21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2015 Grid of the Future Symposium

Transmission Grid Reinforcement with Embedded VSC-HVDC

J. DANIELSSON, S. PATEL, J. PAN, R. NUQUI
ABB
USA

SUMMARY

Increasing bulk power transactions in competitive energy markets together with integration of large-scale renewable energy sources are posing challenges to the operation of regional transmission grids. Environmental constraints and energy efficiency requirements also have significant effects on future transmission infrastructure development. In recent years, Voltage Source Converter based High Voltage Direct Current (VSC-HVDC) transmission systems have been considered as realistic options for reinforcement of regional transmission grids. VSC-HVDC is ideal for embedded applications in meshed AC grids. Its features include flexible control of power-flow and fast dynamic response to various system disturbances. Together with advanced control strategies, the deployment of embedded HVDC systems can greatly enhance transmission grid security, flexibility and efficiency under uncertain supply and demand conditions.

This paper reviews the recent development in VSC-HVDC technologies and the various applications for reinforcement of bulk power transmission grids. The focus of this paper is on the technical and economic benefits that can be obtained from the unique properties of VSC-HVDC systems. In particular, increasing number of embedded VSC-HVDC systems in combination with wide-area measurement and control systems are set to significantly improve economy and reliability of the transmission grids. It is envisioned that the future transmission infrastructure will develop towards AC grid topologies with embedded DC.

KEYWORDS

Transmission grids, VSC-HVDC, embedded HVDC, power flow control, dynamic response, wide area measurement system

jonatan.danielsson@us.abb.com

1. 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 AC transmission grids. 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. Moreover, there is a high demand for controllable transmission to effectively manage variable flow patterns and accommodate intermittent generation sources. As such, reinforcing electric power grids with advanced transmission technologies such as HVDC systems and FACTS devices becomes attractive to achieve the needed capacity and flexibility improvement while satisfying strict environmental and technical requirements. In particular, the embedding of advanced VSC-HVDC systems in AC transmission grids is opening up new possibilities to enhance smart operation of hybrid transmission grids as the deployment of such solutions greatly improves grid security, flexibility and efficiency through inherent power flow controllability and fast dynamic response capability of embedded VSC-HVDC systems [1, 2]. For further performance improvement, the wide area measurement systems can enhance the performance of VSC-HVDC systems by providing the necessary remote measurements to initiate effective and coordinated control for increased transfer capability and system stability against disturbances.

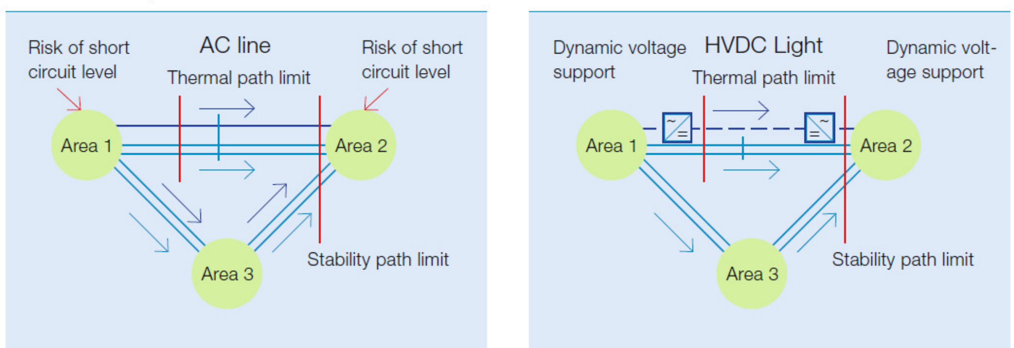

Figure 1: Grid reinforcement with embedded VSC-HVDC

2. HVDC-Light Transmission Technologies

The HVDC Light®, which is the ABB product name for VSC-HVDC, is a transmission technology based on voltage source converters (VSC) using insulated gate bipolar transistors (IGBT). The converters employ pulse width modulation (PWM) switching patterns and can thus control both active and reactive power, rapidly and independently of each other. HVDC-Light® systems offer numerous environmental benefits, including "invisible" power lines, neutral or static electromagnetic fields, oil-free cables and compact converter stations.

The HVDC Light® technology has evolved since its introduction in 1997 [3]. When the technology's first generation was introduced it had the same functionality as HVDC Light® today, but with relatively high losses. The focus of development over the years has been to maintain functionality and reduce losses in order to make it more economical. The two-level converter valve together with custom designed series-connected press-pack insulated-gate bipolar transistors have been the cornerstone of HVDC Light® since the first generation. The first generation 1 was a straight forward two-level converter switching the full voltage in a PWM pattern. Generation 2 was a three-level converter where the losses were reduced, but at a cost of more IGBTs. Generation 3 was going back to a two-level converter with reduced number of IGBTs, but keeping the losses down by using optimized switching pattern and more optimized IGBT design. The technology is now in its fourth generation, and technical developments have made it possible to handle higher DC voltages applying a cascaded two-level converter (CTL). Such enhanced two-level converter topology enables the creation of a nearly sinusoidal output voltage from the converter, which in combination with the low switching frequency significantly reduces station losses. A half-bridge valve configuration has been selected in order to minimize included components and thereby increase reliability [4]. Furthermore, losses and cost will consequently be decreased.

HVDC Light® technology is compatible with land and sea cables as well as overhead lines as means for transmitting the power in the transmission system. HVDC Light® cables (extruded HVDC cables) for land and sea transmission have been developed in conjunction with the converters to offer a matching cable technology. Extruded HVDC cables have become a major player in the portfolio of HV cable transmission systems. The highest voltage on the market today for extruded HVDC cable systems is 320kV. Recently, new 525kV HVDC cable system technology with a power rating range of up to 2.6 GW was developed for both subsea and underground applications [5]. VSC-HVDC systems with overhead lines are feasible options for transmission grid expansions, including conversion of some existing AC lines to DC lines. The main reason for AC/DC conversion is to increase grid transfer capability with minimum environmental impact, minimum investment cost and minimum installation time. There are also other benefits, such as increased efficiency with lower losses, improved controllability of power flow, improved reliability/redundancy (bi-pole), easier to go underground in sensitive areas.

3. Embedded VSC-HVDC for AC Grid Reinforcements

VSC-HVDC is the preferred system for use in a variety of transmission applications, using submarine cables, land cables, overhead lines or connected back-to-back. The established applications include network interconnections, connecting remote offshore wind and oil/gas platforms, connecting remote generation (thermal, hydro, wind, solar) and loads, and direct city infeed. Recently, VSC-HVDC systems have become realistic options for reinforcement of regional transmission grids.

3.1 Mitigation of Network Bottlenecks

Transmission congestion occurs in regional power grids when actual or scheduled flows of electricity across a portion of regional transmission networks are restricted below desired levels either by physical capacity or by system operational security restrictions. Transmission bottlenecks have resulted in consumers of some load areas paying higher prices for electricity and also increased system reliability concerns. Mitigating bottlenecks in heavily loaded AC grid can be achieved by installing embedded HVDC links carrying power directly from one point to another. Because of its capability to inject reactive power into the adjacent AC network, it not only increases transmission power by its own power ratings, it also increases the power transmission capability in the adjacent AC network. The control algorithms that optimize the capabilities VSC-HVDC for enhancing the voltage stability constrained transfer limit have been investigated in [6-8]. It has been shown that the transfer capability can be increased by the full rating or even more than the rating of the VSC-HVDC system due to effective dynamic voltage support to maintain the system voltage stability margin. As shown in Figure 2, a VSC-HVDC link parallel to an AC corridor can be used to control the resulting AC/DC corridor. Optimal power-sharing principle can be implemented for a wide range of power-transfer levels to minimize the total energy losses of the AC/DC corridor. Depending on the operating condition of the AC/DC corridor, the control priority of the VSC-HVDC system could change from minimizing loss to maximizing power transfer. This adaptive control strategy can achieve a desirable balance between power transmission efficiency and corridor capacity utilization.

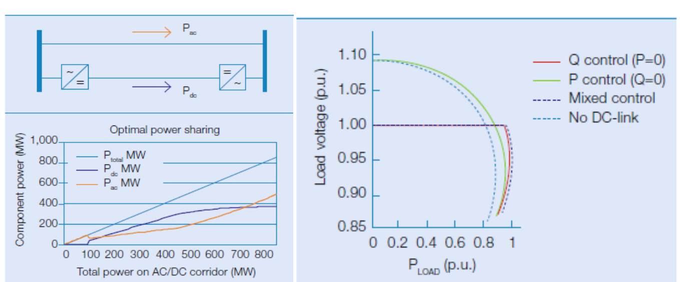

Figure 2: Operational benefits of an AC/DC corridor

3.2 Enhancement of Network Interconnections

Due to increased volumes of bulk power transactions in competitive energy markets, some regional tie lines are frequently loaded to the allowed transfer limits, often caused by voltage or transient stability constraints, and thus restrict the economic power transfer between adjacent regions. Enhancement of regional network interconnections with VSC-HVDC links can effectively improve inter-region transfer capability and capacity utilization of existing lines at the same time reducing the overall losses. The precise control of power flow through a VSC-HVDC system according to a contractual agreement simplifies the pricing of power transfers, billing, and preventing undesired flows. In addition, enhanced regional interconnections with VSC-HVDC also contributes towards grid stabilization under various disturbances and prevents cascading outages.

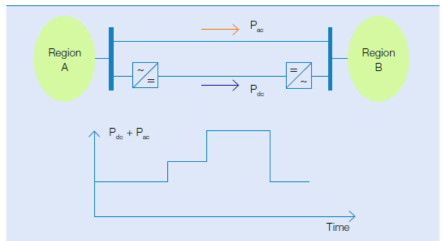

Figure 3: Operational benefits of regional interconnections with VSC-HVDC

3.3 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. Power loads in large cities are increasing as the world urbanizes, and metropolitan transmission networks are continuously upgrading in order to meet the demand for power and replace old-style local generation with power transmission from cleaner sources. Land space being scarce and expensive, substantial difficulties arise whenever new right-of-way must be secured to carry additional power over traditional transmission lines. As power transmission levels increase, the risk of exceeding the short-circuit capability of existing switchgear equipment as well as other network components becomes another real threat to the expansion of power networks. Strategies to develop urban transmission networks must address all these issues and prioritize solutions that may be easily located within urban boundaries, and have short lead times from decision to transmission.

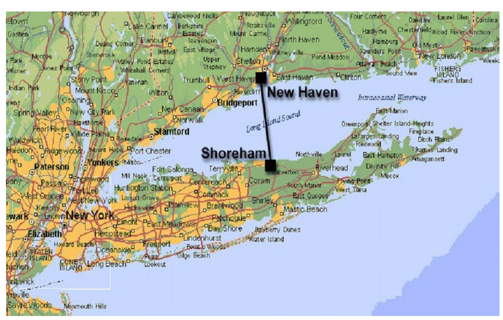

Figure 4: Cross Sound Cable between Connecticut and Long Island

Cross Sound Cable is an HVDC Light® underwater 300MW cable link between Connecticut and Long Island, New York. The Cross Sound Cable improves the reliability of power supply in the Connecticut and New England power grids, while providing urgently needed electricity to Long Island. The HVDC Light® connection is also designed to promote competition in the New York and New England electricity markets by enabling electricity to be traded among power generators and customers in both regions. The Cross Sound Cable has proven itself to be a very valuable asset during grid restoration efforts following the large blackout of August 14, 2003 in the USA, and was the first transmission link to Long Island to go back into service.

3.4 HVDC as a Flow Control Device

Mackinac is a HVDC Light® 200 MW BtB operating as a flow control device embedded in the ac system between Michigan's Upper (UP) and Lower (LP) Peninsula. The ac systems were designed to serve load and not transfer power, and with the increasing demand on low cost environmentally friendly generation, from west of Lake Michigan, the flows through the high impedance path north of the lake increased causing thermal and voltage issues [9]. Splitting the UP become a permanent solution even though it increased reliability risks. When the Mackinac HVDC was put into service 2014 the power flow could be accurately controlled and the split of the systems could be removed. The HVDC Light® technology was chosen because of its ability to control the flows regardless of future system changes, operate under any system short circuit conditions, provide continuous and dynamic MVArs for voltage regulation, and quickly adjust real power in response to system contingencies.

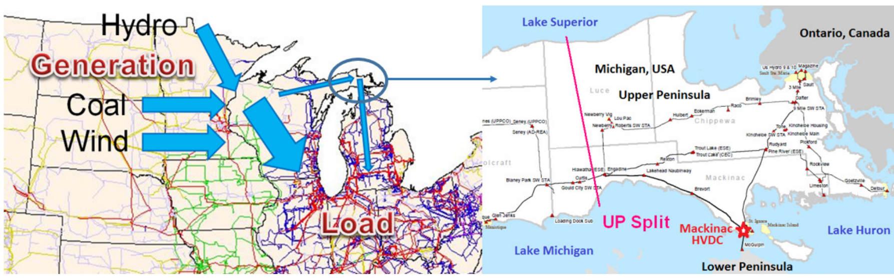

Figure 5: Left: Upper Midwestern US Flow Bias. Right: Eastern UP Transmission System Split

4. WAMS Enhanced VSC-HVDC Systems

Using remote measurements, VSC-HVDC systems can effectively initiate control individually or cooperatively to improve transfer capability and to counter disturbances such as power oscillations. Such remote power grid information could come from a wide area measurement system (WAMS). WAMS, the measurement platform of smart transmission grids, consists of phasor measurement units deployed at geographically disperse locations in the system. GPS time-synchronized measurements of voltage and current phasors together with frequency and binary signals are collected and aligned by a phasor data concentrator. A wide-area control system (WACS) uses these wide-area measurement signals to provide auxiliary controls to power system devices such as HVDC links and FACTS.

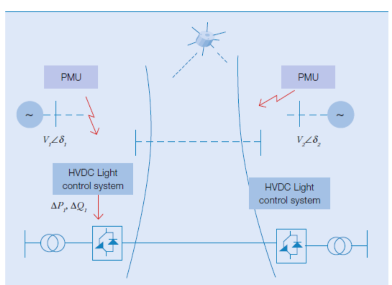

Figure 6: WAMS enabled VSC-HVDC systems

4.1 WAMS Enabled Control for Power 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.

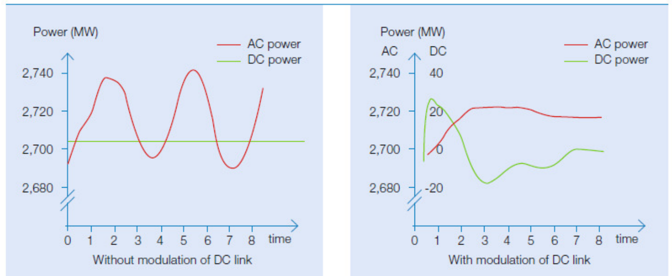

Figure 7: WAMS enabled control for power oscillation damping

4.2 AC Line Emulation in Post-Disturbance Situation

In some cases, it is advantageous to use the DC link to emulate AC-line performance with respect to power flow response to contingencies. The desired AC transmission characteristics allow the DC link to increase power transfer up to its maximum rating or reduce the transmitted power automatically in the post-disturbance period, mitigating possible overloading of adjacent AC lines. An embedded VSC-HVDC system can be autonomously controlled as a pseudo AC-line not requiring frequent schedule decisions from the system operator. This control mode is designed for situations where a centralized dispatch of the VSC-HVDC link is not a requirement. The set points of the DC link are determined as part of short-range operations planning, which determines the desired strength between the two connection points. An AC line emulation function utilizing local measurements at the HVDC was implemented in the Mackinac HVDC Light® BtB to respond to unplanned line tripping to avoid thermal issues and keep the system stable [9].

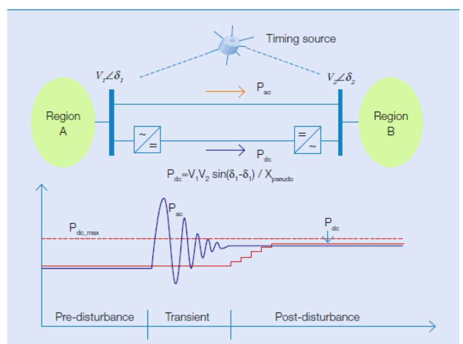

Figure 8: AC line emulation in post-disturbance situation

5. Conclusions

VSC-HVDC technology is now emerging as a robust and economical alternative for future transmission grid expansion. In particular, embedded VSC-HVDC applications within mashed AC regional transmission grids, together with optimal dispatch and control strategies, could significantly improve overall system performance, enabling smart operation of transmission grids with improved security and efficiency. The technology is under continuous development rapidly into higher voltage, higher power and more flexibility. It has also been recognized that AC transmission system with embedded DC together with the wide area measurement system could effectively manage the overall power grid operation security and efficiency under uncertain supply and demand conditions.

In power transmission investments, features such as power quality improvement, stability enhancement, frequency and voltage regulation, emergency power support, controllability of power flow are often considered "nice-to-haves," but otherwise are not usually given sufficient attention in the investment assessment unless they are deemed absolutely essential from a purely technical point of view. Today, however, such features are becoming more and more important for network operators especially with the future high penetration of renewable energy. These need to be addressed when considering the various alternatives for regional transmission grid reinforcements.

BIBLIOGRAPHY

[1] J. Pan, R. Nuqui, K. Srivastava, T. Jonsson, P. Holmberg, Y. Hafner, “AC Grid with Embedded VSC-HVDC for Secure and Efficient Power Delivery”, IEEE Energy 2030, Atlanta, November 2008.

[2] J. Yu, G. Karady, G. Lei, “Applications of Embedded HVDC in Power System Transmission”, IEEE Power Engineering and Automation Conference (PEAM), September 2012.

[3] HVDC Light® - It’s time to connect (http://new.abb.com/docs/default-source/ewea-doc/hvdc-light.pdf?sfvrsn=2).

[4] Bjorn Jacobson, Patrik Karlsson, Gunnar Asplund, Lennart Harnefors, Tomas Jonsson, "VSC-HVDC Transmission with Cascaded Two-Level Converters", CIGRE Conference 2010, Paris, France.

[5] The new 525 kV extruded HVDC cable system, ABB white paper, (http://new.abb.com/docs/librariesprovider138/default-document-library/hannover-messe-2015/whitepaper-525kv.pdf?sfvrsn=4).

[6] S. Johansson, G. Asplund, E. Jansson, R. Rudervall, “Power System Stability Benefits with VSC DC-Transmission Systems”, CIGRE Conference 2004, Paris, France.

[7] O. Urquidez, L. Xie, “Singular Value Sensitivity Based Optimal Control of Embedded VSC-HVDC for Steady-State Voltage Stability Enhancement”, IEEE Trans on Power Systems, 2015.

[8] P. Chodura, R. Graaff, M. Gibescui, W. Kling, “Investigation of the Influence of Embedded VSC-HVDC Transmission on Power System Stability”, CIGRE Conference 2015, Lund, Sweden,

[9] M. Marz, K. Copp, A Manty, D. Dickmander, J. Danielsson, F Johansson, P. Holmberg, P-E Bjorklund, H. Duchen, P. Lundberg, G. Irwin, S. Sankar, “Mackinac HVDC Converter – Automatic Runback Utilizing Locally Measured Quantities”, CIGRÉ Conference 2014, Toronto, Canada.