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Preface

State of art power electronics plays a major role in our society and our daily life. Voltage-source converter (VSC) technologies are utilized in applications such as electric vehicles, variable-speed drives, high-voltage direct current (HVDC) transmission and flexible alternating-current transmission systems (FACTS). Nowadays, converter technologies are an integral part of all renewable power generation technologies such as wind turbine generators and photovoltaic generation units. VSC technologies are key elements for achieving enhanced system yield in power generation and power transmission.

During the past decade, multilevel VSC technology has dominated the market, but the new modular multilevel converter (MMC) technology adopted by the industry in recent years has demonstrated clear advantages with inherent properties such as built-in redundancy, higher efficiency, and lower harmonic content. State-of-the-art MMCs are core components in FACTS equipment and VSC-HVDC schemes.

The fast speed of MMC technology development has left a knowledge gap between the technology specialists and VSC-HVDC project developers and key personnel involved in those projects. There is a need for field engineers, project developers, and those involved in the development and management of these projects and graduate students to gain insights into the design, control, and application of this new MMC technology. In this respect, what is needed is a reference book to fill the gap between field engineers and HVDC specialists.

This book is a result of collaboration between experts from industry and academia. It provides theoretical insights into the design and control of MMC technology and investigate practical aspects of the project planning, design, manufacture, implementation, and commissioning of MMC-HVDC and multi-terminal HVDC transmission technologies.

Separated into three distinct parts, the first part of the book offers an overview of MMC technology, including information on converter component sizing, control and communication, protection and fault management, and generic modeling and simulation. The second part covers the applications of MMC-HVDC transmission technology in offshore wind power plants including planning, technical, and economic requirements and optimization options, fault management, and dynamic and transient stability. Finally, the third part explores the applications of MMC in HVDC transmission and multi-terminal configurations, including supergrids.

The authors hope the reader will find the book useful and stimulating and wish the reader an interesting journey into the world of MMCs.

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About the Companion Website

Don't forget to visit the companion website for this book:

www.wiley.com/go/Sharifabadi/ModularConverters

The companion website material consists of a collection of self-explanatory simulation models in Matlab/Simulink and PLECS for the MMC following closely the theory of control, modulation and modelling described in the chapters 3,4,5 and 6.

Scan this QR code to visit the companion website

Nomenclature

A list of the important symbols that used in this book can be found in Tables 1–4. A list of acronyms can be found in Tables 5–7.

Table 1 Superscripts, subscripts, circumflexes, and prefixes.

$*$	Complex conjugate
$\star$	Reference
f,F	Filtered value
0	Nominal value
$+$	Positive sequence
$-$	Negative sequence
u,l	Upper, lower arm
0	Mean value, zero-sequence component
a,b,c	Phases a, b, c
α,β	Components of the stationary $\alpha\beta$ reference frame
d,q	Components of the synchronous dq reference frame
$\sum$	Sum
Δ	Difference
$\bar{\cdot}$	Mean value
$\hat{\cdot}$	Peak value, estimated value
$\tilde{\cdot}$	Difference
Δ	Ripple quantity, parasitic quantity, difference, increment

Table 2 Variables.

h	Signed multiple of the fundamental frequency
i	Submodule index
k	Phase number
m	Carrier index
n	Sample index, sideband index
$s = \mathrm{d}/\mathrm{d}t$	Differential operator (or, where appropriate, complex Laplace variable)
t	Time
z	Forward-shift operator (or, where appropriate, complex z-transform variable)
$\delta = z - 1$	Delta operator
$i_{\mathrm{u,l}}$	Arm current
$i_{\mathrm{s}} = i_{\mathrm{u}} - i_{\mathrm{l}}$	Output current
$i_{\mathrm{c}} = (i_{\mathrm{u}} + i_{\mathrm{l}})/2$	Circulating current
i_{d}	DC-bus current
$e = i_{\mathrm{s}}^{\star} - i_{\mathrm{s}}$	Output-current control error
e'	Modified control error
$v_{\mathrm{cu,l}}^{i}$	Capacitor voltage in submodule i
$v_{\mathrm{cu,l}}^{\Sigma} = \sum_{i=1}^{N} v_{\mathrm{cu,l}}^{i}$	Sum capacitor voltage per arm
$v_{\mathrm{cu}}^{\Sigma} = v_{\mathrm{cu}}^{\Sigma} + v_{\mathrm{cl}}^{\Sigma}$	Sum capacitor voltage per phase
$v_{\mathrm{c}}^{\Delta} = v_{\mathrm{cu}}^{\Sigma} - v_{\mathrm{cl}}^{\Sigma}$	Imbalance sum capacitor voltage
$n_{\mathrm{u,l}}^{i}$	Submodule insertion index
$n_{\mathrm{u,l}} = \left(\sum_{i=1}^{N} n_{\mathrm{u,l}}^{i}\right)/N$	Insertion index per arm
$v_{\mathrm{u,l}} = \sum_{i=1}^{N} n_{\mathrm{u,l}}^{i} v_{\mathrm{cu,l}}^{i}$	Inserted arm voltage
$v_{\mathrm{s}} = (-v_{\mathrm{u}} + v_{\mathrm{l}})/2$	Output voltage
$v_{\mathrm{c}} = (v_{\mathrm{u}} + v_{\mathrm{l}})/2$	Internal voltage
v_{a}	AC-bus voltage
v_{g}	Grid voltage
v_{PCC}	PCC voltage
$v_{\mathrm{du,l}}$	Pole-to-ground dc-bus voltage
$v_{\mathrm{d}} = v_{\mathrm{du}} + v_{\mathrm{dl}}$	Pole-to-pole dc-bus voltage
$v_{\mathrm{d}}^{\Delta} = v_{\mathrm{du}} - v_{\mathrm{dl}}$	Imbalance dc-bus voltage
v_{R}	R-part output
$W_{\mathrm{u,l}} = C(v_{\mathrm{cu,l}}^{\Sigma})^2/(2N)$	Stored energy per arm
$W_{\Sigma} = W_{\mathrm{u}} + W_{\mathrm{l}}$	Stored energy per phase
$W_{\Delta} = W_{\mathrm{u}} - W_{\mathrm{l}}$	Imbalance stored energy
$W_{\mathrm{d}} = C_{\mathrm{d}}' v_{\mathrm{d}}^{2}/2$	Effective stored dc-bus energy
P	Active output power
P_{d}	DC-side input power
Q	Reactive output power
ω	Instantaneous angular frequency of the control-system dq frame
$\theta = \int \omega\,\mathrm{d}t$	Angle of the control-system dq frame

Table 3 Parameters and functions.

f_1	Fundamental frequency
$\omega_1 = 2\pi f_1$	Fundamental angular frequency
f_s	Sampling frequency
f_{sw}	Switching frequency
$T_s = 1/f_s$	Sampling period
T_c	Computational time delay
$T_d = T_c + 0.5T_s$	Total time delay
K	Space-vector scaling constant
M	Number of phases
N	Number of submodules per arm
C	Submodule capacitance
C_d	Installed dc-bus capacitance
$C'_d = C_d + 2MC/N$	Effective dc-bus capacitance
L	Arm inductance
R	Parasitic arm resistance
R_I	Insertion resistance
$\widehat{V}_s$	Peak value, fundamental component of v_s
$\widehat{I}_s$	Peak value, fundamental component of i_s
$\widehat{V}_{max}$	Maximum allowed $\widehat{V}_s$
$\widehat{I}_{max}$	Maximum allowed $\widehat{I}_s$
φ	Phase angle (lagging) of current relative voltage
φ_h	Phase angle of order-h symmetric component
δ_a	AC-bus-voltage phase angle
δ_g	Grid-voltage phase angle
θ_1	Voltage-reference phase shift
ω_c	Carrier angular frequency
θ_c	Carrier phase shift
m_f	Frequency ratio
m_a	Modulation index
C_h	Complex Fourier series coefficient
C_{mn}	Double complex Fourier series coefficient
J_n	Bessel function of order n
$\mathcal{L}$	Sorted list of submodules
Re	Real part
Im	Imaginary part
sat	Saturation function
satv	Vectorial saturation function

Table 4 Controller parameters and transfer functions.

α_b	PLL low-pass-filter bandwidth
α_c	Output-current control-loop bandwidth
α_d	DC-bus-voltage control-loop bandwidth
α_f	Voltage-feedforward-filter bandwidth
α_h	R-part bandwidth
α_{id}	DC-bus-voltage integrator bandwidth
α_{ip}	PLL integrator bandwidth
α_l	Power-synchronization control low-pass-filter bandwidth
α_p	PLL bandwidth
α_s	Power-synchronization control-loop bandwidth
K_h	R-part gain
K_i	I-part gain
K_p	P-part gain
K_s	Power-synchronization-control gain
K_v	Voltage droop gain
R_a	"Active resistance" for circulating-current control
R_s	"Active resistance" for power-synchronization control
ϕ_h	Compensation angle for resonant filter
F_h	R part
G_c	Closed-loop system
G_k	Open-loop system
H_h	Resonant filter
H_p	PLL low-pass filter

Table 5 Acronyms A—G.

Ag	Silver
ALA	Arm-Level Averaged
ALA-BLK	Arm-Level Averaged with Blocking capabilities
Al	Aluminum
AlN	Aluminum Nitride
AlSiC	Aluminum Silicon Carbide
APOD	Alternative Phase Opposite Disposition
APS	Auxiliary Power Supply
ARCP	Auxiliary Resonant-Commutated Pole
ATB	Average-voltage Tolerance Band
BCA	Bilateral Connection Agreement
BFOM	Baliga's Figure Of Merit
BJT	Bipolar Junction Transistor
BLK	Blocking
BPF	Band-Pass Filter
CCC	Capacitor-Commutated Converter
CCU	Central Control Unit
CTB	Cell-voltage Tolerance Band
CTBoptimized	optimized Cell-voltage Tolerance Band
CTE	Coefficient of Thermal Expansion
CUSC	Connection and Use of System Code
D	Derivative
DBC	Direct-Bonded Copper
DBS	Dynamic Braking System
DCB	DC Circuit Breaker
DCU	Distributed Control Unit
DDSRF	Decoupled Double Synchronous Reference Frame
DECC	Department of Energy & Climate Change
DFT	Discrete Fourier Transform
DPS	Dynamic Performance Study
DPWM	Digital Pulse-Width Modulation
DSOGI	Double Second-Order Generalized Integrator
DSP	Digital Signal Processor
DTC	Direct Torque Control
EMC	Electromagnetic Compatibility
EMF	Electromotive Force
EMI	Electromagnetic Interference
ENTSO-E	European Network of Transmission System Operators for Electricity
EOA	Emergency Overnight Accommodation
ESL	Equivalent Series inductance
ESR	Equivalent Series Resistance
FACTS	Flexible Alternating-Current Transmission System
FAT	Factory Acceptance Test
FEED	Front-End Engineering Design
FB	Full Bridge
FIT	Failures In Time
FPGA	Field-Programmable Gate Array
FPNSC	Flexible Positive/Negative-Sequence Control
FRT	Fault Ride Through
GC	Grid Code
GDU	Gate-Drive Unit
GPS	Global Positioning System
GTO	Gate Turn-Off

Table 6 Acronyms H—R.

HB	Half Bridge
HMI	Human—Machine Interface
HVDC	High-Voltage Direct Current
HW	Hardware
I	Integral
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
ISOP	Input-Series Output-Parallel
IPT	Instantaneous Power Theory
JFET	Junction Field-Effect Transistor
LCC	Line-Commutated Converter
LLA	Leg-Level Averaged
LPF	Low-Pass Filter
LVRT	Low-Voltage Ride Through
MMC	Modular Multilevel Converter
Mo	Molybdenum
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MOV	Metal-Oxide Varistor
MSI	Mixed-Sequence Injection
NLC	Nearest-Level Control
NSCOGI	North Sea Countries Offshore Grid Initiative
NSI	Negative-Sequence Injection
OEM	Original Equipment Manufacturer
OfGEM	Office of Gas and Electricity Markets
OFTO	Offshore Transmission Owner
PA	PolyAmide
PBT	PolyButylene Terephthalate
PCC	Point of Common Coupling
PD	Phase Disposition
PEEC	Partial-Element Equivalent Circuit
PET	PolyEthylene Terephthalate
PFC	Power-Flow Controller
PI	Proportional—Integral
PID	Proportional—Integral—Derivative
PLL	Phase-Locked Loop
PNSE	Positive/Negative Sequence Extraction
PNSRG	Positive/Negative Sequence Reference Generator
POD	Phase Opposite Disposition
PPA	PolyPhthalAmide
PPS	PolyPhenylene Sulphide
P	Proportional
PR	Proportional—Resonant
PSC	Phase-Shifted Carrier
PSI	Positive-Sequence Injection
PWM	Pulse-Width Modulation
QSG	Quadrature Signal Generation
R	Resonant
RES	Renewable Energy Source
RTS	Real-Time Simulator

Table 7 Acronyms S—Z.

SAT	Site Acceptance Test
SC	Short Circuit
SCFM	Short-Circuit Failure Mode
SCR	Short-Circuit Ratio
Si	Silicon
SiC	Silicon Carbide
SLA	Submodule-Level Averaged
SLS	Submodule-Level Switched
SM	Submodule
SOA	Safe Operating Area
SOGI	Second-Order Generalized Integrator
SSOA	Safe Switching Operator Area
STATCOM	Static synchronous Compensator
SVC	Static VAr Compensator
TC	Thermal Conductivity
THD	Total Harmonic Distortion
TIB	Tapped-Inductor Buck
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
VMM	Voltage-Margin Method
VSC	Voltage-Source Converter
VT	Voltage Transformer
WPP	Wind-Power Plant
WT	Wavelet Transform
WTHD	Weighted Total Harmonic Distortion
XLPE	eXtruded cross-bound PolyEthylene
ZVS	Zero-Voltage Switching

Contents