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VSC-HVDC Control and Application in Meshed AC Networks

Jiuping Pan, *Senior Member, IEEE*, Reynaldo Nuqui, *Member, IEEE*, Le Tang and Per Holmberg

***Abstract*— VSC-HVDC is a fully controllable transmission device, allowing rapid and independent control of active power transmitted over the dc link and reactive power at each end of the dc link. Embedding VSC-HVDC in meshed ac networks opens up new possibilities to improve power grid reliability and efficiency. The general control architecture of VSC-HVDC system is presented with focus on converter controls and application control functions that can be implemented in VSC-HVDC for enhancement of ac network steady-state and dynamic performance.**

***Index Terms*—VSC-HVDC, transmission system, control architecture, converter control, application control, interface**

I. Introduction

VSC-HVDC is a transmission technology based on voltage source converters (VSC) and insulated gate bipolar transistors (IGBT). The converter technology 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. Fig. 1 shows the main circuit diagram of HVDC Light © system, the ABB product name of VSC-HVDC transmission. In this paper, VSC-HVDC and HVDC Light are thus used interchangeably.

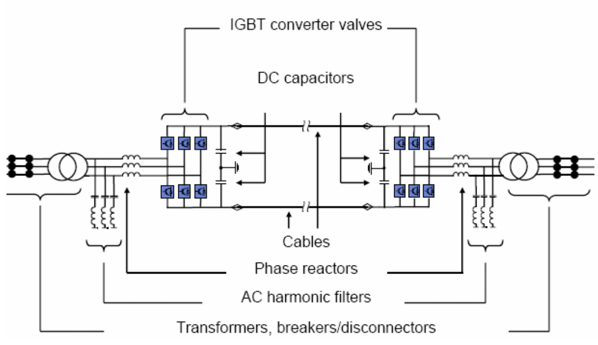

Fig. 1. Main circuit diagram of HVDC Light

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HVDC Light transmission system can transmit power underground and under water over long distances. It offers numerous environmental benefits, including "invisible" power lines, neutral electromagnetic fields, oil-free cables and compact converter stations. With extruded dc cables, power ratings from a few tens of megawatts up to more than thousand of mega-watts are available [1].

So far, eight HVDC Light installations have been in commercial operation as shown in Fig. 2. 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.

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 x 42 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**

Fig. 2. Reference list of HVDC Light

The NORD E.ON 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.

II. PRINCIPAL CONTROL SCHEME

Each HVDC Light converter is provided with an identical control, independent of rectifier or inverter operation [2]. The principal control scheme of one converter station is shown in Fig. 3. PCC is the Point of Common Connection, i.e. the point of converter connection to the ac system, and the reference point for ac voltage.

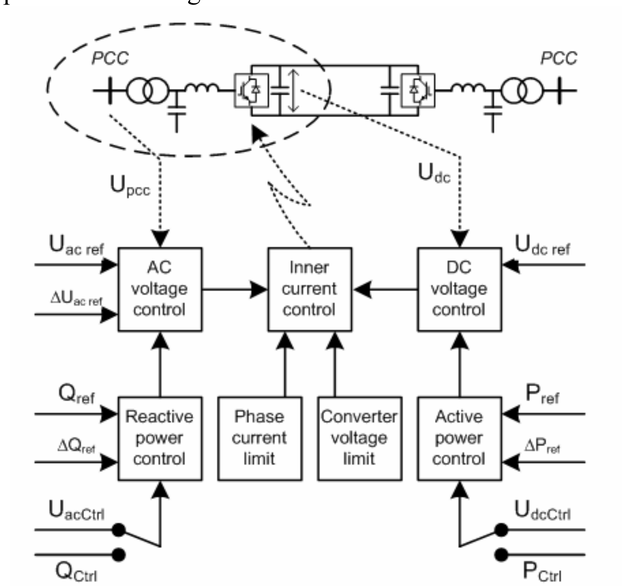


Fig. 3. Principal control scheme of HVDC Light

The control functions of HVDC Light converter include ac and dc voltage control, active and reactive power control, and inner current control. The control system recognizes current output limitation and internal converter voltage limitations. Figure 3 also shows the reference inputs Pref, Qref, Uacref and Udcref as well as the auxiliary inputs ΔPref, ΔQref and ΔUacref. For a two-terminal HVDC Light system, one of the converters should control dc voltage (Udcref) and the other active power (Pref). Each of the converters can be independently set as ac voltage control mode (Uacref) or reactive power control mode (Qref). In normal operations, the power order and voltage setting points of HVDC Light converters are determined by the system operator. The auxiliary inputs ΔPref, ΔQref and ΔUacref can come from HVDC Light application level control and can be used for active and reactive power modulation to achieve desired frequency control, damping control and voltage stability enhancement.

III. AC GRID WITH EMBEDDED VSC-HVDC

It becomes a challenge to increase power delivery with AC expansion options in meshed, heavily loaded ac networks. A key constraint in adding transmission capacity to existing ac grids 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, VSC-HVDC systems may be more attractive in many cases to achieve the needed transfer capability improvement while satisfying strict environmental and technical requirements.

A. *Technology Advantages*

The most attractive technical advantages of VSC-HVDC system for embedded applications in ac networks include

- Power flow control flexibility
- Fast response to disturbances
- Multiterminal configurations

Power Flow Control Flexibility – The power flow on the VSC-HVDC links can be optimally scheduled based on system economics and security requirements. It is also feasible to dispatch VSC-HVDC systems in real-time operations. Thus, the power grid operation will benefit from embedded VSC-HVDC systems due to increased flexibility to utilize more economic and less pollutant generation resources and effective congestion management.

Fast Response to Disturbances – Fast control of active and reactive power of VSC-HVDC system 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 system can also provide effective damping to mitigate electromechanical oscillations by active and reactive power modulation.

Multiterminal Configurations – A multiterminal VSC-HVDC system consists of several converters whose dc terminals are connected in shunt across the buses of a dc network. The VSC-HVDC terminals can be connected to different points in the same ac network or to different ac networks. These dc grids can be radial, meshed or a combination of both. Multiterminal configurations are being considered as feasible alternative for ac network reinforcement to fully exploit the economic and technical advantages of VSC-HVDC technology.

B. *Prospective Applications*

Some likely future VSC-HVDC connection scenarios in meshed ac networks are discussed below.

Regional Network Interconnections – In recent years, due to increased volumes of bulk power transactions in competitive energy markets, some regional network ties lines are frequently fully loaded and thus restrict the economic power transfer between adjacent regions. Regional interconnections through VCS-HVDC links can bypass congestions of ac tie lines and avoid undesirable parallel or loop flows. Precise power flow control of dc links makes the settlement of pricing power transfers, billing customers, and preventing free riders become uncomplicated tasks. In addition, VSC-HVDC system can also be operated as a merchant transmission facility, similar to a merchant generator.

Mitigation of Bottlenecks – Congestion is recognized as a key issue in many regional transmission grids which has resulted in consumers of some areas paying higher prices for electricity and various system reliability concerns. VSC-HVDC system may be a favorable solution in many cases for mitigation of bottlenecks in comparison with ac expansion alternatives. It has been shown in system studies that the transfer capability of voltage or transient stability constrained bottlenecks can be increased by more than the rating of the VSC-HVDC system [3].

City Grid Modernization – 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 into large cities with ac expansion options is often limited by the risk of increased short circuit levels. VSC-HVDC system can be used for city grid modernization for example direct dc infeed or dc network embedded in existing city power grid [4]. In the late connection scenario, power is fed from transmission grid radially from different sources and distributed through a dc-cable ring to the inverter stations located at different in-city load pockets.

DC Segmented Grid – One vision of future application of VSC-HVDC system in bulk power system is called "DC Segmented Grid" as described in [5]. 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 of dc segmented grid has shown improved system reliability and market operations by taking advantages of both ac and dc technologies.

IV. CONTROL ARCHITECTURE OF VSC-HVDC

In principle, each VSC-HVDC converter is able to control active and reactive power independently by simultaneously regulating the amplitude and phase angle of the fundamental component of the converter output voltage. The general control scheme of one VSC-HVDC converter station is shown in the Fig. 4 below [1, 8].

The control functions of VSC-HVDC system can be classified by three control layers: system control layer, application control layer, and converter control layer as shown in Table I. The system layer controller establishes the functions for achieving bulk electric grid objectives such as power flow control, congestion management and voltage support. These objectives determine the function of the application control layer which will be discussed in the next section. The following gives a brief discussion of converter control functions.

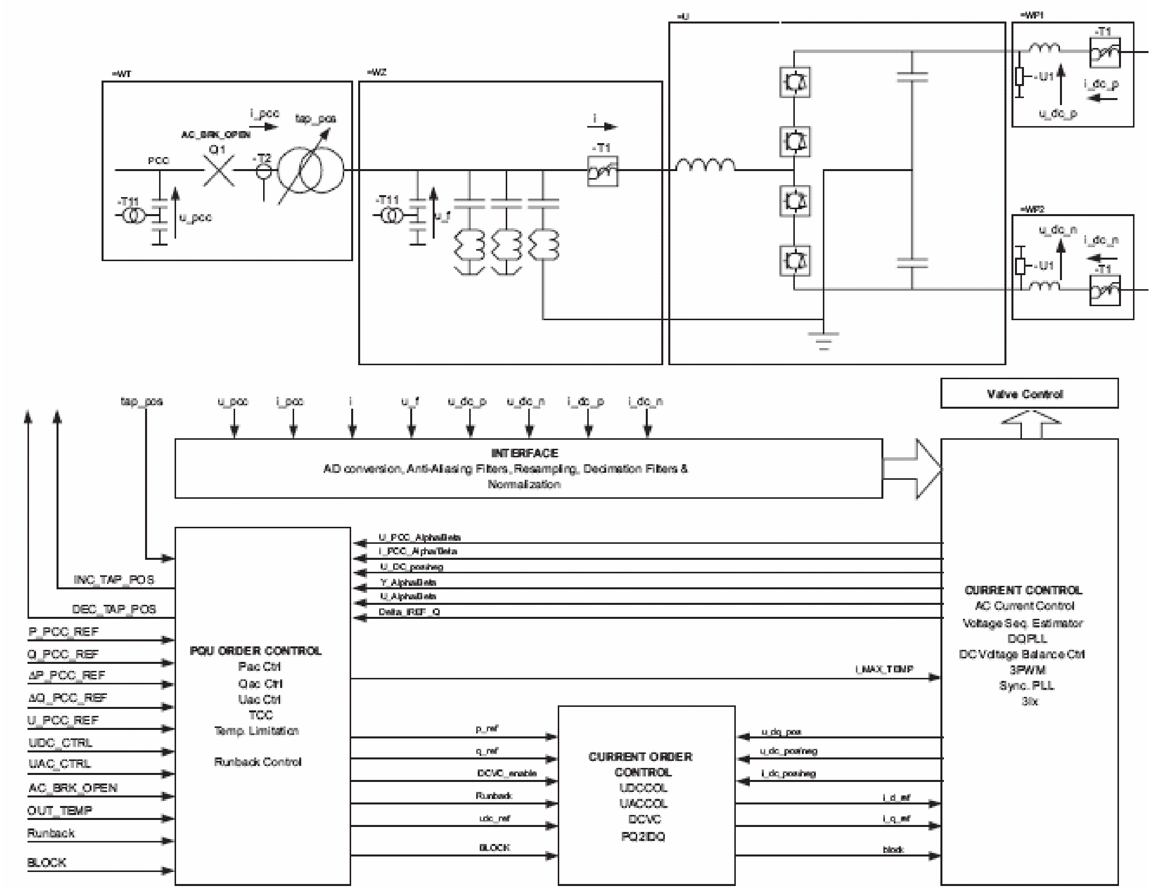
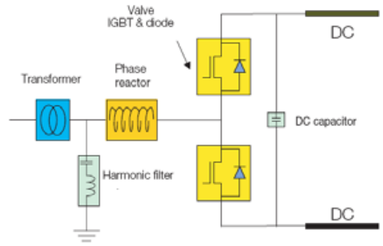


Fig. 4. Control block diagram of one converter station

TABLE 1
FUNCTIONAL ANALYSIS OF VSC-HVDC SYSTEM

System	VSC-HVDC
Simplified one-line diagram	
System control layer	Power flow control, congestion management and voltage support
Application control layer	1- Power flow control 2- Reactive power compensation 3- Transient stability enhancement 4- Power oscillation damping 5- Frequency control 6- Voltage stability improvement
Converter control layer	1- Synchronous timing (PLL) 2- AC line current control 3- Voltage sequence decomposition 4- Optimal pulse width modulation 5- DC voltage control 6- Active and reactive power control 7- AC voltage control 8- Tap changer control

A. *Current Control*

The current control manages the current through the converter phase reactors and the transformer. The control operates in a coordinate system phase synchronous to the fundamental frequency in the network, referred to as dq-frame.

- Voltage Sequence Decomposition provides the true positive voltage sequence for the phase-locked loop, the quasi-positive sequence and the true negative sequence voltage for the ac current control feed-forward voltages.
- DQPLL and SYNCPLL - The phase-locked loop (PLL) is used to synchronize the converter control with the line voltage. The input of the PLL is the three-phase voltages measured at the filter bus. The PLL measures the system frequency and provides the phase synchronous angle for the dq Transformations block.
- AC current control function controls the currents through the converter phase reactors and provides a symmetrical three-phase current to the converter, regardless of whether the ac network voltage is symmetrical or not. The current order is calculated from the power order.
- OPWM - The OPWM (optimal pulse width modulation) control must provide two functions: calculate the time to the next sample instant and modulate the reference voltage vector. OPWM is a modulation method that is used for harmonic elimination and to reduce converter losses. Using PWM makes it possible to achieve fast control of the active and reactive power. This is beneficial when supporting the ac network during disturbances. The control is optimized to have a fast and stable performance during ac system fault recovery.

B. *Current Order Control*

The current order control provides the reference current for the current control and acts as an interface between the PQU order control that operates on RMS values and the momentary control signals within the current control.

- DCVC and UDCCOL - The dc voltage control provides control of the DC voltage using the current order.
- UACCOL - The ac voltage-dependent current order limiter provides control to keep the ac filter bus voltage within its upper and lower limits.
- PQ2idq - The pq2idq control calculates the dq current orders with respect to the positive-sequence voltage.

C. *PQU Order Control*

The PQU order control calculates and provides the current order control block with active and reactive power references.

- Active power control controls the active power flow. In isolated mode the frequency control will control the frequency of the isolated network.
- Reactive power control controls the reactive power.
- AC voltage control controls the AC voltage.
- Tap changer control is used to keep the filter bus voltage and thus the modulation index within suitable limits.

V. APPLICATION CONTROL OF VSC-HVDC

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 Fig. 5 by three categories along the time line for a disturbance that is pre-disturbance, transient and post-disturbance [6]. The application control provides the auxiliary inputs of converter control as shown in Fig. 3.

A. Pre-disturbance Period

In the pre-disturbance period, the control objective of VSC-HVDC is to maintain scheduled power flow and desired voltage support. The set points are normally scheduled by the system operator. In the situations where centralized dispatch is not available or not preferred, the set points of VSC-HVDC system can be determined as part of the system operations planning. It is possible to implement control functions to optimize parallel ac-dc operation with respect to loss minimization and transfer capability improvement [3].

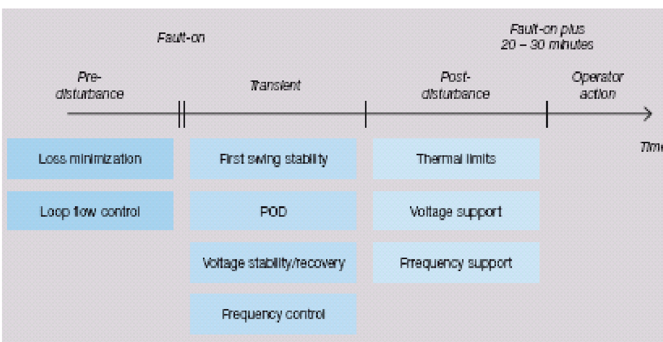


Fig. 5. Application control functions of VSC-HVDC

B. Transient Period

In the transient period, the control objective of VSC-HVDC system is to enhance ac network stability against disturbances.

First Swing Stability - Unlike passive ac lines that only provides a medium for transmitting the first swing after a severe disturbance such as a fault, the VSC-HVDC Link could modulate its active power such as to counteract the swing condition. For example, the VSC-HVDC link could retard generator rotor acceleration by fast run-up or run-back depending on direction of generator electrical power [7]. During fault-on phase, sufficient retarding power could be provided by instant VSC-HVDC power reversal to limit rotor acceleration. Transient stability augmentation can also be achieved by controlling the VSC-HVDC converters to provide supplementary reactive and voltage support.

Power Oscillation Damping - One 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 accomplished 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 [7]. 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.

Voltage Stability – VSC-HVDC could improve voltage stability in a variety of ways. 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. 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.

Frequency Control – If the rectifier and inverter are in two asynchronous power systems, one system can help assist in frequency stabilization of the other disturbed system by modulation of VSC-HVDC power transmission. The control adds or subtracts a contribution to the scheduled power order, proportional to the frequency deviation. With suitable frequency control, the frequency deviations both during steady-state and transient conditions can be minimized. Similarly the frequency control capability could be used to speed up restoration of island ded systems following a system breakup. VSC-HVDC provides required back-up active power to assist in frequency control to a neighboring island. At the same time it acts as additional load to the other island enabling timely start-up of its generators. VSC-HVDC frequency control could be coordinated with existing under-frequency load shedding schemes to limit frequency decay during a major system disturbance.

C. Post-disturbance Period

In the post-disturbance period, the control objective of VSC-HVDC is to help resume secure operation condition of the integrated ac-dc transmission grid. For example, it is advantageous, with suitable control functions, to allow the dc link to increase power transfer or reduce the transmitted power in post-disturbance period to mitigate thermal overloading problems of adjacent ac lines. Further, controlled transformer tap adjustment and SVC like converter voltage regulation characteristics can quickly reestablish desired operation points of terminal voltages.

Both transmitted power and voltage set-points could now be adjusted to establish the prescribed secure margins of operation, based on N-1 contingency criteria considering both thermal and voltages stability considerations. These set-point orders would normally come from the control center. Other post-disturbance control philosophies are possible. The VSC-HVDC voltage set-point could be coordinated with nearby SVC to increase their dynamic Var range, thus, establishing sufficient margins for dynamic stability. At this stage VSC-HVDC could participate in steady-state frequency control in coordination with other governing systems as well as SCADA/EMS AGC system. VSC-HVDC could be controlled to maximize power transfer through voltage stability constrained transmission corridor. With controlled reactive power compensation from the dc link converters, one could provide the required reactive support to remedy voltage stability problems thereby allowing operators to dispatch more power across the transmission corridor.

VI. CONCLUSIONS

The operational benefits of embedded VSC-HVDC systems in meshed ac networks are discussed. A range of advanced control functions can be implemented in VSC-HVDC systems for enhancement of ac network steady-state and dynamic performance. It can be envisioned that VSC-HVDC is an enabling technology for realizing smart transmission grids with improved reliability and economics. Control architecture of VSC-HVDC system is discussed with focus on converter station control block diagram as implemented in HVDC Light.

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VIII. BIOGRAPHIES

Jiuping Pan (M'97, SM'04) 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 consulting R&D engineer with ABB Corporate Research in USA. His expertise includes power system modeling and analysis, HVDC transmission, transmission expansion planning, energy market issues and simulation studies.

Reynaldo F. Nuqui (S'99, M'02) received his Ph.D. in Electrical Engineering from Virginia Tech in 2001. He graduated from the University of the Philippines with BS and MS degrees in Electrical Engineering. He is a Principal Scientist with ABB US Corporate Research Center in Raleigh, NC USA. Previously, he was employed by the National Power Corporation in several positions related to transmission planning, system operations and protection. His research interests are synchronized phasor measurements, High Voltage Direct Current Transmission, protection, voltage stability, and state estimation. Dr. Nuqui is a member of the IEEE Power Engineering Society and the North American Synchrophasor Initiative Working Group.

Le Tang joined ABB Inc. in August 1995. Le earned his B.S. in Electrical Engineering from Xi'an Jiaotong University in 1982 and obtained his M.E. and Ph.D. in Electric Power System Engineering from Rensselaer Polytechnic Institute in 1985 and 1988 respectively. Le is currently Vice President, Director of US Corporate Research Center, ABB Inc. With ABB, as an expert, Le has been involved in various types of research and development activities in different areas of power transmission and distribution. Prior to joining ABB, Le was a Senior Consulting Engineer at Electrotek Concept Inc. responsible for utility system studies, industrial applications, and power quality related training and seminars.

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.