HVDC AND FACTS CONTROLLERS

Applications of Static Converters in Power Systems

Vijay K. Sood

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by

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This book is dedicated to my family for their ever loving support over the years. My thanks to my wife Vinay, daughter Nishi and son Ajay.

Preface

The motivation to write this book came from the observation that the technology of High Voltage DC (HVDC) Transmission and Flexible AC Transmission Systems (FACTS) has evolved much over the past 10 years, and no recent book addressed the developments in these areas in a compact, easily available and readable manner. These new developments came about primarily due to the advances in power electronic switches and microprocessors. This new book hopes to address a small part of the void that existed in the technical book area.

Some words should be said about the title of the book: *HVDC and FACTS controllers*. Modern thinking and terminology usage dictates that HVDC transmission should now be considered as a part of FACTS controllers. However, a look at the evolution in the field shows that the technology started with HVDC transmission and FACTS controllers came along much later. Hence my choice of the title reflects this.

The pioneering books in the field of HVDC and FACTS by well-known authors such as E.W.Kimbark, J.Arrillaga, K.R.Padiyar, N.G.Hingorani and L.Gyugyi were a source of great inspiration to me and will unmistakably have been reflected in the work here ... in some shape or form. I have also referred to many documents and papers from the archives of the IEEE, and this preface would be incomplete without acknowledging these reference sources.

The book writing process often has its own agenda. Furthermore, it is a difficult and time consuming affair. In this case the original, planned for time duration had to slip by many months due to personal health problems and other time commitments. Consequently, the original outline for the content and extent had to be altered somewhat from the final submission. However, I do thank the support and patience of Alex Greene and Melissa Sullivan at Kluwer Academic Publishers for sticking with me during this difficult period. I thank also Dr. M.A.Pai who provided technical support and guidance during the feasibility and review process of the book.

The book is intended for senior under-graduate students, graduate students and practising utility engineers. Consequently, mathematical/theoretical

explanations have been kept to a minimum, and a focus on practical issues was maintained throughout the book.

This book would not have been possible without the efforts and contributions of many individuals. These individuals can be split into two groups: my former and present students at Concordia University, Montreal and many of my colleagues at IREQ (Hydro-Québec). These individuals are true troopers and I thank them for their support, camaraderie and skills over the many years that I had the pleasure of working with them.

My affiliation with the electrical engineering department at Concordia University dates back to 1984 when I started as an Adjunct Assistant Professor. The work of some of my former students figures prominently in this text book and I would like to thank Vijay Khatri, Krish Narendra, Rachit Arora and Anup Mazumder for their contributions.

I have spent most of my working life of 28 years plus, at the research institute of Hydro-Québec (known internationally as IREQ), mostly in the Power Systems Simulation Group, but more recently in the Electrical Equipment Group. I would like to thank my former colleagues P.C.S. Krishnayya, Harbans Nakra, Lewis Vaughan, Ly Bui and David McCallum amongst others. It is not possible to name individually all the other colleagues at IREQ with whom I have inter-acted with over the years, but I do thank them collectively. In addition, there are many other individuals at Hydro-Québec, and elsewhere, who have contributed, in their own way, to the subject matter at hand.

Other associates who have provided indirect moral support and inspiration over the years are Professors Loi Lei Lai at City University, London (UK) and H.S.Chandrasekhariah of IISc, Bangalore (now deceased).

I had considerable support from manufacturers and other corporate sponsors in the preparation of this book. They assisted primarily with the supply of both technical literature and photographs. These individuals include: Niclas Ottosson and Lewis Vaughan (ABB), Peter Lips (Siemens), Michael Baker (Alstom), Paul Wilson (Manitoba HVDC Research Centre), members of RTDS Technologies Inc. and Bahram Khodabakhchian (TransÉnergie Technologies). My grateful appreciation to all of them.

The book starts with a short Introduction to HVDC transmission. This is followed by chapter 2 with a discussion of the two types of converters - namely current and voltage source converters - which form the core converters for applications in HVDC and FACTs controllers. The current source converter has traditionally been associated with HVDC transmis-

sion. However, the more recent development of the voltage source converter has extended the reach and opened new areas of applications. Chapter 3 deals with synchronization techniques for the power converters with the ac system frequency. This topic has not been given the necessary importance in previous textbooks and is likely to gain in importance in the future as (a) inter-connections to weak ac systems become more frequent, and (b) inter-actions between ac-dc-ac systems become more relevant. Chapter 4 deals with HVDC control strategies for two-terminal HVDC systems; an extension to multi-terminal HVDC systems had to be cut due to time limitations. Chapter 5 deals with a fundamental look at forced commutated converters, and lays out some of the basic considerations. With the availability of new switching devices, some of these considerations will take on added importance in the future. The recent success of the capacitor commutated converter is highlighted in chapter 6. This new application of an old configuration demonstrates the need for persistence and research effort needed to develop ideas to fruition. Chapter 7 describes a new converter configuration and a FACTS application which promises an exciting future for this technology. Some of the persistent research efforts have led to new applications and possibilities for using the voltage source converter in future HVDC applications and these are highlighted in chapter 8. The new control paradigms developed in the past ten years have opened the door to exciting new applications of active ac and dc filters. Chapter 9 presents one of these applications and shows the control paradigms required. Much research in this area is on-going and the future holds new applications and reduced costs for the converters. Chapter 10 presents the results of an EMTP based study of typical disturbances on an HVDC system. This demonstrates the need for optimization of controller gains and effort and detail required to do studies to obtain the gain parameters of the controllers. The use of new control algorithms using fuzzy logic, neural networks and intelligent controllers may ease some of the burden placed on existing PI controllers; this is a topic of intense research and will figure prominently in the future. Chapter 11 deals with a simple neuro-fuzzy adaptive controller which could be used to enhance performance of a HVDC system. Chapter 12 is a short introduction to measurement and monitoring aspects related to the controllers. Chapter 13 deals with some of the studies that the author has been associated with and brings out the inter-action aspects of ac-dc systems and controllers. Considerable number of studies of this nature have to be carried out by the practising engineer to verify system behavior and stability. No mathematical development into the topic is presented and will be left to another project in the future. Some of the tools that are used by practising engineers in the afore-mentioned studies are presented in Chapter 14. In the final

chapter, a look at the modern HVDC system where the focus will be on cost reduction using the latest techniques is presented.

Finally, I would like to emphasize the solid faith, effort and contributions of my wife Vinay in the preparation of this book. She was a constant source of support and provided many valuable contributions in typing and re-typing the manuscript, drawing the figures, proof reading and doing the necessary corrections. Her patience in tolerating the many hours that I was away tackling this work while neglecting my other duties is most admirable.

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January, 2004
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Acronyms

ACF	AC Filter
A/D Converter	Analog to Digital Converter
AF	Active Filters
ALPRET	Alpha Retard (at rectifier)
ATP	Alternative Transients Program (a freeware version of EMTP)
BB	Back to Back (Converter)
CC	Circuit Commutation
CC	Current Control
CCC	Capacitor Commutated Converter
CCO	Current Controlled Oscillator
CE	Current Extinction
CEA	Constant Extinction Angle
CF	Commutation Failure
CLC	Chain Link Converter
CSC	Current Source Converter
CSCC	Controlled Series Capacitor Converter
ConTune	Continuously Tuned (Filter)
DCF	DC Filter
DCG	Development Co-Ordination Group (of EMTP)
DCPT	DC Potential Transformer
DSP	Digital Signal Processor
DQO	Direct Quadrature Zero
EHV	Extra High Voltage
ESCR	Effective Short Circuit Ratio
EMTP	Electro-Magnetics Transients Program
EMTPWorks RV	New version of EMTP Restructured Version
EMTDC	Electro-Magnetics Transients for DC
EPC	Equi-Distant Pulse Control
EMI	Electro-Magnetic Interference
FC	Forced Commutation
FACTS	Flexible Alternating Current Transmission Systems
FR	Force-Retard

GFU	Grid Firing Unit
GTO	Gate Turn-Off (Thyristor)
GUI	Graphical User Interface
HB	Hysteresis Band
HVDC	High Voltage Direct Current
HVDC Light	Trade mark of a version of HVDC converter for low powers
HYPERSIM	Trade mark of a version of digital simulator
IGBT	Insulated Gate-Bipolar Transistor
IPC	Individual Phase Control
IPP	Inter-Mountain Power Project
IOLIM	Current Order Limited
IMIN	Current Order Minimum
LCC	Line Commutated Converter
LC	Line Commutation
LPOF	Low Pressure Oil Filled
LTT	Light-Triggered Thyristor
LU	Lower Upper
MAP	Maximum Available Power
MTDC	Multi-terminal Direct Current
MVA	Mega Volt Amps
MCT	MOS Controlled Transistor
MOSFET	MOS Field Effect Transistor
MP	Mid Point
MISO	Multiple-Input Single-Output
MODELS	New EMTP subroutine for controls
OCP	Over Current Protection
OOM	Object Oriented Method
OCT	Optical Current Transducer
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
PFC	Pulse Frequency Control
PPC	Pulse Phase Control
PS	Periodical Sampling
PPCO	Pulse Phase Control Oscillator
PDP	Pole Differential Protection
PT	Potential Transformer
PSCAD	Power System Computer Aided Design

RoW	Right of Way
RBF	Radial Basis Function
RBFNN	RBF Neural Network
RLC	Resistor, Inductor and Capacitor
RV	Restructured Version
SIL	Surge Impedance Loading
SI	Static Induction Thyristor
SVC	Static Var Compensators
SCR	Short Circuit Ratio
STATCOM	Static Compensator
SLG	Single Line to Ground (Fault)
THD	Total Harmonic Voltage Distortion
TNA	Transient Network Analyzer
TC	Triangular Carrier
UHV	Ultra High Voltage
VC	Voltage Control
VH	Valve Hall
VY	Valve Yard
VAR	Volt Amps reactive
VCO	Voltage Controlled Oscillators
VDCL	Voltage Dependent Current Limit
VDCOL	Voltage Dependent Current Order limit
VSC	Voltage Source Converter
VGP	Valve Group Protection
XLPE	Cross Linked Poly-Ethylene
HVDC ^{PLUS}	HVDC Power Link Universal System from Siemens
NF	Neuro-Fuzzy

Corporate entities

CEPEL	Name of research organization (of Brazil)
CESI	Name of research organization (of Italy)
CPRI	Central Power Research Institute (of India)
ABB	Manufacturer of electrical equipment
Siemens	Manufacturer of electrical equipment
CIGRÉ	*Conseil International des Grands Réseaux Électriques*
IEEE	Institute of Electrical and Electronics Engineers
BPA	Bonneville Power Administration
IREQ	Institute of research of Hydro-Québec, Varennes, Québec.
RTDS	Real Time Digital Simulator Technologies Inc.

About the Author

Vijay Kumar Sood obtained his B.Sc.(1st Class Hons.) from University College, Nairobi in 1967 and his M.Sc. degree from Strathclyde University, Glasgow in 1969. He obtained a Ph.D. degree from the University of Bradford, England in 1977.

From 1969-76, he was employed at the BR Railway Technical Centre, Derby, UK. In 1976, he emigrated to Canada and was employed as a Researcher at IREQ (Hydro-Québec) in Montreal. In 1984, he also joined Concordia University, Montreal as an Adjunct Professor.

He is a Member of the *Ordre des ingènieurs du Québec*, a Senior Member of the Institute of Electrical and Electronic Engineers (IEEE), a member of IEE (UK) and a Fellow of the Engineering Institute of Canada. He has received numerous awards; among them are the 1998 Outstanding Service Award from IEEE Canada, the 1999 *Meritas Award* from the *Ordre des ingènieurs du Québec*, the IEEE Third Millennium Award from IEEE in 2000, the IEEE Regional Activities Board Achievement Award for 2001, and the Engineering Institute of Canada's Canadian Pacific Railway Engineering Medal for 2002. He is presently the Managing Editor of the *IEEE Canadian Review* (a quarterly journal of IEEE Canada); his term ends in 2005. He serves as an associate editor of the journal Control Engineering Practice for Pergamon Press, a Director and Treasurer of IEEE Montreal Conferences Inc. and a Director of the IEEE Canadian Foundation (till 2006).

Dr. Sood has worked on the modeling of electrical power systems and their controllers for over 28 years. His research interests are in the monitoring, control and protection of power systems using artificial intelligence techniques. He has published over 70 articles and written two book chapters. He has supervised 14 post-graduate students and examined 17 Ph.D. candidates from universities all over the world.

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