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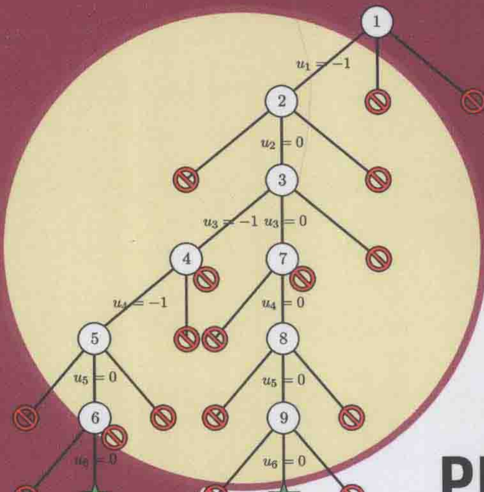
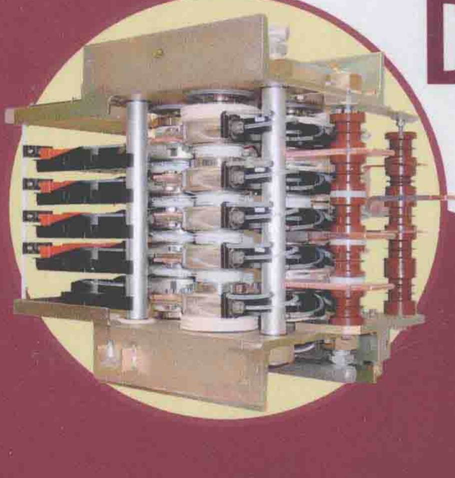


MODEL PREDICTIVE CONTROL OF HIGH POWER CONVERTERS AND INDUSTRIAL DRIVES



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MODEL PREDICTIVE CONTROL OF HIGH POWER CONVERTERS AND INDUSTRIAL DRIVES

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WILEY

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To Luci, David, and Jan

Preface

This book focuses on model predictive control (MPC) schemes for industrial power electronics. The emphasis is on three-phase ac–dc and dc–ac power conversion systems for high-power applications of 1 MVA and above. These systems are predominantly based on multilevel voltage source converters that operate at switching frequencies well below 1 kHz. The book mostly considers medium-voltage (MV), variable-speed drive systems and, to a lesser extent, MV grid-connected converters. The proposed control techniques can also be applied to low-voltage power converters when operated at low pulse number, that is, at small ratios between the switching frequency and the fundamental frequency.

For high-power converters, the pulse number typically ranges between 5 and 15. As a result, the concept of averaging, which is commonly applied to power electronic systems to conceal the switching aspect from the control problem, leads to performance deterioration. In general, to achieve the highest possible performance for a high-power converter, averaging is to be avoided, and the traditionally used current control loop and modulator should be replaced by one single control entity.

This book proposes and reviews control methods that fully exploit the performance potential of high-power converters, by ensuring fast control at very low switching frequencies and low harmonic distortions. To achieve this, the control and modulation problem is addressed in one computational stage. Long prediction horizons are required for the MPC controllers to achieve excellent steady-state performance. The resulting optimization problem is computationally challenging, but can be solved in real time by branch-and-bound methods. Alternatively, the optimal switching sequence to be applied during steady-state operation—the so-called optimized pulse pattern (OPP)—can be precomputed offline and refined online to achieve fast closed-loop control.

To this end, the research vision is to combine the benefits of deadbeat control methods (such as direct torque control) with the optimal steady-state performance of OPPs, by resolving the antagonism between the two. Three such MPC methods are presented in detail.

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Over the years, I had the privilege of collaborating with many outstanding control and power electronics researchers. I would like to particularly mention Daniel Quevedo, Toit Mouton, Stefan Schröder, Georgios Papafotiou, and Petros Karamanakos. I would also like to thank Johann Kolar, José Rodríguez, and Ralph Kennel for their support and encouragement.

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At ABB, I have had the pleasure of working with many able colleagues on control-related topics that are part of this book. I am particularly grateful to Nikolaos Oikonomou, Wim van der Merwe, Peter Al Hokayem, Vedrana Spudić, Christian Stulz, Eduardo Rohr, Andrea Rüetschi, Thomas Burtscher, Christof Gutscher, Andrey Kalygin, Rick Kieferndorf, Silvia Mastellone, Helfried Peyrl, Jan Poland, Tobias Thurnherr, and Michail Vasiladiotis. A special word of gratitude is reserved for Gerald Scheuer for his steadfast support of and conviction in modern control methodologies.

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List of Abbreviations

Abbreviations

ac	alternating current
A/D	analog-to-digital
AFE	active front end
ANPC	active neutral-point-clamped
CB-PWM	carrier-based pulse width modulation
CPU	central processing unit
DB	deadbeat
dc	direct current
DFE	diode front end
DFT	discrete Fourier transform
DPC	direct power control
DSC	direct self-control
DSP	digital signal processor
DTC	direct torque control
EMF	electromotive force
FACTS	flexible ac transmission system
FC	flying capacitor
FCS	finite control set
FOC	field-oriented control
FPGA	field-programmable gate array
GCT	gate-commutated thyristor
IGBT	insulated-gate bipolar transistor
IGCT	integrated-gate-commutated thyristor
IM	induction machine
LQR	linear quadratic regulator
MIMO	multiple-input multiple-output
MLD	mixed logical dynamical
MMC	modular multilevel converter
MPC	model predictive control
MPDBC	model predictive direct balancing control
MPDCC	model predictive direct current control

MPDPC	model predictive direct power control
MPDTC	model predictive direct torque control
MP^3C	model predictive pulse pattern control
MV	medium-voltage
NPC	neutral-point-clamped
OPP	optimized pulse pattern
PCC	point of common coupling
PI	proportional–integral
PMSM	permanent magnet synchronous machine
pu	per unit
PWM	pulse width modulation
QP	quadratic program
rms	root-mean-square
SHE	selective harmonic elimination
SISO	single-input single-output
SVM	space vector modulation
TDD	total demand distortion
THD	total harmonic distortion
VC	vector control
V/f	volts per frequency
VOC	voltage-oriented control
VSD	variable-speed drive
VSI	voltage source inverter

Variables

i, v	instantaneous value of variables that are functions of time
$\vec{i}, \vec{v}$	space vectors
I, V	rms values
$\boldsymbol{x}$	column vector
$\boldsymbol{x}^T$	row vector
$\boldsymbol{X}$	matrix
$\mathcal{S}$	set

Symbols

$\mathbf{0}_{n\times m}$	zero matrix of dimensions $n \times m$
$\boldsymbol{A}$	system matrix (discrete time)
$\boldsymbol{B}$	input matrix (discrete time)
c	coefficient
C	capacitance (F)
$\boldsymbol{C}$	input matrix (continuous or discrete time)
d	pulse number
D	determinant
e, E	energy (J or pu)
f	frequency (Hz or pu)
$\boldsymbol{F}$	system matrix (continuous time)
$\boldsymbol{G}$	input matrix (continuous time)

$\boldsymbol{H}$	Hessian matrix
$i, \boldsymbol{i}, I$	current (A or pu)
$\boldsymbol{I}_n$	identity matrix of dimensions $n \times n$, $\boldsymbol{I}_n = \text{diag}(1, 1, \ldots, 1)$
j	imaginary unit, $\sqrt{-1}$
J	cost function
k	discrete time step
$\boldsymbol{K}$	transformation matrix
ℓ	discrete time step (relative to k)
L	inductance (H)
m	modulation index
M	moment of inertia (kg m^2 or pu)
n	order of harmonic, number of modules
N	length of switching sequence
p	number of pole pairs
pf	power factor
P	(instantaneous) real power (W or pu)
Q	(instantaneous) reactive power (Var or pu)
$\boldsymbol{q}, \boldsymbol{Q}$	penalty vector or matrix
R	resistance (Ω or pu)
sl	slip
S	apparent power (V A or pu)
t	time (s or pu)
T	torque (N m or pu)
$u, \boldsymbol{u}$	switch position, input (or manipulated) variable
$\Delta u, \Delta\boldsymbol{u}$	change in switch position
$U, \boldsymbol{U}$	sequence of switch positions (switching sequence)
$v, \boldsymbol{v}, V$	voltage (V or pu)
$\boldsymbol{V}$	generator matrix
$x, \boldsymbol{x}$	state variable
X	reactance (pu)
$y, \boldsymbol{y}$	output variable
Z	impedance (Ω or pu)
α	switching angle in pulse pattern (rad)
γ	load angle, that is, angle between the stator and rotor flux vectors (rad)
δ	(half of the) bound width
$\varepsilon, \boldsymbol{\varepsilon}$	degree of bound violation (at a time step)
$\epsilon, \boldsymbol{\epsilon}$	rms bound violation (over the prediction horizon)
λ	scalar penalty weight
$\boldsymbol{\lambda}$	flux linkage vector (Wb)
ϕ	phase angle (rad)
ρ	radius of sphere
σ	total leakage factor
θ	angle (argument) in pulse pattern (rad)
$\nu, \boldsymbol{\nu}$	insertion index
φ	angular position of a reference frame (rad)
$\psi, \boldsymbol{\psi}$	flux (linkage) (pu)

Ψ	flux (linkage) magnitude (pu)
τ	time constant (s or pu)
ω	rotational speed or angular frequency (rad/s or pu)
$\xi, \boldsymbol{\xi}, \zeta, \boldsymbol{\zeta}$	slack or auxiliary variable

Subscripts

$c_{\text{on}}, c_{\text{off}}, c_{\text{rr}}$	turn–on, turn–off and reverse recovery energy loss coefficients (J/(VA))
C_m	module capacitance (F)
f_c	carrier frequency
f_{DL}	frequency of deadlocks
f_{sw}	switching frequency
i_1	fundamental current
i_a, i_b, i_c	phase a, b, and c currents
i_α, i_β	real and imaginary parts of the current (in the stationary reference frame)
i_B	base current
$\boldsymbol{i}_c$	converter current vector
$\boldsymbol{i}_{\text{circ}}$	circulating current vector
i_d, i_q	real and imaginary parts of the current (in the rotating reference frame)
$\boldsymbol{i}_{\text{err}}$	current error vector
$\boldsymbol{i}_g$	grid current vector
i_n	neutral point current
$\boldsymbol{i}_r$	rotor current vector
i_R	rated current
$\boldsymbol{i}_{\text{rip}}$	ripple current vector
$\boldsymbol{i}_s$	stator current vector
i_T	anode current
I_{TDD}	total demand distortion (TDD) of the current
L_{br}	branch inductor
L_{ls}	stator leakage inductance
L_{lr}	rotor leakage inductance
L_m	main (or magnetizing) inductance
L_σ	total leakage inductance
N_p	prediction horizon (number of time steps)
N_s	switching horizon (number of switching events)
T_e	electromechanical torque
$T_{e,\min}$	lower bound on the electromagnetic torque
$T_{e,\max}$	upper bound on the electromagnetic torque
T_ℓ	load torque
T_p	prediction horizon (length in time)
θ_p	prediction horizon (angular interval)
T_s	sampling interval
u_{opt}	optimal control input (or manipulated variable)
v_{dc}	instantaneous dc-link voltage
V_{dc}	nominal dc-link voltage
$v_{\text{dc,lo}}, v_{\text{dc,up}}$	instantaneous voltage of the lower and upper dc-link half, respectively
v_n	neutral point potential

v_{ph}	phase voltage
ω_1	fundamental frequency
ω_{fr}	angular speed of the reference frame
ω_g	electrical grid frequency
ω_m	mechanical shaft speed
ω_r	electrical angular speed of the rotor
ω_s	stator frequency
ω_{sl}	slip frequency

Superscripts

i^*	current reference
$\vec{i}$	current space vector
$\hat{i}_n$	amplitude of harmonic current of order n
i'	scaled version of i, e.g., when turned into the per unit system
$\bar{\boldsymbol{u}}$	switch position multiplied with the generator matrix $\boldsymbol{V}$

Operations

$\mathrm{d}x/\mathrm{d}t$	time derivative of the variable x
$\exp(x)$, e^x	exponential of the variable x
$\Re\{x\}$	real part of the complex variable x
$\Im\{x\}$	imaginary part of the complex variable x
$\mathrm{conj}\{x\}$	complex conjugate of the complex variable x
$\boldsymbol{x} \times \boldsymbol{y}$	cross product of the vectors **x** and **y**
$x \in \mathcal{S}$	variable x belongs to the set $\mathcal{S}$
$\boldsymbol{x}^T$	transpose of the vector $\boldsymbol{x}$
$\boldsymbol{X}^{-1}$	inverse of the matrix $\boldsymbol{X}$
$\|x\|$	absolute value of the scalar x
$\|\boldsymbol{x}\|_1$	1-norm of the vector **x** (sum of the absolute values)
$\|\boldsymbol{x}\|_2$	2-norm or length of the vector **x** (square root of the sum of the squared values, Euclidian norm). To simplify the notation, we will often simply write $\|\boldsymbol{x}\|$
$\|\boldsymbol{x}\|_\infty$	infinity-norm of the vector **x** (largest absolute value)

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