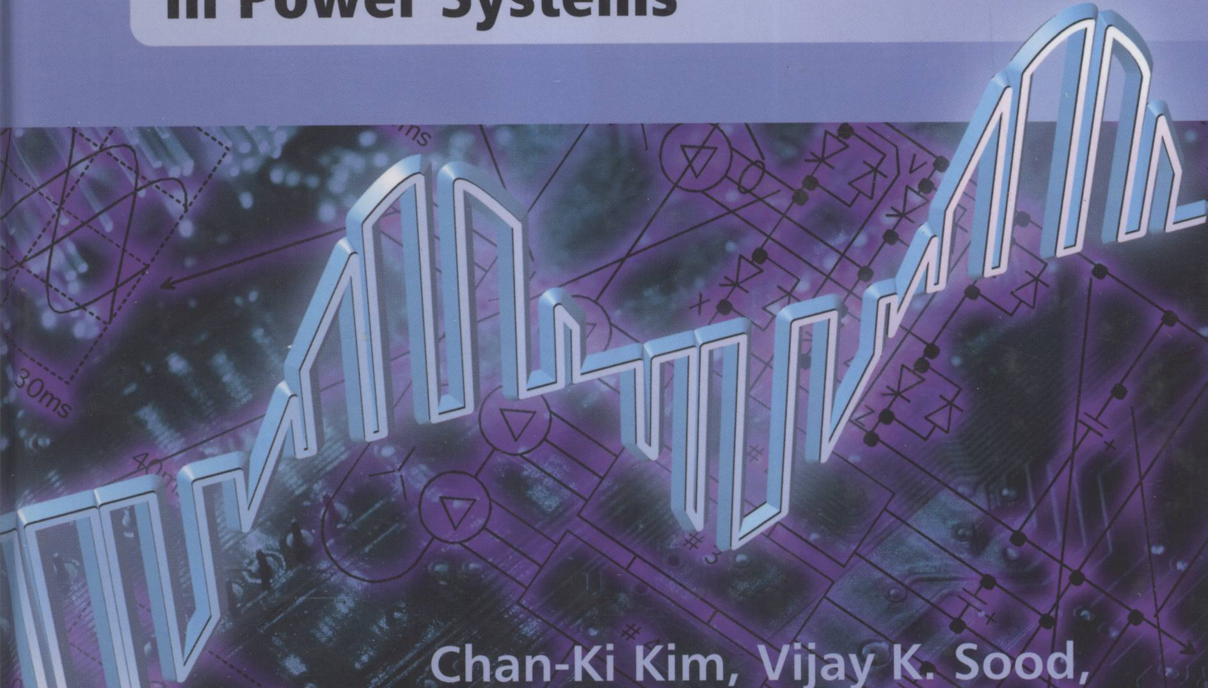
HVDC TRANSMISSION

Power Conversion Applications in Power Systems



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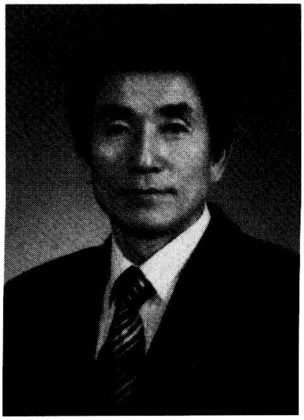
Foreword



Ten years ago Korea began the operation of its first HVDC system, linking Cheju Island to Haenam on the mainland. It was an extremely important contribution to our industry. In the future, issues such as systemic links and the quality of large scale, renewable energy will become crucial. HVDC is critical to solving these major concerns, I am proud to be a part of that project.

This book, a compendium of work relating to HVDC technology, is a key resource. Enormous effort has been undertaken to produce this great body of material in such a short period of time.

In our industry, we must acknowledge the inevitable depletion of fossil fuels and the growing importance of environmental awareness. As such, electricity offers a number of advantages in terms of efficiency, economy, and clean energy, especially compared to coal, oil, and gas. HVDC can resolve a number of issues, including voltage stability in alternating current systems, reducing growing fault currents, and increasing electric power reserves. Clearly, it plays a crucial role in the future of electric power.

Most significantly, HVDC is the most effective solution in areas which require high quality electricity or links to large scale renewable resources.

This book encompasses a number of studies which cover basic and advanced HVDC applications, all conducted under the supervision of world-renowned experts. Without doubt, this is one of the best volumes of information available for HVDC technology. Science has no boundaries, so I believe that this book will be a useful resource and beneficial to electric industries around the world.

I sincerely hope that the authors of this book continue to dedicate their vast skills and efforts to further research in the HVDC field.

I'm reminded of the tireless dedication of researchers I worked with when I was the president at KEPRI. They had a slogan written across their desks that 1 believe in whole heartedly. It said:

HVDC will bring benefits and improvement to the world!

Korea Electric Power Corporation
Transmission Division
Senior Vice-President Kim, Moon-Duk

Moon Duk, Kim

Preface

Although HVDC transmission is considered to be a mature technology by some, it is quite amazing how many new aspects and projects are under consideration. The complexity of electrical power systems is increasing owing to its interconnections with existing systems and application of new technology and at the same time, many economic and other constraints are forcing the utilities to operate their system near the maximal limits of stability and provide realiable and clean power at the lowest cost. In developing nations such as China, India, and Brazil, the ongoing demand for power is forcing the need for HVDC bulk power transmission over long distances. Developed nations wishing to interconnect networks and provide flexibility are relying on HVDC B-to-B connections. Furthermore, there is growing interest to incorporate renewable energy sources into the grid, again relying on HVDC links. It seems that applications of HVDC transmission technology are necessary as a means to overcome such problems.

The history of DC transmission began in 1897 when Thomas Edison succeeded in implementing the supply and consumption of electricity at a low DC voltage. At that time, the technological standards for electrical power industries were still being developed and the technological competition between the DC power transmission and the AC power transmission method through transformers, developed by George Westinghouse, were quite severe.

Subsequently, large-scale generation and transmission of electricity was in high demand as people began to realize its importance. Since AC technology was superior in terms of generation, reliability, transformation, and transmission voltage, it became the backbone of the electric power industry. On the other hand, DC transmission gained respect only after the development of the mercury arc valve in the 1930s. The HVDC type of electrical power transmission began its first commercial operation in Gotland, Sweden in 1954 through a submarine cable interconnection.

The unique characteristics of HVDC transmission continued to make the technology viable for special niche applications. In the early 1970s, the advent of the thyristor valve gave a boost to the applications of HVDC and considerably enhanced reliability and lowered the costs of implementation. The availability of high power forced commutated switches in the 1990s further enhanced the applications for HVDC. Today, the technology of HVDC is well established and operates in partnership with FACTS-based AC transmission to provide complex and versatile modes of power transmission. However, new applications are always being developed. It is important, therefore, that the technology continues to be developed too and that new researchers and engineers continue to understand this technology. We find, however, that the literature on this subject is often lacking and not available in a comprehensive manner. Consequently, it was felt that practicing engineers should add their expertise to this information pool for upcoming generations.

The Korea Electric Power Corporation (KEPCO) is currently actively pursuing an electrical power interconnection project encompassing the North-East Asian region domestically and abroad. The engineers, who have many years of practical experience behind them, got together to prepare this textbook. As a result of their first-hand knowledge of the actual station between Cheju and Haenam, this text combines practical and theoretical knowhow not available elsewhere on the subject of HVDC transmission.

In Chapters 1 and 2, we provide an introduction to DC power transmission and describe the basic components of a converter, which is the most essential element for HVDC transmission. In addition, we describe the methods for compensating the reactive power demanded by the converter and the methods for simulation of HVDC systems.

In Chapters 3–5, we have described the types of filters for removing harmonics and the characteristics of the system impedance resulting from AC filter designs. We also describe the IPC (Individual Phase Control) method, which is the basic method to control the phase of a thyristor, as well as the EPC (Equidistant Pulse Control) method and the DC system control method.

In Chapters 6–8, the design techniques for the main components of an HVDC system are described: thyristor converters, converter transformers, smoothing reactors, overhead lines, cable lines, ground electrodes, and Back-to-Back converters.

In Chapters 9–10, DC and AC transmission, in terms of their capacity of power transmission, environmental impact, and economical characteristics, are compared. Based on the actual application of electrical power transmission, we have fully described the current status of the HVDC type of electrical power transmission technology and the trend for HVDC technologies around the world.

Useful supplements for this title are available on the book's companion website at the following URL: http://www.wiley.com/go/hvdc.

It is our sincere hope that this text will add to the wealth of literature available on the subject of HVDC transmission. We do realize that it is not possible to cover all aspects of this vast technology, although we have tried to bring in a practical focus not available elsewhere.

Chan-Ki Kim
Vijay K. Sood
Gil-Soo Jang
Seong-Joo Lim
Seok-Jin Lee

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- L. Weimers – Chief Engineer Marketing HVDC, ABB
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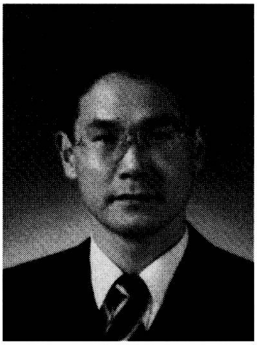
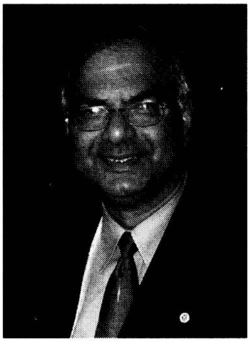


Chan-Ki Kim obtained his M.Sc. and Ph.D. degrees in Electrical Engineering from Chung-Ang University, Korea in 1993 and 1996, respectively.

Since 1996, he has been with KEPRI, the R&D center of KEPCO (Korea Electric Power Corporation). His research interests are HVDC, Power Electronics and Generator Control. In the field of HVDC and Power Electronics, he has helped to develop the HVDC simulator, HVDC commissioning technology and HVDC control algorithms. Related to these developments, until now he has published over 150 technical papers in widely read journals, including *KIEE* and *IEEE*, and submitted 40 patents and programs and has published three books.

He received the Technical Award from the Ministry of Science and Technology of the Korean Government and Excellent Paper Awards from *KIEE* in 2002 and 2004, respectively.

He is a Fellow and Editor of the Korea Institute of Electrical Engineers (KIEE). He is also a Senior member of the Institute of Electrical and Electronics Engineers (IEEE).



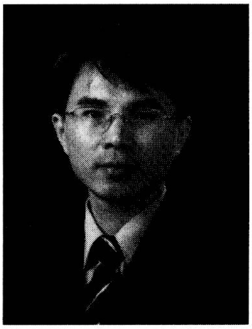
Vijay Sood obtained his B.Sc. (1st Class Honors) from University College, Nairobi, Kenya in 1967 and his M.Sc. degree from Strathclyde University, Glasgow, UK in 1969. He obtained his Ph.D. degree in Power Electronics from the University of Bradford, UK in 1977.

From 1969 until 1976, he was employed at the Railway Technical Centre, Derby, UK. From 1976 until 2006, he was employed as a Researcher at IREQ (Hydro-Québec) in Montreal, Canada. He is an Adjunct Professor at the following Universities: Concordia University, Montreal, Canada since 1979, at the University of Western Ontario, Canada, at the ETS in Montreal, Canada and at Ryerson University, Toronto, Canada. Presently, he is on special assignment at the University of Ontario Institute of Technology (UOIT) in Oshawa, Ontario.

He is a Member of the Ordre des ingènieurs du Québec, a Fellow of the IEEE, a member of IEE (UK) and a Fellow of the Engineering Institute of Canada. He was the recipient of the 1998 Outstanding Service Award from IEEE Canada and the 1999 Meritas Award from the Ordre des ingènieurs du Québec. In addition, he has received IEEE Regional Activities Board Achievement Awards for 2001 and 2006, the IEEE Third Millennium Medal and the 2002 Canadian Pacific Railway Engineering Award from the EIC. He was the Managing Editor of the *IEEE Canadian Review* (a quarterly journal for IEEE Canada) for a period of ten years from 1996 until 2006. He is a Director of the IEEE Canadian Foundation. He is also the Editor of the *IEEE Transactions on Power Delivery*, Co-Editor of the *CJECE* and an Associate Editor of the *Journal of Control Engineering Practice*.

Dr Sood has worked on the analog and digital modeling of electrical power systems and their controllers for over 35 years. His research interests are focused on the monitoring, control and protection of power systems using artificial intelligence techniques.

Dr Sood has published over 70 articles, written two book chapters and a textbook on HVDC Transmission. He has supervised 40 postgraduate students and examined 41 Ph.D. candidates from universities all over the world. He is well known amongst the electrical engineering community in Canada.



Gil-Soo Jang earned his B.Sc. and M.Sc. degrees in Electrical Engineering from Korea University, Seoul, Korea, in 1991 and 1994, respectively and his Ph.D. degree in Electrical Engineering from Iowa State University, Ames, IA, USA, in 1997. After receiving his Ph.D., he took a scientist position in the Department of Electrical and Computer Engineering at Iowa State University, and then a research engineer position in the Korea Electric Power Research Institute (KEPRI). He has been with Korea University since 2000, where he is currently an Associate Professor in the School of Electrical Engineering.

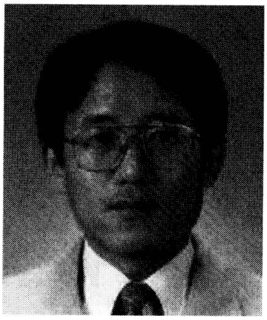
His research interests include power quality, power system dynamics and controls, computer applications in power systems, and distributed generation. He is the author or co-author of more than 70 technical publications including refereed journals, proceedings, and books. He teaches courses in power system related fields. He has performed more than 20 research projects funded by government and power industries since 2000.

He is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE). He received the Outstanding Paper Award from *KIEE* in 2004 and 2006. Also, he was selected as a recipient of the LG Yonam Fellowship in 2006.

Seong-Joo Lim obtained his B.Sc. degree in Electricity and Electrical Engineering from Dongguk University, Korea in 1982 and joined KEPCO in the same year.

He is a recipient of the following honors: Employee of the Year Quality Management and Quality Improvement, 2004 and Distinguished Project Management, Ministry of Commerce, Industry and Energy, 1997. He received the First National Electrical Engineer License from the Korea Government in 1987. He is the author or co-author of more than 10 technical publications.

At present, he is the Manager for the Cheju HVDC Link Project Team of the Transmission and Substation Construction Department, KEPCO.



Seok-Jin Lee obtained his B.Sc. and M.Sc. degrees in Electrical Engineering from the Seoul National University, Seoul, Korea, in 1980 and 1982, respectively.

He was the designer of Cheju HVDC #1 in 1992 and the manager of Cheju HVDC #1 in 1994. His fields of interest are HVDC and Power Quality. He received the First National Electrical Engineer License from the Korea Government in 1983. He is the author or co-author of more than 30 technical publications and he has five patents related to HVDC.

At present, he is a Vice-Director of the KEPCO (Korea Electric Power Corporation).

List of Symbols

$1/N$	Turns-ratio
α	Firing angle
βC	β control
γ	Turn-off angle
γC	γ control
$v_{c@}$	@-phase voltage of the converter
ρ_0	Specific resistance of the paper at the inside radius (conductor)
ω_G	Generator rotor speed
A	Pole-to-pole distance
AC	Alternating current
AG	Amplifying gate
AVR	Automatic voltage regulation
BC	Busbar connection
BOD	Break-over-diode
C	Recovery voltage at end of commutation
CC	Current control; Constant current
CCC	Capacitor commutated converter
CEA	Constant extinction (firing) angle
CFO	Critical flashover voltage
CP	Connecting pipe
CSCC	Controller series capacitor converter
CT	Current transducer
CTCs	Continuous transposed conductors
d	Diameter of the individual conductor; Conductor strand diameter
D	Diameter of the bundle
D′	A function of the overlapping angle reduced by the serial capacitor
D_e	Electrical damping
D_m	Mechanical damping
E_{FL}	Rated voltage
$E_{\max}$	Maximum surface gradient
EPC	Equidistant pulse control
ESCR	Effective short-circuit ratio
ESDD	Equivalent salt deposit density
F	Firing at start of commutation
f_0	Fundamental frequency (60 Hz)

F_0	Radio interference (field strength)
F_{demand} (Hz)	Frequency order value
F_{order} (Hz)	Frequency output value
f_t	Torsional mode
H	Heat sink
H	Average height above ground of the conductor
H_C	Denotes the contact strength while m/σ is the parameter in terms of the roughness
I_1	Fundamental current
I_d	Constant; DC current
I'_d	Newly increased DC current
I_{DC}	Level of direct current
I_{dFL}	Rated current
I_{dN}	Nominal DC current (A)
I_{hCCC}	Amount of harmonics in the CCC–HVDC system
I_{hCon}	Amount of harmonics in the general HVDC system
I_{order}	Current order from the power control
i_{s^*}	*-phase current
iA	Surge current
ILED	Infrared light emitting diode
iN	Follow current
IPC	Individual phase control
iS	Control current
IVIL	Inverter valve insulation level
K_S	Coefficient for the harmonic heat conduction
L_d	DC-side inductance (H)
L_s	Inductance of the input terminal of the converter
LCC	Line commutated (current source) converter
LI	Lightning impulse
LIWL	Lightning impulse level
LTT	Light triggered thyristor
m	Number of strands per bundle
MVA	Rating as per subscript (HVDC or ith unit)
n	An integer; Number of conductors per bundle
N_p	Guaranteed protection level
NV	Neutral voltage
OCT	Optical current transducer
OSCR	Operating short-circuit ratio
P	Denotes the contact pressure
P_c	Corona losses
P_d	DC power
P_{order}	DC power order
Pdc	(MW) DC power
PFC	Pulse frequency control
PPC	Pulse phase control
PSS	Power System Stabilizer

Q	Heat transfer
Q_F	Total reactive shunt compensation, including AC filters, with neutrals grounded (MVA)
QESCR	Q effective short-circuit ratio
R	Equivalent conductor bundle radius
r_0	Radius of the cable conductor
Rb	Bypass resistor
RH	Relative humidity
RS	SSDC output signal
RS	Grading resistor
RVIL	Rectifier valve insulation level
s	Distance of the strands within the bundle
S	Distance between conductors
S_N	Total rating of Y–Δ connected convertor transformers with neutrals grounded (MVA)
Sn	Transformer power $=\sqrt{3}\, U_{1n}I_{1n}$
S_{SC}	Short-circuit level (MVA)
$\underline{SC_{TOT}}$	Short-circuit capability at HVDC commutating bus including ith unit
$\overline{SC_{i\cdot}}$	Short-circuit capability at HVDC commutating bus excluding ith unit
SCR	Short-circuit ratio
SI	Switching impulse
SIWL	Switching impulse level
Slope (%droop)	Speed-droop characteristic of the system
SSDC	Subsynchronous damping control
SSO	Sub-synchronous oscillations
T_A	Ambient temperature
T_e	Generator electrical torque
T_J	Junction temperature of the semiconductor
Ta	Air temperature
Td	Dew temperature
TOV	Temporary overvoltage
U	Conductor-ground voltage in kV
U	Service voltage at arrester assembly
U_1	Fundamental voltage
U_d	Line-to-ground voltage
U_{dN}	Nominal DC voltage of the HVDC per pole (kV)
Ua	Sparkover voltage
UIF_i	Unit interaction factor of ith unit
UL	Arc voltage during quenching
Up	Residual voltage during diversion
URa	Voltage drop across Ra resistors during quenching
Us	Surge voltage
V1	Operation voltage peak of any normal operation condition including dynamic overvoltage
V2	VBO detection level
V3	Thyristor repetitive turn-on voltage

V4	Arrester protection level per element, unbalance factor included
V5	Thyristor non-repetitive turn-on voltage
V_d	DC voltage (of the inverter)
V_{d0}	No-load bridge voltage
V_{dc}	DC voltage value
V_k	Corona losses in kW/km per pole
V_L	AC terminal
V_m	Highest primary busbar voltage of the converter transformer (line-to-line, RMS)
VBE	Valve base electronics
Vc	Commutation recovery overvoltage spike
VC	Voltage control
VCO	Voltage controlled oscillator
VSC	Voltage source converter
VSF	Voltage sensitivity factor
Vw	Wind speed in ms
x	Leakage reactance (per unit)
X	SSDC input signal; Lateral distance from the conductor
X_1	Leakage reactance of convertor transformer (pu)
X_C	Commutation inductance
Z_0	Zero-sequence impedance of AC network
Z_1	Positive-sequence impedance of AC network
ZFCT	Zero flux current transformer

Contents