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Digital Signal Processing in Power Electronics Control Circuits

Second Edition

Springer

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This book is dedicated to my dear parents Maria and Kazimierz, and my darling children, Anna, Mateusz and Andrzej.

Preface

Preface to the Second Edition

The first edition of the book was one of the elements of my habilitation (a qualification above a Ph.D., which is a necessary step for obtaining the title of a professor in Poland and other European countries), and as a result it was subsequently very carefully reviewed by four reviewers. The habilitation was a success. Using the insightful comments from my reviewers, I have improved the current version and eliminated some typographic errors that were initially overlooked.

This book is based on the first edition of the book and besides some changes to the previous material, there are some new elements I include in the new edition. In particular, I add more MATLAB listings, which would further complement and enrich the text by providing worked examples of the solutions proposed in the book.

More figures are added and all the existing ones are revised and in color. My new solution for a shunt active power filter is also included in the new edition. All those changes are introduced in the Chapters from the first edition.

This book also includes a new Chapter considering selected problems of simulation of power electronic systems together with digital control circuits. These simulations are conducted using MATLAB and PSIM. In the case of the PSIM programs, the considered methods use C code for describing the digital control algorithm.

I have written this book in his endeavor to abide by the following maxim *nulla dies sine linea* ↔ *nie ma dnia bez kreski* ↔ *not a day without a line drawn* (Apelles, Greek painter, flourished 4th century bc). However, this is not always easily achieved.

Zielona Góra, Poland
February 2017

Krzysztof Sozański

Preface to the First Edition

Power electronics circuits are becoming increasingly important in the modern world due to the rapid progress in developments of microelectronics in areas such as microprocessors, digital signal processors, memory circuits, complementary metal-oxide-semiconductors, analog-to-digital converters, digital-to-analog converters and power semiconductors—especially metal-oxide-semiconductor field-effect transistors and insulated gate bipolar transistors.

Specifically, the development of power transistors has shifted the range of applications from a few amperes and hundreds of volts to several thousands of amperes and a few kilovolts, with a switching frequency measured in millions of hertz. Power electronics circuits are now used everywhere: in power systems, industry, telecommunications, transportation, commerce, etc. They even exist in such modern popular devices as digital cameras, mobile phones, and portable media players. Power electronics are also used in micropower circuits, especially in energy harvesting circuits.

In the early years of power electronics, in the sixties and seventies, analog control circuits were most commonly used, meaning that only the simplest control algorithms could be applied. Some years later, in the eighties and early nineties, hybrid control circuits were used, which consisted of both analog and digital components. In subsequent years there followed a slow transition to fully digitalized control systems, which are currently widely used and enabled the application of more complex digital signal processing algorithms.

In this book the author considers signal processing, starting from analog signal acquisition, through its conversion to digital form, methods of its filtration and separation, and ending with pulse control of output power transistors. The author has focused on two applications for the considered methods of digital signal processing: an active power filter and a digital class-D power amplifier.

Both applications require precise digital control circuits with very high dynamic range of control signals. Therefore, in the author's opinion these applications will provide very good illustrations for the considered methods. In this book the author's original solutions for both applications are presented. In the author's opinion the adopted solutions can also be extended to other power electronics devices.

The discussion of the first application, APF, starts with the analysis of first harmonic detectors based on: IIR filter, wave digital filters, sliding DFT and sliding Goertzel, moving DFT. Following that, author's implementation of classical control circuits based on $p - q$ algorithm is presented. Next, the dynamics of APF is considered. Dynamic distortion of APF makes it impossible to fully compensate line harmonics. In some cases, the line current *THD* ratio for systems with APF compensation can reach a value of a dozen or so percent. Therefore the author has dealt with this problem by proposing APF models suitable for analysis and simulation of this phenomenon. For predictable line current changes, it is possible to develop a predictable control algorithm to eliminate APF dynamics compensation errors. In the following sections the author's modification using a predictive circuit to eliminate dynamic compensation errors is described. In this book control circuits with filter banks which allow the selection of compensated harmonics are described. The considered filter banks are based on sliding DFT, sliding Goertzel, moving DFT and $p - q$ algorithm.

For unpredictable line current changes the author has developed a multirate APF. The presented multirate APF has a fast response for sudden changes in the load current. So, using multirate APF, it is possible to decrease the *THD* ratio of line current even for unpredictable loads.

The second application is a digital class-D amplifier. Both APFs and the amplifiers are especially demanding in terms of the dynamics of processed signals. However, in the case of a class-D amplifier, the dynamics reach 120 dB, which results in high requirements for the type of algorithm used and its digital realization. The author has proposed a modulator with a noise shaping circuit for a class-D amplifier. Interpolators are also considered that allow for the increasing of the sampling frequency whilst maintaining a substantial separation of signal from noise. The author also presents an original analog power supply voltage fluctuation compensation circuit for the class-D amplifier. The class-D amplifier with digital click modulation is given special consideration too. Finally, two-way and three-way loudspeaker systems, designed by the author, are presented, where the signal from input to output is digitally processed.

The great majority of the presented methods and circuits is the original work of the author. Listings from MATLAB or in C language are attached to some of the considered algorithms to make the application of the algorithms easier. The presented methods and circuits can be successfully applied to the whole range of power electronics circuits.

The issues concerning digital signal processing are relatively widely described in the literature. However, in the author's opinion, there are very few publications combining digital signal processing and power electronics, due to the fact that these two areas of knowledge have been developed independently over the years. The author hopes that this book will, to some extent, bridge the gap between digital signal processing and power electronics. This book may be useful for scientists and engineers who implement control circuits, as well as for students of electrical engineering courses. It may also be of some value to those who create new topologies and new power electronics circuits, giving them some insights into possible control algorithms.

Zielona Góra, Poland — Krzysztof Sozański
December 2012

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Many thanks also to my English consultants, Peter Preston from the University of Zielona Góra and my daughter Anna Sozanska who is studying at the University of Cambridge. I hope that I successfully applied all of your comments and corrections.

I would also like to thank everyone who supported me during the writing of this book.

Contents

Abbreviations and Symbols

Abbreviations

AC	Alternating current
A/D	Analog-to-digital converter
ALU	Arithmetic-logic unit
APF	Active power filter
av	Average value of signal
BPF	Band-pass filter
BSF	Band-stop filter
CM	Click modulator also called zero position coding
D/A	Digital-to-analog converter
D/t	Digital-to-time converter
DAI	Digital audio interface
dB	Decibel, $20\log(U_2/U_1)$, $10\log(P_2/P_1)$
DC	Direct current
DFT	Discrete Fourier transform algorithm
DPWM	Digital pulse width modulation
DSM	Delta sigma modulator
DSP	Digital signal processor
e.g.	For example (exempli gratia—Latin)
EMI	Electromagnetic interference
etc.	And other things, or and so forth (et cetera—Latin)
FFT	Discrete fast Fourier transform algorithm
FIR	Finite impulse response digital filter
FLOPS	Floating-point operations per second
FPGA	Field programmable gate array
HPF	High-pass filter
i.e.	This is (id est—Latin)
IC	Integrated circuit
IGBT	The insulated gate bipolar transistor
IIR	Infinite impulse response digital filter

IIS	Inter-IC sound, integrated interchip sound, or IIS, is an electrical serial bus interface standard used for connecting digital audio devices together
$\mathrm{Im}(x), \Im(x)$	Imaginary part of x
IPS	Instructions per second, MIPS
IPT	Instantaneous power theory
LBWDF	Lattice bireciprocal wave digital filter
LC	LC circuit, circuit composed of capacitor and inductor
LogChrip	Logarithmic chirps signal
LPF	Low-pass filter
LR	Linkwitz–Riley filter
LSB	Last significant bit
LTI	Linear time-invariant circuit (system)
LWDF	Lattice wave digital filter
MAC	Multiplication and accumulation, special arithmetic operation of DSP
MDFT	Moving discrete Fourier transform algorithm
MIPS	Million instructions per second
MLS	Maximal length sequence signal
MOSFET	Metal–oxide–semiconductor field-effect transistor
MSB	Most significant bit
MWDF	Modified wave digital filters
PCB	Printed circuit board
PCM	Pulse code modulation
PDF	Probability density function
PLL	Phase locked loop or phase lock loop circuit
PWM	Pulse width modulation
QMF	Quadrature mirror filter
$\mathrm{Re}(x), \Re(x)$	Real part of x
RLC	Circuit, circuit composed of resistor, capacitor and inductor
rms	Root mean square
S/PDIF	Sony/Philips digital interconnect format (more commonly known as Sony Philips digital interface)
SA	Successive approximation
SC	Strictly complementary digital filter bank
SDFT	Sliding discrete Fourier transform algorithm
SGDFT	Sliding Goertzel discrete Fourier transform algorithm
SH	Sample–and–hold circuit, sampling circuit
SOS	Second-order section
SPS	Sample per seconds
TR	Time reversal
U2	Two's complement binary code
WDF	Wave digital filters
ZePoC	Zero position coding also called click modulation
μC	Microcontroller
μP	General-purpose microprocessor

Symbols

C	Capacitance
δ_p	Ripple in the passband
δ_z	Ripple in the stopband
f_c	Filter crossover (cutoff) frequency
f_s	Sampling rate, sampling frequency
f_k	Power transistor switching frequency
f_M	Line voltage frequency
f_p	Passband frequency
f_z	Stopband frequency
$H(s)$	Analog transfer function
$H(z)$	Digital transfer function
$i_C, i_C(t)$	Instantaneous value of APF compensation current
$i_C(n)$	Discrete signal represents APF compensation current
$i_M, i_M(t)$	Instantaneous value of line current, power line current
$i_M(n)$	Discrete signal represents power line current
$i_L, i_L(t)$	Instantaneous value of load current
$i_L(n)$	Discrete signal represents load current
L	Inductance
N	Length of sample block
N_M	Number of samples per line voltage period
R	Signal oversampling ratio
R	Resistance
M	Signal decimation ratio
$SINAD$	Signal to noise and distortion ratio
SNR	Signal to noise ratio
THD	Total harmonic distortion
T_M	Line voltage period
T_s	Sampling period
Q_g	MOSFET total gate charge
Q_{rr}	Diode reverse recovery charge
$u_{C1}, u_{C1}(t)$	Instantaneous value of capacitor voltage
$X(s)$	Analog signal transmittance
$X(z)$	Digital signal transmittance
Z	Impedance
Z_C	APF compensation circuit output impedance
Z_M	Power line impedance
Z_L	Load impedance
z^{-1}	Unit delay operator