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AC Grid with Embedded VSC-HVDC for Secure and Efficient Power Delivery

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Abstract- **Increased bulk power transactions in competitive energy markets together with large scale integration of renewable energy sources are posing challenges to high-voltage transmission systems. Environmental constraints and energy efficiency requirements also have significant effects on future transmission infrastructure development. This paper reviews the recent development in HVDC technologies and discusses the needs of the hybrid AC/DC grid structure for future power systems with focus on VSC-HVDC applications in meshed ac grid. It has also been recognized that hybrid AC/DC transmission system together with the wide area measurement system (WAMS) could effectively manage the overall power grid operation security and efficiency under uncertain supply and demand conditions.**

***Index Terms*—Transmission expansion, security and efficiency of power delivery system, HVDC transmission, VSC-HVDC, wide area measurement system**

I. Introduction

THE electric power grid is experiencing increased needs for enhanced bulk power transmission capability, reliable integration of large-scale renewable energy sources, and more flexible power flow controllability. However, it has become a challenge to increase power delivery capability and flexibility with conventional AC expansion options in meshed, heavily loaded high voltage AC networks. A key constraint in adding transmission capacity to existing AC grid is the requirement to neutralize environmental impact - often making overhead grid extensions impossible. AC expansion options, both overhead and underground, are often limited by voltage or transient instability problems, risk of increased short circuit levels, impacts of unaccepted network loop flows. As such, upgrading electric power grids with advanced transmission technologies such as HVDC systems and FACTS devices becomes more attractive in many cases to achieve the needed capacity improvement while satisfying strict environmental and technical requirements. The favorable economics of bulk power transmission with HVDC together with its controllability make it an interesting alternative or complement to ac transmission. Therefore, the strategies for future transmission infrastructure development go clearly in the direction of hybrid AC/DC grid structure.

This paper reviews the recent development in HVDC transmission technologies and discusses the needs of the hybrid AC/DC grid structure for future power systems. The focus is on the benefits of embedded VSC-HVDC transmission systems in meshed ac grid for secure and efficient power delivery. The paper also discusses how the hybrid AC/DC transmission system together with the wide area measurement system (WAMS) could effectively manage the overall power grid operation security and efficiency.

II. HVDC Technologies

Two basic converter technologies are used in modern HVDC transmission systems [1]. These are classical line-commutated current source converters (CSCs) and self-commutated voltage source converters (VSCs).

A. Classical HVDC Technologies

The classical HVDC technique, introduced in the early 1950s, employs line-commutated CSCs with thyristor valves. Such converters require a relatively strong synchronous voltage source in order to operate. **Figure 1** shows a classical HVDC converter station with current source converters.

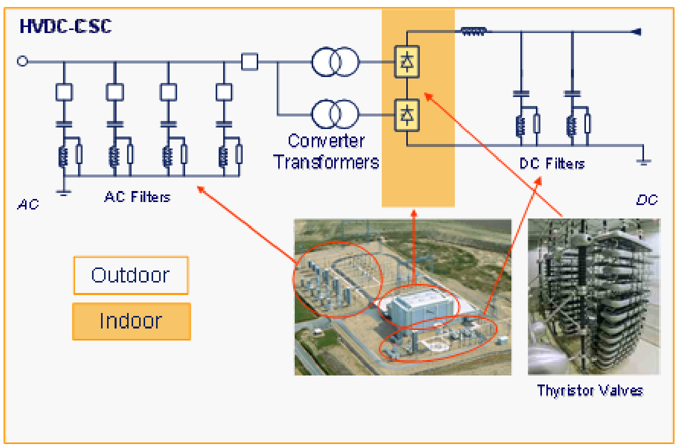

Figure 1 HVDC station with current source converters

Today there are about 100 classical projects around the world. Typically, a classical HVDC transmission has a power

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of more than 100 MW and many are in the 1,000-3,000 MW range. One of the major efforts for classical HVDC today is the development of Ultra High Voltage DC Systems (±800 kV) to transport more power over longer distances. The largest HVDC project so far, (6400 MW, ±800kV) is already under construction in China. More such projects have been planned in China and India as well as in Southern Africa and Brazil [2].

One major reason for the increased interest in HVDC is that more power can be transmitted more efficiently over long distance, say over 1000-2500 km, than by ac lines. HVDC systems can carry 2-5 times the capacity of an ac line of similar voltage. As such the environmental impact of HVDC is more favorable than ac lines because less right-of-way land is needed. HVDC transmission has been widely used to interconnect two ac systems where ac ties would not be feasible because of system stability problems or different nominal frequencies of the two systems. HVDC transmission is also needed for underwater cables longer than 50 km where HVAC transmission is impractical because of the high capacitances of the cable requiring intermediate compensation stations. With an HVDC system, the power flow can be controlled rapidly and accurately.

B. VSC-HVDC Technologies

VSC-HVDC is a transmission technology based on voltage source converters (VSC) and insulated gate bipolar transistors (IGBT). The converter operates with high frequency pulse width modulation (PWM) and thus has the capability to rapidly control both active and reactive power, independently of each other, to keep the voltage and frequency stable. The ABB product name of VSC-HVDC is HVDC-Light [3]. The maximum power of bipole HVDC Light® is 1200 MW with cables and 2400 MW with overhead lines [2]. **Figure 2** shows a HVDC Light® converter station.

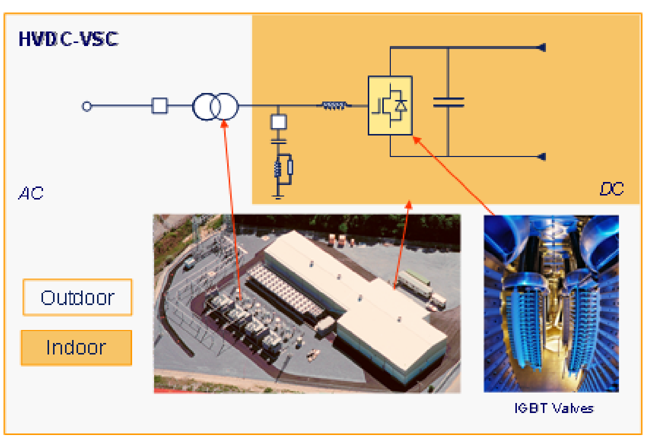

Figure 2 HVDC Station with voltage source converters

VSC-HVDC systems can transmit power underground and underwater over long distances. It offers numerous environmental benefits, including “invisible” power lines, neutral electromagnetic fields, oil-free cables and compact converter stations. **Table 1** shows the eight HVDC Light® installations that have been in commercial operation.

Table 1 Reference list of HVDC Light®

Project	Rating	Dist.	Application	Comm.
Gotland	50 MW	70 km	Small scale gen. (Wind power)	Jun 1999
Tjæreborg	7 MW	4 km	Small scale gen. (Wind power)	Aug 2000
Directlink	180 MVA	65 km	Connecting asynchron. networks	Dec 2000
Eagle Pass	36 MW	B-t-B	Interconnection	Jun 2000
Cross Sound Cable	330 MW	40 km	Interconnection	Jun 2002
Murraylink	200 MW	180 km	Interconnection	Jun 2002
Troll A	2 x42 MW	70 km	Offshore	Oct 2002
Estlink	350 MW	105 km	Connecting asynchronous networks	2006
NORD E.ON 1	400 MW	203 km	Offshore wind power	2009
CAPRIVI LINK	300 MW	970 km (OH)	Connecting weak AC networks	2009
VALHALL	78 MW	292 km	offshore electrification	2010

The most recently commissioned project is the Estlink Transmission System which operates at ±150 kV DC and is rated at 350 MW of active power in either direction. The link interconnects the national grids of Estonia and Finland, enabling the exchange of electric power between the Baltic States and the Nordel electric system for the first time. The NORD E.ON 1 project will interconnect the world largest offshore wind park in Germany by 2009, rated at 400MW, over 200 km long sub-sea and underground cable system to the power grid. The CAPRIVI Link project will be constructed in Namibia by 2009 to connect two parts of the country’s power grid and strengthen electricity networks in southern Africa. The two networks are very weak and the HVDC Light® technology will help stabilize them. This project extends the voltage for HVDC Light® to 350 kilovolts (kV) and marks the first time the technology will be used for long overhead transmission lines.

C. Comparison of Classical and VSC-HVDC

Classical HVDC and VSC-HVDC can both be used for the following typical applications:

- Long-distance bulk power transmission
- Underground and submarine cable transmission
- Interconnection of asynchronous networks

New converter designs have significantly extended the range of applications of HVDC transmission. In particular, self-commutation, dynamic voltage control, and black-start capability allow compact VSC-HVDC transmission to serve isolated loads on islands or offshore production platforms over long-distance submarine cables. **Table 2** summarizes the main characteristics of the classical HVDC and VSC-HVDC technologies [4].

Table 2 Comparison of classical HVDC and VSC-HVDC

Attributes	Classical HVDC	VSC-HVDC
Converter technology	Thyristor valve, grid commutation	Transistor valve (IGBT), self commutation
Max converter rating at present	6400 MW, ±800 kV (overhead line)	1200 MW, ±320 kV (cable)
Relative size	4	1
Typical delivery time	36 months	24 months
Active power flow control	Continuous ±0.1Pr to ±Pr (Due to the change of polarity, normally changing the power direction takes some time, which is not the case for VSC-HVDC)	Continuous 0 to ±Pr
Reactive power demand	Reactive power demand = 50% power transfer	No reactive power demand
Reactive power compensation & control	Discontinuous control (Switched shunt banks)	Continuous control (PWM built-in in converter control)
Independent control of active & reactive power	No	Yes
Scheduled maintenance	Typically < 1%	Typically < 0,5%
Typical system losses	2.5 - 4.5 %	4 - 6 %
Multiterminal configuration	Complex, limited to 3 terminals	Simple, no limitations

III. AC Grid with Embedded VSC-HVDC

VSC-HVDC transmission technologies provide necessary features for embedded applications in meshed ac grids [5]. The resulting hybrid AC/DC grid structure enables more efficient congestion management, reliable integration of large-scale renewable energy sources, and improved system dynamic response against disturbances.

A. Technology Advantages

The most attractive technical advantages of VSC-HVDC systems for embedded applications in ac grid are power flow control flexibility, fast response to disturbances and feasible multiterminal configurations.

Power Flow Control Flexibility – The power flow on the VSC-HVDC systems can be optimally scheduled based on system economics and security requirements. It is also feasible to dispatch VSC-HVDC systems in real-time power grid operations. Such increased power flow control flexibility allows the System Operators to utilize more economic and less pollutant generation resources and implement effective congestion management strategies.

Fast Response to Disturbances – Fast control of active and reactive power of VSC-HVDC systems can improve power grid dynamic performance under disturbances. For example, if a severe disturbance threatens system transient stability, fast power run-back and even instant power reversal control functions can be used to help maintain synchronized power grid operation. VSC-HVDC systems can also provide effective damping to mitigate electromechanical oscillations by active and reactive power modulation.

Multiterminal Configurations – Another advantage is that the power direction is changed by changing the direction of the current and not by changing the polarity of the dc voltage. This makes it easier to build VSC-HVDC systems of more than a few terminals. These terminals can be connected to different points in the same ac network or to different ac networks. The resulting dc grids can be radial, meshed or a combination of both. Multiterminal VSC-HVDC systems are particularly attractive for integration of large-scale renewable energy sources such as offshore wind farms and for reinforcement of interconnected regional ac grids.

B. Prospective Applications

In the following, a number of existing and likely future applications of VSC-HVDC in meshed ac grid are discussed.

1) Network Interconnections

In recent years, due to increased volumes of bulk power transactions in competitive energy markets, some regional network tie lines are frequently fully loaded and thus restrict the economic power transfer between adjacent regions. Regional interconnections enhanced through VCS-HVDC links can effectively improve the transfer capability between regional networks. In addition, precise power flow control of dc links makes the settlement of pricing power transfers, billing customers, and preventing free riders become uncomplicated tasks. VSC-HVDC system can also be operated as a merchant transmission facility, similar to a merchant generator. One example is the Murry-link project which benefits both South Australia and Victoria by enabling electricity trading in Australia's deregulating power market. Another example is the Estlink project which enables the exchange of electric power between the national grids of Estonia and Finland.

2) Bottleneck Mitigations

Transmission congestion occurs when actual or scheduled flows of electricity across a portion of network are restricted below desired levels either by physical capacity or by system operational security restrictions. Transmission bottlenecks have resulted in consumers of some areas paying higher prices for electricity and system reliability concerns. In many cases, the capacity of ac lines comprising the bottleneck is not fully utilized because of stability concerns. VSC-HVDC system may be a desirable solution in comparison with ac alternatives. It has been shown in system studies that the transfer capability of those voltage or transient stability constrained bottlenecks can be increased by more than the rating of the VSC-HVDC system due to effective damping control and dynamic voltage support [6]. For parallel AC/DC transmission schemes, full power flow controllability of VSC-HVDC system allows optimized power sharing between ac lines and dc link.

3) Integration of Renewable Energy Sources

With several GWs of offshore wind generation now in the advanced stages of planning, particularly in Europe, the demand for reliable and robust power transmission to shore is now a fact. In this case, VSC-HVDC is the most appropriate duo to compact converter station and flexible voltage and frequency control [2, 7]. **Figure 3** shows the converter station at sea in the Nord E.ON 1project where 400 MW wind power will be transmitted from the North Sea to Northern Germany, a distance of 200 km. VSC-HVDC transmission allows efficient use of long-distance land or submarine cables.

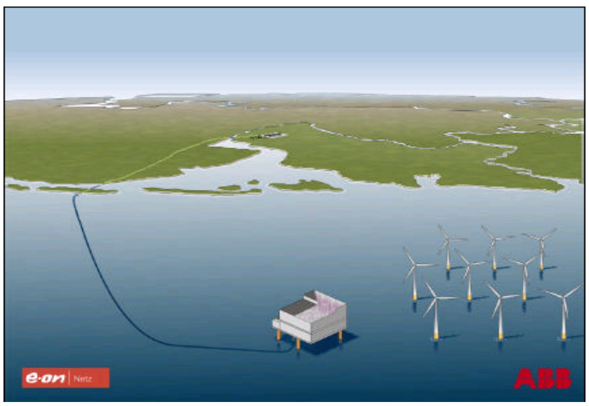

Figure 3 Converter station for offshore wind generation

The following summarizes the main features of VSC-HVDC transmission for large-scale offshore wind power evacuation:

- VSC-HVDC can fully cope with grid code.
- WTGs no longer need to be designed for fulfilling the grid code, and the optimization can focus on cost, efficiency and robustness.
- VSC-HVDC can separate the windfarm from the AC network. Faults in the AC grid will not give stress or disturbances on wind turbine, and faults in the windfarm will not affect the AC network.
- VSC-HVDC provides voltage and frequency control, and desired inertia can be emulated to enhance the stability of the AC network.

4) DC Infeed to Large Urban Areas

Majority of large city power grids are characterized by high load densities, strict requirements for reliability and power quality, and excessive reliance on power import from outside sources. Increasing power delivery to large urban areas with ac expansion options is often limited by the risk of increased short circuit levels. The feasibility of direct dc infeed to large urban areas has been discussed in [8]. **Figure 4** shows the two envisioned city infeed schemes with VSC-HVDC system. In one scheme, point-to-point or multiterminal VSC-HVDC system directly deliver power to in-city load pockets. Another scheme is equivalent to closing an open loop of ac circuit which gives extended system without increasing the short circuit power. **Figure 5** shows a version of multiterminal VSC-HVDC network that is embedded in the existing city power grid. Power is fed from transmission grid radially from different sources and distributed through a dc-cable ring to the inverter stations located at different load pockets.

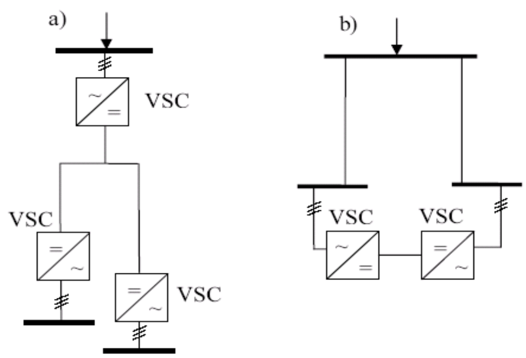

Figure 4 City infeed with VSC-HVDC

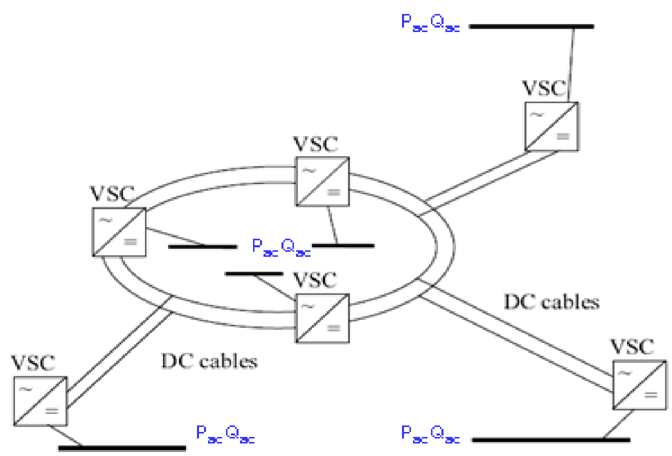

Figure 5 DC network embedded in existing city grid

5) DC Segmented Grid

One vision of future application of VSC-HVDC system in bulk power system is called “DC Segmented Grid” as described in [9]. The basic idea is to decompose interconnected large interregional power system into sets of asynchronously operated sectors interconnected exclusively by dc links. The main argument for promoting dc segmented grid is the increased difficulties with existing large ac grids such as risk of widespread disturbances, transfer capability limitations, and expansion restrictions. Technical feasibility study has shown improved system reliability and market operations by taking advantages of both ac and dc technologies.

IV. WAMS ENHANCED VSC-HVDC SYSTEMS

A. *WAMS Enabled VSC-HVDC Control*

A broad range of application control functions can be implemented in VSC-HVDC systems for enhancement of ac network steady-state and dynamic performance. These control functions are shown in **Figure 6** by three categories along the time line for a disturbance that is pre-disturbance, transient and post-disturbance.

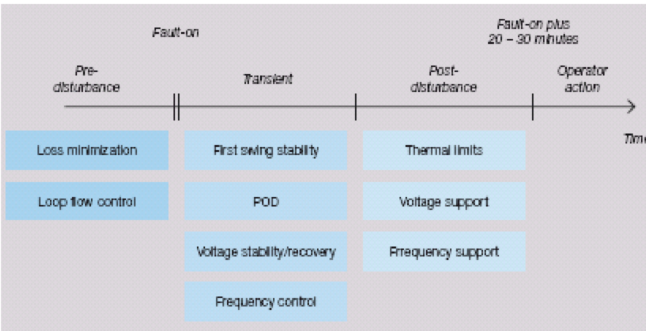

Figure 6 Application control functions of VSC-HVDC

Wide area measurement systems could enhance the performance of VSC-HVDC systems by providing the necessary remote measurements to initiate effective control for transfer capability improvement and against disturbances such as power oscillations. A wide area measurement system, as shown in **Figure 7**, consists of phasor measurement units deployed at geographically dispersed locations in the system [10]. The phasors are collected and aligned by a phasor data concentrator. WAMS applications range from monitoring such as state estimation and voltage security monitoring to wide area control such as power oscillations damping.

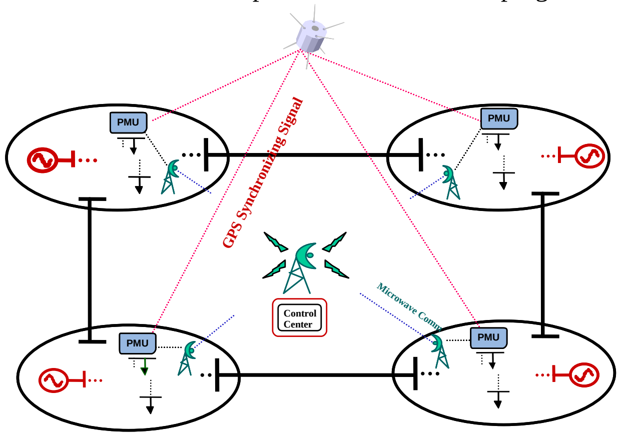

Figure 7 A wide area measurement system

B. *WAMS Enabled Control for Oscillation Damping*

VSC-HVDC system could superimpose modulated active power to damp oscillations in the ac system. A feedback signal such as from active power flow measurement could be used to drive a supplementary damping control scheme. Alternatively, one can take advantage of the SVC-like characteristic of the converter stations and accomplish damping via injecting modulated voltage signals in the converter voltage control circuit. The feedback signal could come from any desired ac quantity based on observability analysis. Logically, both P and Q could be modulated concurrently to achieve a more effective means of damping oscillations. Embedded VSC-HVDC could damp both local and inter-area modes of oscillations. In the latter, the feedback signal could come from remote synchrophasor measurements of bus voltage angles from a wide area measurement system such as depicted in **Figure 8**.

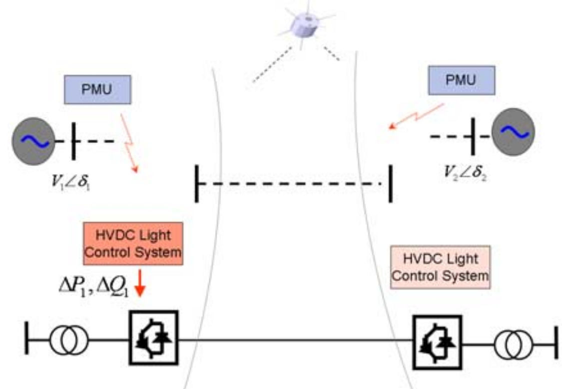

Figure 8 WAMS enabled control for oscillation damping

C. *WAMS Enabled Control for Maximum Power Transfer*

A system with voltage stability limits along a transmission corridor experience congestion due to accompanying transmission constraint. Embedded VSC-HVDC provides countermeasures for both transient and longer term voltage instability mechanisms. Fast modulation of its reactive power could provide the VAR requirements for the transient problem. In the longer term instability, where tap-changers, excitation system responses come into play, VSC-HVDC can help prevent voltage collapse via gradual P and Q modulation, including reducing active power to increase reactive power capability if needed. By operating the converter as an SVC or STATCOM during and after the fault, dynamic voltage stabilization can be enhanced and voltage variations can be minimized. This greatly helps power system recovery from a disturbance and reduces impacts on sensitive loads.

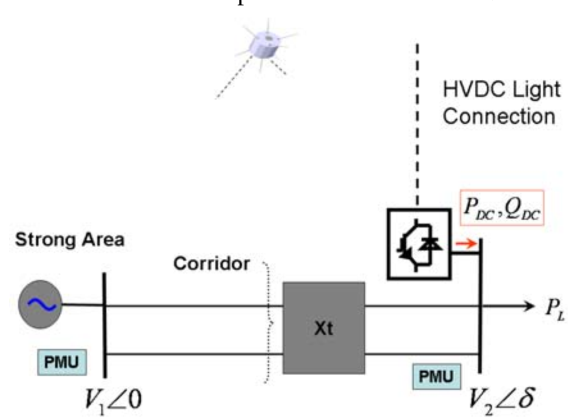

Figure 9 WAMS enabled control for maximum loadability

Figure 9 shows an example transmission corridor configuration with VSC-HVDC infeed into a weak load area constrained by loadability limits. A direct Q injection or voltage control from VSC-HVDC will increase real power into the area by providing local reactive power support. Similarly, the same effect could be achieved by modulating the local voltage. Alternatively, increased corridor transfer capability could be achieved by modulating both P and Q injections from the VSC-HVDC. To realize this maximum power transfer scheme requires measurement of the bus voltage angle difference by phasor measurement units in bus 1 and bus 2. Any status change in the ac transmission infeed would automatically be reflected as a change in the phasor angle. With this angle as reference point, we could adjust P and Q to achieve maximum power transfer.

V. CONCLUSIONS

VSC-HVDC technology is now emerging as a robust and economical alternative for future transmission grid expansion. In particular, embedded VSC-HVDC applications, together with the wide area measurement system, in meshed AC grids could significantly improve overall system performance, enabling smart operation of transmission grids with improved security and efficiency. VSC-HVDC transmission also offers a superior solution for many challenging technical issues associated with integration of large-scale renewable energy sources such as offshore wind power. The technology is under continuous development rapidly into higher voltage, higher power and more flexibility.

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VII. BIOGRAPHIES

Jiuping Pan received his B.S. and M.S. in Electric Power Engineering from Shandong University, China and his Ph.D. in Electrical Engineering from Virginia Tech, USA. He is currently a Principal Scientist with ABB US Corporate Research Center. Prior to joining ABB, He was with the faculty of Electric Power Engineering Department of Shandong University in China. From 1993 to 1995, He was a visiting scholar at the Center of Energy and Global Environment at Virginia Tech USA. His expertise includes power system modeling, HVDC transmission, transmission planning, T&D asset management, energy market simulation studies.

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Kailash Srivastava was born at Fatehpur in India, on October 3, 1962. He graduated in Electrical Engineering from MMM Engineering College Gorakhpur (India) in 1983 He did his MTech and PhD in Power Systems from IIT Kanpur (India) in 1986 and 1995 respectively. He worked in India and Italy for different companies before joining ABB Corporate Research Sweden where he has been working for past 11 years.

Tomas Jonsson received his M. Sc. degree in Electrical Engineering from the Lund Institute of Technology in 1987. He has been employed by ABB in Ludvika and Västerås since 1988. From the year 1988 to 1993 he was working with control system design, system studies and commissioning related to HVDC systems. Between 1993 and 1999, he worked with development of capacitor commutated and voltage source converters for HVDC. Since 1999, he has been employed at ABB Corporate Research as HVDC expert and project leader for power electronic development for HVDC and FACTS applications.

Per Holmberg received his M.Sc. in Electrical Engineering from the Technical University of Chalmers, Sweden in 1986. Since then he has been working for ABB Power Systems/HVDC with control design, digital simulation, technical coordination and commissioning of HVDC projects. In 2007 he was appointed Specialist in the field Power System Analysis and Control of HVDC Systems. He is presently working with dynamic performance studies for both conventional HVDC and HVDC Light®.

Ying Jiang-Hafner received her B. Sc. And M. Sc. Degrees in electrical engineering from Huazhong University of Science and Technology, China, respectively in 1984 and 1987. She received Ph. D. Degree in electrical engineering from Royal Institute of Technology (KTH) of Sweden in 1998. She joined the System Development Department of ABB Power System in Sweden in 1998. She has been involved in the development and design of control system for HVDC Light since she joined ABB. She is now a senior specialist in the technical area of HVDC Light control.