electronics. The second and third authors have been actively contributing to the areas of aircraft safety systems and electric vehicle (EV) power electronics, respectively, at reputable organizations and add a flavor of industry into the contents of this textbook. The authors of this book recommend the below instructions for instructors and students in making the best use of this book.

The key aspects of this book include and are not limited to:

- (1) Derive averaged equations for buck, boost, buck–boost, and flyback power stages operating in continuous-conduction mode (CCM).
- (2) Develop DC, averaged, large-signal, and small-signal models for the four converters by the circuit-averaging technique.
- (3) Show a methodology of modeling power converters with disjoint switching devices.
- (4) Derive small-signal transfer functions and transient responses of the power stage, which are relevant for the design of inner-current and outer-voltage control loops.
- (5) Identify the appropriate control circuit (Type I, Type II, or Type III) based on the outcomes of power-stage characteristics for the inner current and outer voltage loops.
- (6) Characterize the closed-inner current loop and closed-outer voltage loop.
- (7) Identify the key differences between peak current-mode control, classical average current-mode control, and modified average current-mode control.
- (8) Give specific examples of transfer functions, input and output impedances, and step responses.
- (9) Quick reference to key design equations, MATLAB codes, instructions to operate simulation tools, and component parameters.

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Marian K. Kazimierczuk
Dalvir K. Saini
Agasthya Ayachit

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We have sincerely attempted at making this edition of the book error-free so that readers gain a better understanding of the material. The authors would welcome and greatly appreciate readers' suggestions and corrections for improvements of the technical content and the presentation style and ideas for newer topics, which can be implemented in possible future editions.

1

Introduction

Current-mode control of pulse-width modulated (PWM) DC–DC converters has been one of the most challenging and interesting topics of study in the vast field of power electronics for almost two decades. Even to this day, rigorous research to establish a solid and systematic characterization of current-mode controlled DC–DC power converters is being performed. Continuing research in current-mode control is focused toward analysis, design, modeling, and efficient implementation in a wide variety of important applications such as power-factor correctors, battery chargers, and LED drivers. Chapters 2–5 seek to develop a complete characterization of the average current-mode control of basic DC–DC power converter topologies.

Current-mode control, particularly peak current-mode control, was first introduced by T. A. Froeschle in 1967 [1] and Cecil of Bell Labs/Western Electric in 1978 [2]. The invention mainly helped to balance the AC flux in a transformer of a push–pull converter to keep the core from walking off into saturation caused by a minor difference in the volt-sec balance. Core saturation generally occurred in converters with slightly asymmetric drive waveforms or was due to load transients. In view of the growing demand for DC–DC converters, especially in military, telecommunication, and aerospace industries, it became extremely necessary to develop static and dynamic models of power electronic systems. A significant advancement came when Dr. Slobodan Ćuk introduced the state-space averaging technique, where the circuit behavior in switching sub-intervals was mathematically represented in the form of state variables with the state variables being the inductor current and capacitor voltage. Another advancement that came via pioneering research, which realized the important aspects of closed-loop stability of peak current-mode controlled DC–DC converters, was conducted by Dr. David Middlebrook and Dr. F. D. Tan of California Institute of Technology in 1985. To this day, these works serve as a starting point for establishing stability criteria, especially in cascaded or multilevel power converters [3–6].

The concept of average current-mode control was reinstated by Lloyd Dixon from Unitrode Electronics in 1990 [7, 8]. In the following years, closed-loop modeling of the average current-mode controlled AC–DC and DC–C converters was performed by various researchers including Raymond B. Ridley *et al.* [9–11] and Jian Sun and

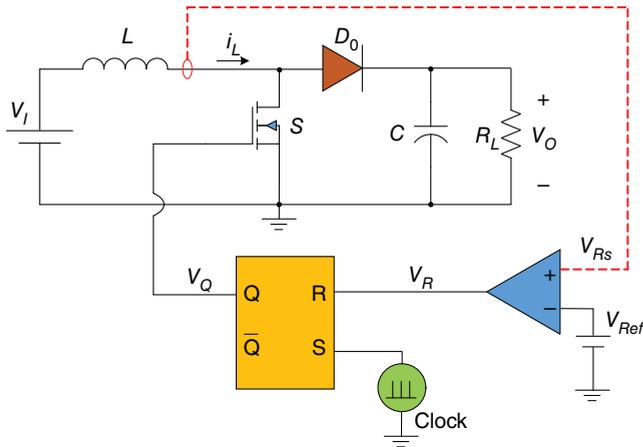


Figure 1.1 Boost DC–DC converter with a peak current-mode control, showing only the inner current loop.

R. M. Bass [12]. The peak current-mode control and the average current-mode control were also studied in [7–11, 13–35].

Before describing the principle of operation of the average current-mode control, it is imperative to discuss properties of peak current-mode control. Figure 1.1 depicts boost DC–DC converter with a peak current-mode control, showing only the inner current loop. In the peak current-mode control, the peak of the inductor current waveform is tracked and controlled [53]. The peak inductor current is compared with the reference current set by the outer-voltage loop of the DC–DC converter (not shown in Figure 1.1). As the peak value of the sensed inductor current becomes equal to the reference current, the comparator outputs a logic low at the instant of comparison and a logic high for all other values. The comparator output is connected to the reset pin R of the RS latch, whereas the set pin S is connected to a clock tuned to operate at the switching frequency. Initially, the set pin S enables the latch output Q to the ON state. Eventually, as the reset pin receives a logic high, the output of latch resets the switch to the OFF position and remains in this state until the clock sets it back to high position. The clock determines the beginning of the cycle, and the crossing of the inductor current waveform with the reference current determines the end of the high level of the gate-source voltage. The following operational disadvantages are observed as a consequence of peak current-mode control:

- Switching is highly susceptible to noise. At the instant of comparison of the peak inductor current and the current reference, a noise spike is created. The noise signal can create false triggering of the logic gates, resulting in the undesirable switching events.
- Slope compensation is required. The peak current-mode control needs slope compensation circuitry for duty cycles higher than 0.5 to avoid instability. The fixed compensation ramp provides adequate compensation; however, it will overcompensate much of the time, resulting in the performance degradation and increased distortion [7].

