HVDC TRANSMISSION Power Conversion Applications in Power Systems

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Contents

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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- T. Sakai – Chief Director, TMEIC
- L. Travin – IEC HVDC WG Secretary
- L. Weimers – Chief Engineer Marketing HVDC, ABB
- D. Woodford – President, RTDS and IEEE Fellow

Author Biographies

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)
$\mathrm{F_{demand}}$ (Hz)	Frequency order value
$\mathrm{F_{order}}$ (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
$\mathrm{I_{order}}$	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 *i*th 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
$\mathrm{P_{order}}$	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)
SC_{TOT}	Short-circuit capability at HVDC commutating bus including *i*th unit
$\overline{SC_{i\cdot}}$	Short-circuit capability at HVDC commutating bus excluding *i*th 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 *i*th 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

1

Development of HVDC Technology

1.1 Introduction

The development of HVDC (High Voltage Direct Current) transmission system dates back to the 1930s when mercury arc rectifiers were invented. In 1941, the first HVDC transmission system contract for a commercial HVDC system was placed: 60 MW were to be supplied to the city of Berlin through an underground cable of 115 km in length. In 1945, this system was ready for operation. However, due to the end of World War II, the system was dismantled and never became operational. It was only in 1954 that the first HVDC (10 MW) transmission system was commissioned in Gotland. Since the 1960s, HVDC transmission system is now a mature technology and has played a vital part in both long distance transmission and in the interconnection of systems.

HVDC transmission systems, when installed, often form the backbone of an electric power system. They combine high reliability with a long useful life. Their core component is the power converter, which serves as the interface to the AC transmission system. The conversion from AC to DC, and vice versa, is achieved by controllable electronic switches (valves) in a 3-phase bridge configuration.

An HVDC link avoids some of the disadvantages and limitations of AC transmission and has the following advantages:

- No technical limit to the length of a submarine cable connection.
- No requirement that the linked systems run in synchronism.
- No increase to the short circuit capacity imposed on AC switchgear.
- Immunity from impedance, phase angle, frequency or voltage fluctuations.
- Preserves independent management of frequency and generator control.
- Improves both the AC system's stability and, therefore, improves the internal power-carrying capacity, by modulation of power in response to frequency, power swing or line rating.

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

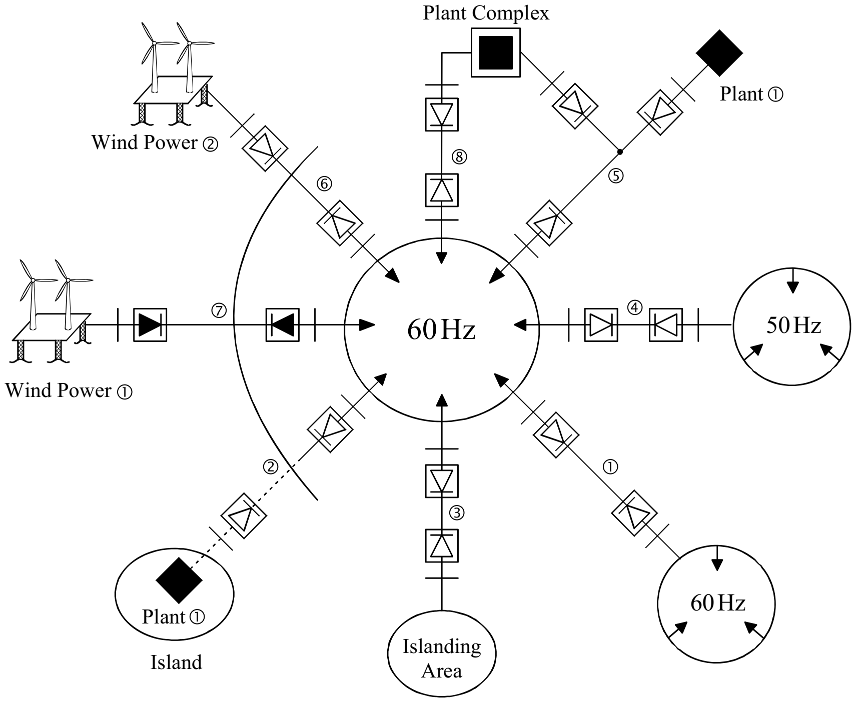

Figure 1.1 Various applications of an HVDC system.

Figure 1.1 shows example applications of HVDC transmission systems in which the labeling is as follows:

1. Power transmission of bulk energy through long distance overhead line.
2. Power transmission of bulk energy through sea cable.
3. Fast and precise control of the flow of energy over an HVDC link to create a positive damping of electromechanical oscillations and enhance the stability of the network by modulation of the transmission power by using a Back-to-Back.
4. Since an HVDC link has no constraints with respect to frequency or to phase angle between the two AC systems, it can be used to link systems with different frequencies using an Asynchronous Back-to-Back.
5. When power is to be transmitted from a remote generation location across different countries or different areas within one country, it may be strategically and politically necessary to offer a connection to potential partners in the areas traversed by using a multi-terminal DC link.
6. An HVDC transmission system can also be used to link renewable energy sources, such as wind power, when it is located far away from the consumer.
7. VSC (Voltage-Source Converter) based HVDC technology is gaining more and more attention. This new technology has become possible as a result of important advances in the development of Insulated Gate Bipolar Transistors (IGBT). In this system, Pulse-Width

Modulation (PWM) can be used for the VSC as opposed to the thyristor based conventional HVDC. This technology is well suited for wind power connection to the grid.
8. Since reactive power does not get transmitted over a DC link, two AC systems can be connected through an HVDC link without increasing the short circuit power; this technique can be useful in generator connections.

1.2 Advantages of HVDC Systems

The classical application of HVDC systems is the transmission of bulk power over long distances because the overall cost for the transmission system is less and the losses are lower than AC transmission. A significant advantage of the DC interconnection is that there is no stability limit related to the amount of power or the transmission distance.

Long Distance Bulk Power Transmission. When large amounts of power are to be delivered over long distances, DC transmission is always an alternative to be considered. AC transmission becomes limited by:

- Acceptable variation of voltage over the transmission distance and expected loading levels.
- Need to maintain stability, that is, synchronous operation across the transmission, after a disturbance, both transiently and dynamically.
- Economic effects of additions necessary to correct the above limitations.

The DC line, requiring as few as two conductors (one only for submarine with earth return) compared to the AC line's use of three, requires a smaller right of way and a less obtrusive tower. Figure 1.2 shows schematically the tower configurations for 1200 MW (two circuits AC,

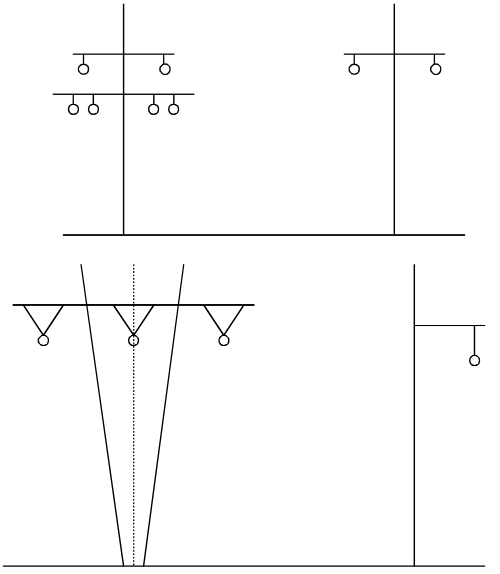

Figure 1.2 Tower configurations for AC and DC transmission.

bipolar DC) and 1500–2000 MW transmission at EHV AC single circuit or monopolar DC by alternative tower designs. (Note: a single circuit or a single pole above 1600 MW capacity has not been built to date (2008) because of the effect of the potential loss of such a high capacity circuit on the system.)

As an AC line reaches either the limit imposed by system stability or its thermal capacity and if adding a parallel line is impossible, it may be possible to convert it to DC. Applying DC up to three times the AC capacity should be possible for transmission by altering the tower head configuration, but not the foundations, tower size nor the right of way. Running AC and DC lines on the same tower are also possible. At present, no example of these being put into effect can be reported.

Interconnection by AC or HVDC. If two or more independent systems are to be interconnected by a synchronous AC link, the common rules concerning security, reliability, frequency control, voltage control, primary and secondary control of reserve capacity and so on need to be respected. When the basis for synchronism is established, it depend on the structure and the strength of the power systems, the number of interconnecting lines, and whether or not stability problems, for example, inter-area oscillations, may occur. In most cases, more than one AC link is necessary for reliability; however, there are examples of single-circuit interconnections for energy and reserve exchange, where limited reliability of the link is accepted.

By contrast, interconnecting the systems with DC removes any constraints concerning stability problems or control strategies. The common rules listed above concerning security and so on can largely be left within the jurisdiction of the separate AC systems, remaining independent of the agreement to link. The interconnection can be made by HVDC back-to-back stations along the border or by interconnecting load and generation centers within the systems by long distance transmission.

For submarine interconnection, as distance increases, AC cables generate an increasingly wide variation of voltage with power flow until the rating of the cable is fully taken up by its charging current. Since intermediate, reactive compensation units cannot be installed, the maximum practical distance was 50 km until recently. In recent years, the advent of the XLPE cable (cross-linked polyethylene) for submarine use, with a lower shunt capacitance than earlier types, has increased this limit to about 100 km. Beyond this distance, DC is the only technically viable solution. An HVDC connection requires only positive and negative (pole and return) conductors, or in some cases a single conductor with sea return and there is no practical technical limit to length except cost.

HVDC Multi-Terminal Systems. When power is to be transmitted from a remote generation location across different countries or different areas within one country, it may be economically and politically necessary to offer a connection to potential partners in the areas traversed. Multi-terminal DC is a possibility for this type of application.

HVDC multi-terminal systems allow more participants. They have proved to be feasible, for example, the SACOI 3-terminal cable system between Italy, Corsica (France), and Sardinia (Italy) and the Quebec–New England 3-terminal overland system in Canada/USA. The Pacific Intertie and the Nelson River DC links are examples of multi-terminal DC put to practical use. These are examples of parallel multi-terminal systems. Series multi-terminal systems have also been proposed but no practical applications exist at present.

A further example for interconnecting more systems via long distance HVDC links is the planning of the East–West High Power Trans, connecting Russia, the Baltic States, Belarus, Poland and Germany, where a multi-terminal HVDC system is under consideration. The advantages of interconnection can be exploited without establishing common rules (for example, of frequency control) and AC systems can continue to operate and develop independently. If, in the longer term, the requirements for AC interconnection are fulfilled and it is agreed to synchronize, the HVDC transmission becomes a strong backbone within the interconnected system and brings considerable stability advantages.

A control choice is available to operate multi-terminal systems with either a coordinated master power controller, or with each terminal having its own power controller and the voltage-controlling terminal supplies the balance of power. New control concepts may become available to overcome the need for a master controller and to allow expansion with more terminals, each convertor operating with locally available information.

Care has to be taken when weak systems have to be integrated into a multi-terminal system, so that faults within them do not cause too widespread a disturbance. Furthermore, if a multi-terminal system is to develop and grow independently, as AC systems can do, the integration of a new converter station needs a review and re-coordination of the control structure and parameters of all converters. However, smaller converters (with current rating below or equal to the current margin, that is, about 10% of the existing system) may be integrated at a later date.

AC System Support. An AC load flow depends on the difference in angle between voltage vectors in different parts of the network. This angle cannot be influenced directly but depends on the power balance. Secondly, a change in power generation or in the load demand will cause a change in system frequency that has to be restored by altering the generation. As this task has to be fulfilled by the generator speed controllers, the frequency restoration is a slow action. System stability also depends on there being sufficient flexibility to allow the automatic adjustment of the voltage vectors.

If stability problems are encountered which can be solved by fast frequency control, HVDC systems can fulfill this task by drawing the energy from the remote network. Due to the ability to change the operating point virtually instantaneously, HVDC can feed (or reduce) active power into the disturbed system to control the frequency much faster than a normally controlled generator. If the feeding AC system is strong enough, the DC link can, within its rating, control the frequency in the receiving system. A prerequisite for this kind of system support is only the appropriate mode of control.

Take the case of an AC system containing relatively long transmission lines, where electromechanical oscillations can be excited by system faults and are weakly damped. Assume the addition of a DC link (point-to-point or back-to-back) from outside into this system. Control features for power modulation, with the appropriate phase angle, can actively introduce damping torque. In general, this valuable feature of an HVDC link is inherent and requires no significant extra costs. Where the systems at each end of the DC have different natural frequencies of oscillation, the damping torque can be applied to either/or both systems simultaneously if necessary.

Two controls are available. Where a terminal's AC network is part of a large system, the DC controls can react to swings of power and attempt to mitigate their effect by damping power to maintain synchronism. Where it is a separate system, applying a slope characteristic similar to that of a generator can be used to apply frequency control.

Limitation of Faults. Faults causing depression of voltage on power swings do not transmit across a DC barrier. They may emerge on the other side of a DC link simply as a reduction in power, but voltage will not affected. Constraining the influence of certain critical faults on AC systems can be a valuable attribute of DC.

Limitation of Short Circuit Level. When new lines are built to extend AC systems, the short circuit level of the system will unavoidably be increased. The switchgear apparatus must cope with the short circuit requirements or an expensive refurbishment has to take place. Since reactive power is not transmitted over a DC link, it provides a means to extend the active power exchanged without increasing the short circuit level.

Power Flow Control. An HVDC link operates at any condition of voltage and frequency of the two AC systems. An independent control is therefore available to transmit power, leaving each system's existing load frequency control to act normally. A valuable strategy then is to hold in reserve the system control features given above for occasions when voltage or frequency stray outside the normal bands of operation.

Where a link is contained within one AC system the same applies, but special stability controls act when system oscillations exceed a certain band of, for example, the rate of change of bus bar voltage angle.

Voltage Control. An HVDC link can also be used for voltage control. The converter absorbs reactive power depending on its control angle, which normally will be compensated for by filters and/or capacitor banks. By extending the control angle operating range (to a lower voltage) and additional capacitor banks (to raise voltage) together with a fast acting transformer tap-changer, the reactive power demand can be used for independent voltage control at both connection points. This operation, outside the optimum (minimum) control angles, leads to higher short-time operational losses and stress on components, but these are usually marginal compared to the operational improvement. If it is to be used as a permanent feature, this method of operation has to be taken into account in the design phase of the DC link.

It is important to realize that the normal constant power regime of a DC link can destabilize an AC network under distress. A normal feature of the DC link is the voltage-dependent current limit where DC power is limited when voltage drops below the normal range, so that the reactive power is made available to the AC system. Under disturbed conditions, it is a good principle to look after the AC voltage first, and then order the power flow accordingly. There are substantial AC filters at the converter stations, which can be used to bolster AC voltage if stability is threatened. The DC control drops DC power, so that the converters absorb less reactive power and the reactive capacity of the filters is available to the network. Though the loss of power flow is unwelcome, the boost to AC voltage maybe more valuable.

Self-commutated VSCs are able to provide independent control of active and reactive power. Reactive power generation or absorption is possible, within converter ratings, at any DC power transfer rate.

System Reserve. The maximum unit site of generation in the system is determined by the maximum loss of power for which the system frequency can be maintained, within defined limits. When a large amount of power is fed into an AC system by an HVDC long distance transmission system, it can also be thought of as generation. The maximum power of one pole of the HVDC link is in the same way limited by the system parameters.

The largest possible loss of power of an HVDC link, in case of a fault causing line outages, depends on the DC line tower configuration and on the ability to transmit power via ground or metallic return. Assuming that the current carrying capacity of a conductor is well above its nominal current rating, there can be a short-time capacity of overload in the converter and line on the remaining healthy equipment, to reduce the shock to the system as a whole in case of pole