Power-Flow Modelling of HVDC Transmission Systems

Shagufta Khan
Suman Bhowmick

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This book deals exclusively with the power-flow modelling of HVDC transmission systems. Different types of HVDC transmission systems, their configurations/connections and control techniques are covered in detail. Power-Flow modelling of both LCC- and VSC-based HVDC systems is covered in this book. Both the unified and the sequential power-flow methods are addressed. DC grid power-flow controllers and renewable energy resources like offshore wind farms (OWFs) are also incorporated into the power-flow models of VSC-HVDC systems. The effects of the different power-flow methods and HVDC control strategies on the power-flow convergence are detailed along with their implementation.

Features:

- Introduces the power-flow concept and develops the power-flow models of integrated AC/DC systems.
- Different types of converter control are modelled into the integrated AC/DC power-flow models developed.
- Both unified and the sequential power-flow methods are addressed.
- DC grid power-flow controllers like the IDCPFC and renewable energy resources like offshore wind farms (OWFs) are introduced and subsequently modelled into the power-flow algorithms.
- Integrated AC/DC power-flow models developed are validated by implementation in the IEEE 300-bus and European 1354-bus test networks incorporating different HVDC grids.

This book aims at researchers and graduate students in Electrical Engineering, Power Systems, and HVDC Transmission.

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Preface

Over the past few decades, the construction of generation facilities and new transmission lines has been delayed in light of rising energy costs, environmental concerns, rights-of-way (RoW) restrictions and other legislative and cost problems. In addition, system stability issues may render long-distance AC transmission infeasible. In this respect, high-voltage DC (HVDC) transmission requires a smaller RoW, simpler, lighter and cheaper transmission towers, reduced conductor and insulator costs, reduced losses and is not limited by stability considerations. A HVDC link can augment system reliability by interconnecting two asynchronous AC grids and can be used to integrate offshore wind farms with onshore AC grids.

The first commercial application of HVDC transmission took place between the Swedish mainland and the island of Gotland in 1954, using mercury arc valves. Subsequently, the first 320 MW thyristor-based HVDC system was commissioned in 1972 between the Canadian provinces of New Brunswick and Quebec. Continuous development in conversion equipment led to reduced size and costs which resulted in more widespread use of HVDC transmission. The thyristor-based line commutated converter (LCC)–high-voltage DC (LCC-HVDC) technology now constitutes the bulk of the installed HVDC transmission corridors over the world.

With LCC-HVDC, for controlling the active power, both the rectification and the inversion processes consume reactive power. This necessitates the use of reactive power sources to match the reactive power demand at both ends. To reduce the effects of harmonic voltages and currents generated by the converters, harmonic filters are used on both the AC and DC sides. Also, a minimum short circuit level is required to avoid voltage instability. However, despite its limitations, LCC-HVDC possesses high reliability, good overload capability and lower converter losses. It requires low maintenance and capital costs, and is robust to DC fault currents due to its current-regulating nature.

Subsequently, the development of the Insulated Gate Bipolar Transistor (IGBT) paved the way for the Voltage-Sourced Converter (VSC)-based HVDC (VSC-HVDC) technology, which offered significant advantages over the LCC-HVDC. VSC-HVDC facilitates independent active and reactive power control, along with reduction in filter size. VSC-HVDC also enables the integration of offshore wind farms with AC grids. Compact, modular designs of the VSCs enable rapid installation, commissioning and relocation. Unlike LCC-HVDC, fixed DC voltage polarity in the VSC-HVDC enables the use of stronger and lighter XLPE cables, suitable for under-sea environments and attractive for offshore transmission. In addition, VSC-HVDC systems can be integrated with AC systems having low short circuit ratios.

The first 3-MW, VSC-HVDC link was commissioned at Hellsjon in Sweden in 1997. Subsequently, rapid development in the VSC technology has now resulted in the availability of higher rated (up to 2000 MW) VSC-HVDC links. This has resulted in the installation and commissioning of a large number of VSC-HVDC systems worldwide. Present VSC-HVDC solutions use the modular multilevel converter (MMC) technology, which is more advantageous than two- or three-level VSCs in terms of reduced converter losses, increased modularity and scalability along with elimination of filter requirements.

Now, in both LCC-HVDC and VSC-HVDC systems, the converter stations can be connected in two ways—back-to-back (BTB) and point-to-point (PTP). Most of the MTDC systems installed worldwide are in PTP configurations, their DC sides being interconnected through DC links or cables.

Unlike a 2-terminal HVDC interconnection, a multi-terminal HVDC (MTDC) system is more versatile and better capable of utilising the economic and technical advantages of HVDC technology. Moreover, sources of renewable energy can be easily integrated with a MTDC system, as and when the need arises.

For proper MTDC operation, DC voltage control is an essential requirement. In this respect, several control techniques have been envisaged. These include DC slack-bus control (also known as DC master-slave control), distributed DC voltage droop control, power synchronization control, hierarchical power control and transient management control.

However, among all the DC voltage control techniques, the DC slack-bus control and distributed DC voltage droop control have been the more popular and widely employed ones.

In DC slack-bus control, the voltage of one DC terminal, known as the DC slack bus, is maintained constant by the master converter. The main disadvantage of this control scheme is the DC grid instability following a failure of the master converter.

The above problem can be tackled by ensuring that individual converters contribute to the DC voltage regulation scheme by adjusting their active power flow in response to changes in the DC voltage with the operating point, known as DC voltage droop control. For MTDC control, both linear and nonlinear types of DC voltage droop characteristics have been envisaged to ensure proper sharing based on the converter ratings. Voltage-Power (V-P), Voltage-Current (V-I), Voltage Margin (VM), V-P droop with power Dead-Band (DB) and V-P droop with voltage limits are some of the more widely used characteristics.

To manage power-flows within the DC grids, DC power-flow control devices have been conceptualized and developed. They include the use of DC transformers, variable resistors, current flow controllers (CFCs), thyristor power-flow controllers (TPFCs), DC series voltage sources and Interline DC Power-Flow Controllers (IDCPFCs) for power-flow control in meshed DC grids. The IDCPFC is a DC power-flow controller without an external AC or DC source and is used for power-flow management of DC grids, similar to its AC counterpart—the flexible AC transmission systems (FACTS)-based Interline Power-Flow Controller (IPFC).

Now, for proper planning, design and operation of AC power systems integrated with multi-terminal DC grids, the development of suitable power-flow models of both LCC- and VSC-based integrated AC–DC systems is a fundamental requirement.

The requirement of suitable power-flow models of both LCC and VSC-based hybrid AC–DC systems along with the adoption of the Newton-Raphson algorithm as the de-facto standard for industrial power-flow solutions has resulted in a lot of interest in the development of Newton-Raphson power-flow models of such hybrid AC–DC systems.

Now, the development of Newton-Raphson power-flow models of both LCC- and VSC-based integrated AC–DC systems has resulted in two distinctly different approaches known as the unified and the sequential Newton algorithms, respectively. In the former, the AC and DC quantities are solved simultaneously, while in the latter, the AC and DC systems are solved separately in each iteration. Unlike the unified method, the sequential method is easier to implement and poses lesser computational burden due to the smaller size of the Jacobian matrix.

Although a number of books on modelling, analysis, control and applications of HVDC systems do exist, very few books dwell on their power-flow modelling. This book intends to deal exclusively with the power-flow modelling of HVDC systems. The book starts by detailing the different types of HVDC systems, their configuration and connections and the control techniques adopted. Next, the power-flow modelling concept is gradually built up. At first, the power-flow modelling of LCC-based HVDC systems is covered, followed by that of VSC-based HVDC systems. Subsequently, the introduction and incorporation of DC grid power-flow controllers like IDCPFC into the power flow modelling of VSC-HVDC systems is addressed. Finally, the power-flow modelling of HVDC systems integrated with renewable energy sources is covered. For each of these technologies (LCC / VSC), both the unified and the sequential power-flow models are developed. The different types of HVDC control strategies employed are also incorporated into the LCC and the VSC-based HVDC power-flow models. For realistic analysis, the losses in the converter transformer and the VSCs have been incorporated in all the power-flow models. The effect of the power-flow methods (unified or sequential) as well as the HVDC control strategies adopted on the convergence of the power-flow algorithm, is detailed clearly, along with their implementation in the IEEE 300-bus and the European 1354-bus test networks.

This book is intended for senior undergraduate and graduate students in electrical power systems, design engineers and researchers in the area of integrated AC–DC systems. The reader is expected to have an undergraduate-level background in electric circuits, electric power systems, engineering mathematics and power electronics.

The proposed book is organized into six chapters. Chapter 1 provides a brief introduction to the HVDC transmission systems, the power-flow problem and the Newton-Raphson method for solving power-flow problems.

Chapter 2 deals with the development of power-flow models of LCC-based integrated AC–DC systems, in light of different per-unit AC–DC system models and diverse DC link control strategies employed.

Chapter 3 addresses the development of power-flow models of VSC-based integrated AC–DC systems for both the back-to-back (BTB) and the point-to-point

(PTP) VSC-HVDC configurations, employing DC slack-bus (master-slave) control for the MTDC grid.

Chapter 4 details the development of power-flow models of VSC-based integrated AC–DC systems employing DC voltage droop control. The DC voltage droop control comprises both linear {voltage-power (V-P) and voltage-current (V-I)} as well as nonlinear {power dead-band and voltage limits} droop characteristics. Based on the terminal end line active and reactive power specifications of the VSCs, two different droop control models are considered.

Chapter 5 addresses the development of power-flow models of VSC-based integrated AC–DC systems incorporating IDCPFC(s) for the power-flow management of the DC grid. The IDCPFC(s) employs both DC link current and DC link power controls.

Chapter 6 details the development of Newton power-flow models of VSC-based integrated AC–DC systems interfaced with offshore wind farms (OWFs). The VSCs employ both linear and nonlinear DC voltage droop controls. The effects of OWFs on the DC grid voltage profile and the power-flow convergence, vis-à-vis varying wind farm powers, are explained in detail.

Converter transformer and VSC losses are included in all the power-flow models. All the models developed in this book have been implemented in the IEEE 300-bus and European 1354-bus test systems.

The appendix at the end of this book presents the derivations of all the difficult formulae used in the different chapters.

The authors would like to express sincere thanks to all the reviewers for their critical review and suggestions in the proposal of this book. We would also like to thank the publisher and our families for their efforts in pursuing us to take up the project of writing this book.

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List of Abbreviations

BTB	Back-to-back
CT	Computational time in seconds taken by the algorithm to converge to a specified tolerance
FACTS	Flexible AC transmission systems
HVDC	High-voltage direct current
IDCPFC	Interline direct current power-flow controller
IGBT	Insulated gate bipolar transistor
IPFC	Interline power-flow controller
LCC	Line commutated converter
MLDC	Multi-terminal LCC-based HVDC
MTDC	Multi-terminal Direct Current
MVDC	Multi-terminal VSC-based HVDC
NI	Number of iterations taken by the algorithm to converge to a specified tolerance
NR	Newton-Raphson
OWF	Offshore wind farm
PTP	Point-to-point
PWM	Pulse width modulation
RoW	Right of way
VSC	Voltage source converter
XLPE	Cross-linked poly ethylene

List of Symbols

CAPITALS

$\mathbf{E}$	Vector of mismatch error
$\mathbf{E}_{\mathbf{AC}}$	Vector of mismatch error in AC network
$\mathbf{E}_{\mathbf{DC}}$	Vector of mismatch error in DC network
$I_{(\text{AC base})}$	AC base current
$I_{(\text{DC base})}$	DC base current
I_{DC}	DC current
$\mathbf{I}_{\mathbf{sha}}$	Current through the converter transformer of the a$^{\text{th}}$ VSC
I^{*}_{DCa}	DC current reference for linear V-I droop line of the a$^{\text{th}}$ VSC
$\mathbf{J}$	Jacobian matrix
$\mathbf{J}_{\mathbf{old}}$	Conventional power-flow Jacobian sub-block
P_{Di}	Active power demand at bus ‘i’
P_{i}	Net active power injection at bus ‘i’
$\mathbf{P}$	Bus active power injection vector
P_{i}^{sp}	Specified active power injection at bus ‘i’
P_{DCR}	Active power associated with the rectifier
P_{DCI}	Active power associated with the inverter
P_{sha}	Active power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus
$P_{\text{sha}}^{\text{sp}}$	Specified active power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus
$P_{\text{sha}}^{\text{cal}}$	Calculated active power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus
P_{lossa}	Losses of the a$^{\text{th}}$ VSC
P^{*}_{DCa}	DC power reference for linear V-P droop line of the a$^{\text{th}}$ VSC
P_{IDCPFC}	Power delivered by the IDCPFC
P_{DCWF}	Rectifying power of wind farm injected into the DC grid
$\mathbf{P}_{\mathbf{DCWF}}$	Vector of rectifying powers of wind farms
$\mathbf{Q}$	Bus reactive power injection vector
Q_{DCR}	Reactive power associated with the rectifier
Q_{DCI}	Reactive power associated with the inverter
Q_{Di}	Reactive power demand at bus ‘i’
Q_{i}	Net reactive power injection at bus ‘i’
Q_{i}^{sp}	Specified reactive power injection at bus ‘i’
Q_{sha}	Reactive power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus
$Q_{\text{sha}}^{\text{sp}}$	Specified reactive power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus
$Q_{\text{sha}}^{\text{cal}}$	Calculated reactive power flow in the line connecting the a$^{\text{th}}$ VSC to its AC terminal bus

R_{DC}	Resistance of DC link
R_a	Droop control gain of the ath VSC
R_{sha}	Resistance of the ath VSC transformer
$R_{(DC\ base)}$	Base value of DC resistance
$\mathbf{R}$	Mismatch vector of control specifications
R_{max}	Maximum droop control gain
S_{base}	Base MVA
$\mathbf{S_{sha}}$	Complex line power flow at the terminal end of the line connecting the ath VSC to its AC bus
$\mathbf{V}$	AC bus voltage vector
$V_{(AC\ base)}$	Base value of AC voltage
V_{DC}	DC bus voltage
$V_{(DC\ base)}$	Base value of DC voltage
V_{DCI}	DC bus voltage at the inverter side
V_{DCI1}	DC bus voltage at the inverter-1 side
V_{DCI2}	DC bus voltage at the inverter-2 side
V_{DCR}	DC bus voltage at the rectifier side
V_i	AC bus voltage magnitude (rms) at ith bus
$\mathbf{V_{sha}}$	Voltage phasor representing the output (fundamental) of the ath VSC
V_{doR}	No load direct voltage at the rectifier side
V^*_{DCa}	DC voltage reference for the droop line of the ath VSC
V_{doI}	No load DC voltage at the inverter side
V^*_{DCav}	Average value of DC voltage references in a DC grid
V_{DCav}	Average value of the DC voltages in a DC grid
V_{Bus}	Specified AC bus voltage
V_{DCs}	DC voltage source of IDCPFC
V^*_{DChigh}	Upper DC voltage threshold of nonlinear DC voltage droop characteristics
V^*_{DClow}	Lower DC voltage threshold of nonlinear DC voltage droop characteristics
$V_{(DC\ max)}$	Maximum DC voltage threshold of nonlinear DC voltage droop characteristics
$V_{(DC\ min)}$	Minimum DC voltage threshold of nonlinear DC voltage droop characteristics
X_c	Commutating reactance
$X_{(c\ base)}$	Base value of the commutating reactance
X_{sha}	Leakage reactance of the ath converter transformer
Y_{ik}	Magnitude of the element in the ith row and kth column of the bus admittance matrix
$\mathbf{Y_{dc}}$	Admittance matrix of DC grid
$Z_{(AC\ base)}$	Base value of AC impedance
$\mathbf{Z_{sha}}$	Leakage impedance of the ath converter transformer
$Z_{(DC\ base)}$	Base value of DC side impedance

LOWERCASE

a_1	Constant representing no load VSC losses
a_I	Converter transformer tap ratio at the inverter side
a_R	Converter transformer tap ratio at the rectifier side
b_1	Constant representative of the linear dependency of the VSC losses on the converter current magnitude
c	Constant representative of the VSC architecture
c_1	Constant representative of the quadratic dependency of the VSC losses on the converter current magnitude
f	Vector of control functions
g	Number of generators in the AC system
k	Constant which depends on the type of converter in the LCC-HVDC system
m	Modulation index of the VSC
n	Total number of buses in the AC system
n_b	Number of bridges in the LCC-HVDC system
p.u.	Per unit
p	Total number of DC terminals
q	Total number of VSCs
$\mathbf{y_{sha}}$	Admittance of the converter transformer of the a^{th} VSC
z	Total number of DC voltage sources in IDCPFC

UPPERCASE GREEK

Σ	Summation symbol
Δ	Mismatch in electrical quantity of interest; mismatch vector

LOWERCASE GREEK

α_R	Firing angle of the rectifier in the LCC-HVDC system
γ_I	Extinction angle of the inverter in the LCC-HVDC system
θ_i	Phase angle of voltage at AC bus ‘i’
$\boldsymbol{\theta}$	Vector comprising phase angles of AC bus voltages
$\boldsymbol{\theta_{sh}}$	Vector of phase angles of output voltage phasors of the VSC
θ_{sha}	Phase angle of the output voltage phasor of the a^{th} VSC
ϕ_R	Power factor angle at the rectifier end of the LCC-HVDC system
ϕ_I	Power factor angle at the inverter end of the LCC-HVDC system
ϕ_{sha}	Phase angle of $\mathbf{y_{sha}}$

SUBSCRIPTS

i	Bus ‘i’ quantity
AC	AC side quantity

DC	DC side quantity
DCR	DC quantity at rectifier end
DCI	DC quantity at inverter end
AC_{base}	AC base values
DC_{base}	DC base values
b	Number of bridges
R	Rectifier
I	Inverter
sha	Shunt connected quantity of a^{th} VSC
DCs	DC voltage source of IDCPFC
IDCPFC	IDCPFC quantities
Loss	VSC loss quantity
DC_{min}	Minimum DC quantity
DC_{max}	Maximum DC quantity
DCavg	Average value of DC voltage

SUPERSCRIPTS

$()^T$	Transpose of a matrix
$()^{cal}$	Calculated or unknown quantity
$()^*$	Conjugate of a complex quantity
$()^{sp}$	Specified or known quantity
$()^{old}$	Quantity in the original network without any HVDC link

1 HVDC Transmission Systems

1.1 INTRODUCTION

In recent years, the global demand of electric power has increased exponentially. Therefore, the generation and transmission facilities have to be upgraded from time to time to match the peak demand. In this respect, HVDC transmission systems provide additional transmission capacity along with power-flow controllability. Unlike AC transmission, for the same power, HVDC transmission requires less right-of-way (RoW), cheaper towers, smaller number of conductors and insulator costs along with reduced losses. In addition, the length of the HVDC transmission line is not limited by stability considerations. For transmission line lengths exceeding about 500 km, HVDC transmission is more economical as compared to AC [1–16]. In recent times, rapid, large-scale integration of renewable energy sources with the existing power network has been taking place globally to fulfil the requirement of increased electricity demand. In this respect, the integration of offshore wind farms (OWFs) with onshore AC grids is possible using HVDC links [4,12,15,16].

The first 10 MW HVDC transmission system using mercury arc valve was commissioned between the Swedish mainland and the island of Gotland in 1954. In due course, significant technical advancement with solid-state valves (thyristors) paved the way for the first 320 MW thyristor-based HVDC system commissioned between the Canadian provinces of New Brunswick and Quebec in 1972 [2–4]. Subsequently, there has been rapid development of this HVDC technology with further reduced size and costs and popularly known as line commutated converter (LCC)-based HVDC (LCC-HVDC) technology. Based on this technology, several LCC-HVDC links were installed worldwide, and some of these are listed in Table 1.1.

In a LCC-based HVDC system, the commutation process is achieved using the source voltage and the leakage reactance of the converter transformer. Thus, for controlling the active power, both the rectification and inversion processes consume reactive power. Also, the reactive power consumption varies with load. This necessitates the use of reactive power sources to match the reactive power demand at both ends [1,6,7]. If nearby generators are not capable of accounting for the reactive power, additional shunt capacitors or other reactive power sources are needed to match the requirement of reactive power. Also, in LCC-HVDC systems, a minimum short circuit level is required to avoid voltage instability. Due to the switching operation of the thyristor, harmonics are introduced in the power system voltages and currents. This influences the use of filters at both AC and DC

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TABLE 1.1
LCC-Based HVDC Systems Throughout the World

		Transmission Line Length (km)			Rated Voltage (kV)	Nominal Capacity (MW)	Commissioning Date	Remark
S.N.	HVDC Link	OHL	Cable	Total				
1	New Brunswick-Eel River (Canada)	-	-	-	80×2	320	1972	BTB
2	Skagerrak (Denmark-Norway)	113	127	240	±250	500	1977	
3	David A. Hamil (United States of America)	-	-	-	50	100	1977	BTB
4	Square Butte (Centre, North Dakota-Arrowhead, Minnesota), US	749	0	749	±250	500	1977	
5	Shin-Shinano (Japan)	-	-	-	125×2	300	1977	BTB (50/60 Hz)
6	Nelson River Bipole 2 (Sundane-Rosser), Canada	930	0	930	±250	900	1978	
7	Cabora Bassa – Apollo (Songo, Mozambique-Apollo, South Africa)	1414	0	1414	±533	1920	1977/79	
8	Vancouver Pole 2 (Delta-North Cowichan), British Columbia	41	33	74	−280	370	1977/79	
9	Cu (Underwood Minneapolis) (Coal Creek, North Dakota-Dickinson, Minesota), US	710	0	910	±400	1000	1979	

(*Continued*)

TABLE 1.1 (*Continued*)
LCC-Based HVDC Systems Throughout the World

		Transmission Line Length (km)			Rated Voltage	Nominal Capacity	Commissioning	
S.N.	**HVDC Link**	**OHL**	**Cable**	**Total**	**(kV)**	**(MW)**	**Date**	**Remark**
10	Hokkaido-Honshu (Japan)	124	44	158	250	300	1979/80	
11	Acaray (Paraguay-Brazil)	-	-	-	26	50	1981	BTB (50/60 Hz)
12	EPRI Compact Station (USA)	-	0.6	0.6	100/400	100	1981	
13	Vyborg (USSR-Finland)	-	-	-	±85×3	170	1982	BTB
14	Inga Shaba (Kolwezi-Inga), Zaire	1700	0	1700	±500	560	1982	
15	Dumrohr (Lower Austria)	-	-	-	±145	550	1983	BTB
16	Gotland 2 Swedish Mainland (Vastervik-Yigne), Sweden	7	91	98	150	130	1983	
17	Eddy County (USA)	-	-	-	82	200	1983	BTB
18	Itaipu (Brazil)	783/806	0	783/806	±300	1575	1984	
19	Chateauguay (Canada)	-	-	-	140	1000	1984	BTB
20	Oklaunion (US)	-	-	-	82	200	1984	BTB
21	Pacific intertie (US)	-	-	-	±500	400	1985	
22	Madawaska (Canada)	-	-	-	144	350	1985	BTB
23	Miles City (US)	-	-	-	82	200	1985	BTB
24	Walker Co. (US)	246	0	246	±400	500–1500	1985	
25	Black water (US)	-	-	-	56	200	1985	BTB
26	Highgate (US)	-	-	-	56	200	1985	BTB
27	Cross-Channel 2 (Les Mandarins, France-Sellindge, UK)	0	72	72	±270×2	2000	1985/86	

(*Continued*)

TABLE 1.1 (*Continued*)
LCC-Based HVDC Systems Throughout the World

S.N.	HVDC Link	Transmission Line Length (km)			Rated Voltage (kV)	Nominal Capacity (MW)	Commissioning Date	Remark
		OHL	Cable	Total				
28	Corsica Tap (France)	-	-	-	200	50	1986	
29	Des Cantons Camerford (Canada-USA)	175		175	±450	690	1986	
30	Sidney (US)	-	-	-		200	1986	BTB
31	Wien Sud Ost (Austria)	-	-	-	145	550	1987	BTB
32	Intermountain (intermountain, Utah-Adelanto, California), US	794	0	794	±500	1600	1987	
33	Gotland 3-Swedish Mainland	-	98	98	150	130	1987	
34	Itaipu (Foz do Iguacu, Parana-Sao Roque, Sao Paulo), Brazil	783/806	0	783/806	±600×2	6300	1985–87	
35	Uruguiana (Brazil-Argentina)					50	1986/87	BTB
36	Ekibastus Centre (USSR)	2400	0	2400	±250	6000	1985–88	
37	Greece (Bulgaria)	-	-	-	NA	300		BTB
38	Virginia Smith (US-Sidney Nebraska)				150	200	1988	BTB
39	Vindhyachal (India)	-	-	-	70	250×2	1988	BTB
40	Kanti-Skan 2 (Sweden-Denmark)	95	85	160	250	270	1988/89	
41	Skagerrak 2 (Denmark-Norway)	113	127	240	300	320	1988–89	

(*Continued*)

TABLE 1.1 (*Continued*)
LCC-Based HVDC Systems Throughout the World

S.N.	**HVDC Link**	**Transmission Line Length (km)**			**Rated Voltage (kV)**	**Nominal Capacity (MW)**	**Commissioning Date**	**Remark**
		OHL	**Cable**	**Total**				
42	Fenno-Skan (Dannebo, Sweden-Rauma, Finland)	33	200	233	400	500	1989	
43	HVDC Sileru-Barsoor (India)	196	-		±200	400	1989	
44	Store Baelt (Denmark)	35	30	55	280	350	1989–90	
45	Liberty Mead (US)	400	0	400	±364/±500	1600/2200	1989–90	
46	Chicoasen (Mexico)	720	0	720	±500	900/1800	1985/90	
47	Quebec New England	175/375		175/375	±450	690/2070	1986/92	
48	SACOI 2 (Suvereto, Italia-ucciana, France; Codrongianos)	304	118		200	300	1992	MT
49	HVDC Inter-Island 2 (Benmore Dam-Haywards), New Zealand	570	40		350	640	1992	
50	Pacific Intertie II (US)				±500	1100		
51	South Finland Fast Sweden	35	185	220	350	420	1989/90	
52	Cameford-Sandy Pond	200				1400	1990	
53	Rihand-Dadri (India)	814	-	814	±500	1500	1990	
54	Gezhouba-Nan Qiao (China)	1080	-	1080	±500	1200	1987–91	

(*Continued*)

TABLE 1.1 (*Continued*)
LCC-Based HVDC Systems Throughout the World

		Transmission Line Length (km)						
S.N.	**HVDC Link**	**OHL**	**Cable**	**Total**	**Rated Voltage (kV)**	**Nominal Capacity (MW)**	**Commissioning Date**	**Remark**
55	Cross-Skagerrak 3 Tjele, Denmark-Kristiansand, Norway	100	130		350	500	1993	
56	Etzenricht (Germany)				160	600	1993	BTB
57	Nelson River Bipole 3 (Canada)	930	0	930	±500	2000	1992/97	
58	Chandrapur-Pdghe (India)	900			±500	1500	1997	
59	Minami Fukumitsu (Japan)				125	300	1999	BTB
60	SwePol (Starno, Sweden-Slupsk, Poland)		245		450	600	2000	
61	(Galatina, Italy-Arachthos Greece)	110	200		400	500	2001	
62	East South 2 Talcher (Orissa)-Kolar (Karnataka), India	1450			±500	2000	2002	
63	HVDC Three Gorges-Changzhou Longquan-Zhengping (China)	890	-		±500	3000	2003	
64	HVDC Three Gorges-Guangdong Station 1: Jingzhou, IIuizhou (China)	940	-	-	±500	3000	2003	

(*Continued*)

TABLE 1.1 (*Continued*)
LCC-Based HVDC Systems Throughout the World

		Transmission Line Length (km)						
S.N.	**HVDC Link**	**OHL**	**Cable**	**Total**	**Rated Voltage (kV)**	**Nominal Capacity (MW)**	**Commissioning Date**	**Remark**
65	Basslink (Loy Yang-George Town), Australia	71.8	298.3		400	600	2005	
66	Vizag-2 Eastern Grid and Southern grid, India				176	500	2005	BTB
67	Norned (Feda, Norway-Eemshaven Netherlands)	-	580		±450	700	2007	
68	Sharyland (Texas, USA)				21	150	2007	BTB
69	Al Fdhili (Saudi Arabia)					1800	2008	BTB
70	SAPEI (Latina, Italy-Fiume Santo, Sardinia)	-	435		±500	1000	2008/9	
71	Xianjiba, Shanghai (China)	2071	-		800	6400	2010	
72	Yannan–Guangdong (China)	1400	-		±800	5000	2010	
73	Ballia (UP)-Bhiwadi (Rajasthan) (India)	780			±500	2500	2010	
74	North East Agra (Biswanath Chariali) (Assam), Agra (UP), Alipurduar (West Bengal) (India)	1775			±800	6000	2016	MT
75	Champa Kurukshetra (India)			1365	800	2×3000	2016	

BTB, back-to-back; MT, multi-terminal; OHL, overhead line.