# MTDC VSC Technology and its applications for Wind Power

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**Abstract - Given the global changes in energy generation and transmission, flexible multi-terminal HVDC networks have the potential to offer energy transfer from diverse and isolated generation sources, particularly offshore wind. In this review paper, the characteristics and control philosophies of multi-terminal networks are discussed and relevant applications are asserted. Future challenges for the widespread deployment of this technology are discussed. It is concluded that multi-terminal networks have the potential to play a significant part in the future of energy generation and transmission.**

## 1. Introduction

The development of High Voltage Direct Current (HVDC) technology has taken place over the last 50 years. Throughout this time has always remained a viable option in particular transmission projects. HVDC has been successful for long distance, high power applications or where a requirement to join asynchronous AC networks existed. In recent times, the way in which energy is generated and transmitted between AC grids has changed. This has meant that the advantages that HVDC offers have reignited interest within the field. The characteristics and configurations of HVDC networks can be found in previous papers (Andersen 2006; Bahrman 2008; Breuer et al. 2004; CIGRE-WG-B4.39 2009; Cole and Belmans 2009; Flourentzou et al. 2009; Schettler et al. 2000; Szechtman et al. 2008) and is only discussed briefly here.

HVDC technologies are often categorised by the power electronic switching device used within the AC to DC converter. Line commutated, current source converters (LCC-CSC) use thyristor based converters and are capable of achieving high power ratings. However they require a synchronous voltage source to operate due to the limited flexibility inherent within the thyristor valve. Self commutated, voltage source converters (VSC) utilise more flexible power electronic devices within the converter such as the IGBT (insulated gate bipolar transistor), allowing a more controllable unit. Although the ratings of the power electronics are improving the maximum power of such converters still trails the LCC-CSC technology in terms of ratings.

Given the complexity of multi-terminal HVDC links (MTDC), it is useful to consider some of the advantages the VSC transmission systems offer. A comprehensive description of the superior features of VSC converters compared to CSC can be found in (Bahrman et al. 2003; CIGRE-WG-B4.37 2005) but important advantages include:

- The ability to control reactive and active power independently.
- The link is operational with weak AC systems.
- No commutation failures within the converter.
- Black-start capability.
- No polarity reversal required to reverse the power flow direction.
- The footprint of converter stations is reduced.

Applications for multi-terminal HVDC transmission systems can be far reaching and examples can be found in (Hongbo and Ekstrom 1998; Liang et al. 2009; Lianxiang and Boon-Teck 2007). In the UK, offshore wind farms have been earmarked to provide a large proportion of future energy supplies and would benefit particularly by the use of MTDC networks (Spahic and Balzer 2005; Yao et al. 2008). It would be feasible to connect the multiple offshore wind farms and onshore grid connections together. Another potential application would be for a European Super Grid, a network of DC transmission systems across Europe, as described in (Kreusel and Retzmann 2008). This proposal would allow regional balancing of energy across the continent and also encourage renewable energy generation to occur in the best suited areas. However, there are still challenges that need to be overcome before MTDC becomes cost effective and practical to deploy on a large scale. Areas of particular development interest are minimising power losses, increasing voltage/power ratings, coordinating control between multiple terminals, protection against faults and compatibility between converter technologies.

This paper will summarise the progress and research undertaken into MTDC using both CSC-LCC technology and the more recent advances in VSC. Approaches for controlling these multi-terminal systems will be described along with the features and characteristics of some projects that have been designed and commissioned. Some of the challenges that engineers currently face will be described and potential areas for future developing trends and research will be presented.

## 2. Multi-Terminal CSC HVDC

Traditionally, line-commutated current source converters (CSC-LCC) have been the technology of choice for engineers desiring to transmit vast amounts of energy from point to point within an HVDC system. This tried and tested technology is primarily chosen because of the reliability and robustness inherent within the thyristor valves at the heart of the converter. Over the last decades, progress within the rating and dependability of the thyristor valve has allowed this technique to become more practical and cost effective, it has become the primary technique for medium to long distance electrical transmission with a total of more than 80GW worldwide.

The extension of this technology into multi-terminal systems has remained problematic despite being the subject of much research in the 1980's. An example is the control system used in (Sakurai et al. 1983) for a CSC-LCC multi-terminal system without communications. Terminals are arranged under a control method whereby an operating point is obtained between all terminals which automatically re-configures in the event of a terminal disconnection.

However, despite the need for a multi-terminal CSC-HVDC system very few projects have so far been commissioned. The largest is the Hydro-Quebec-New England link, which at its inception was intended to become a five terminal system, however anticipated performance problems limited the project to a three terminal network. A detailed review of the project can be found in (McCallum et al. 1994), which includes the control strategy of the network and the commissioning of the final terminal at Nicolet.

Two future control schemes of note for CSC-MTDC have been proposed; in (Meah and Sadrul Ula 2009) a control scheme based on a master-slave fuzzy logic controller. This uses the master controller to generate current orders to satisfy the loads. Control of further parameters is exercised by the converter terminals. (Jovcic 2006) uses current source inverters (CSI) to build an integrated wind farm connection without the requirements of a proportion of wind farm connection components, thus reducing costs.

## 3. Multi-Terminal VSC HVDC

### 3.1 Principles

Recent developments within power electronics have engendered the rise of a contending technology parallel to CSC-LCC. Previously, self-commutated voltage source converters (VSC-SCC) had lacked the robustness, plus the high voltage and current rating to be considered for high power transmission. This changed following the development of, amongst others, the Insulated Gate Bipolar Transistor, a device which marries the controllability of the MOSFET with the reliability and power rating of the BJT. The full controllability and switching symmetry through both turn-on and turn-off operation allows the device to reverse power flow much more quickly than its predecessor. Current flowing in the opposite direction is conducted by a reversed diode in parallel to the IGBT. However, this additional component brings a weakness to the system when a fault occurs on the DC side by creating a path for the resulting fault current.

### 3.2 Features

The component parts of the voltage source converter are examined to individually explain their role within the conversion process. A typical topology of a voltage source converter with the most significant component parts shown:

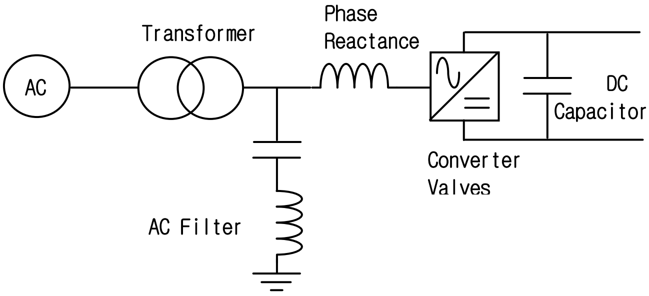

**Figure 1: A typical configuration of a VSC converter terminal**

AC filters are used in VSC to reduce harmonics in the converter, In order to use standard transformers; there is a requirement for the AC filtering circuits to be installed between the transformers and phase reactors. This is to prevent damaging DC voltage stresses and harmonics affecting the transformers operation. The phase reactors within the converter serve many purposes; they are responsible for the flow of reactive and active power, they reduce harmonic current content. They also have a key role in reducing any fault currents, separating the AC system (and its short circuit current) from the converter that it is connected to. The main component of these valve units is the switching device that is utilised to control the converter, the most common of these devices being the IGBT. By controlling the operation of theses switches, an AC waveform can be constructed from a constant DC signal by ‘chopping’ the incoming signal. To increase the voltage rating of the valve unit, IGBT’s are organised into a series arrangement comprising of some 300 devices where necessary (Arrillaga et al. 2007). The primary application of the capacitor on the DC side of the converter is to stabilise this DC voltage.

The topology of the converter valves has been the subject of much research and industry development in recent times. Broadly two approaches have been adopted when designing the converter valve. Early projects tended to use series arranged valves to switch across the full voltage range, a recently developed alternative is a more modular topology. These topologies are covered in a more comprehensive in the review of manufacturers’ current position later in this paper.

### 3.3 Advantages

The use of IGBT’s virtually eradicates the risk of commutation failure. This technology also has the ability to absorb and generate both active and reactive power independently of one another. This negates the requirement for the expensive reactive power compensators used extensively within CSC-LCC projects. Further advantages are that there is no requirement for regulation of the short-circuit level as commutation can operate without an AC system voltage source. Also, the generation of harmonics is greatly reduced, minimising the volume of filters required to absorb them. An additional feature of the VSC-SCC is the capability to ‘black start’. That is, restoring power without the aid of an external power source. This is advantageous in a wide area power outage as these power sources can be brought on-line first to begin the progressive resurrection of the network grid. Although the VSC-SCC transmission technique is still maturing, the total commissioned capacity of these transmission developments has reached nearly 2GW as of 2009.

The advantages listed above make the VSC particularly attractive within complex multi-terminal systems, such as offshore grids for wind farms, linking three or more terminals together. Previous attempts at MTDC using thyristor based converters simply lacked the control flexibility to make the system successful. The development of this new technology finally makes widespread multi-terminal systems a potential reality. However, particular disadvantages include the cost and complexity of potential stations. Future development in this area must demonstrate that the benefits can outweigh the difficulties, subsequent chapters look in more detail at the challenges faced by academia and industry.

### 3.4 Control

Control philosophies for multi-terminal systems have broadly followed two distinct routes. Those which use a master controller to specify certain control of some parameters and those which employ a coordinated control system where no master controller is required. A communication system can be employed between terminals and master controller (where used) to stabilise the system.

Initial work extended principles previously used for two-terminal control to further terminals. The development is the addition of a master controller to set major control signals such as start/stop and power flow direction. Then further local control of parameters such as active and reactive power, DC and AC voltage control where achieved within the control system of each terminal. An example of this approach is (Nakajima and Irokawa 1999) where the ‘voltage margin method’ has been developed. In this system each terminal in the system is set at a referenced $V_{DC}$ level which is slightly offset giving a voltage margin. The point at which the terminal characteristics intersect becomes the operating point for the system and defines the direction of power flow. In a three terminal system, one terminal controls the dc voltage and active power the responsibility of the other two. Communication between the terminals is kept to a minimum with only master to local control information exchange where necessary.

More recently, a coordinated control approach between all the terminals in the system has been developed. The DC voltage is often assigned to one particular terminal with power flow controlled individually at each terminal, should the voltage controlling terminal disconnect, another terminal will assume the role of DC voltage regulation. (Haileselassie et al. 2008) demonstrate this approach is capable of keeping the steady state voltage within preset limits even after the disconnection of certain terminals. An additional feature of this method can be the use of a voltage droop control as described in (Haileselassie et al. 2009). The voltage droop control loops smother changes in DC voltage caused by changing power flow, thus sharing the responsibility of DC voltage setting between terminals. Communications are not necessary for this mode of operation however they can become desirable with highly complex MTDC networks.

### 3.5 Manufacturers

Major manufacturers have already developed converter topologies and control philosophies for point-to-point links and it is likely that these will be extended to form the basis of multi-terminal link. HVDC Light (ABB website 2010), which was first introduced by ABB in 1997 uses a sinusoidal based PWM control philosophy to control the IGBT’s gate switching frequency producing a two level AC waveform, this is then improved to a sinusoidal form by the phase reactors. Switching frequencies between 1 and 2 kHz are used to balance the compromise of harmonics and losses at the output. The switching instances are actually varied in a style called *optimum PWM*: as the current increases the switching frequencies are reduced, this efficiently manages the switching losses across the converter valves whilst maintaining harmonic elimination. To eliminate harmonics, they are concentrated into a narrow band where small filters can be used. The series connected IGBT's need to switch at exactly the same moment, to do this the voltage over each individual IGBT is measured and a boost signal is provided to the gate of the transistor depending on the measured voltage. The monitoring system for the IGBT states is managed by a patented ABB control technology.

An alternative approach is Siemens' new technology and control system called HVDC Plus (SiemensAG website 2010) which uses multi-level converters. The first project to use HVDC Plus has been commission this year and is called the Trans Bay Cable in California. The AC waveform is built using small voltage steps formed by controlling the modules which are turned off or turned on at any given instant. In each HVDC Plus valve there will be a separate small capacitor for each module forming a half bridge rectifier. This is rather than a large capacitor for the whole valve, meaning that the exact switching synchronisation criteria necessary in PWM is not applicable as each IGBT module can not carry the whole DC voltage. This approach of using modules maximises the output voltage of the converter as many modules can be used in series.

In addition to the two above manufacturers, AREVA is expected to come to market with HVDC Extra, their VSC-HVDC solution (Kim et al. 2009).

### 3.6 Projects

Despite the relative immaturity of VSC technology, some point-to-point VSC schemes have been designed and built around the world. Although no projects, so far have been commissioned using VSC-MTDC, it is likely that future schemes will use this technology in complex multi-terminal projects due to its superior controllability. For large scale offshore transmission grids such as the European Super Grid and North Sea wind farms, VSC-MTDC should be a considered technology.

## 4. Challenges

### 4.1 Power Loss

Historically, losses within VSC have been significantly higher than LCC-CSC converters of equal ratings. This has been traditionally caused by the reliance of converter control philosophies on two level PWM, which due to their high switching frequency, have high associated losses. However, as described in (Andersen et al. 2002; Feng et al. 2007; Jih-Sheng and Fang Zheng 1995), next generation multi-level topologies have been developed in recent times which are designed to minimise switching losses by stepping through multiple voltage levels. There is still a requirement for improvements to bring VSC converter losses down from their current level of ～3% to the ～1% loss level found in LCC-HVDC converters (CIGRE-SC-B4 2009). One way in which this may be achieved is by the use of new materials, such as Silicon Carbide, in the next generation of semiconductor devices and power electronics. Alternatively the development of improved converter topologies could reduce the inherent switching and conduction losses.

### 4.2 Voltage/Power Ratings

Currently VSC transmission systems are available up to voltage ratings of ±320kVDC and power ratings approaching 1000MW, this is limited by the ratings of converters and cables. The current limits for LCC-CSC technology is rated at ±800kVDC for converters, however this drops to ±500kVDC due to present day cable constraints for submarine cables (CIGRE-SC-B4 2009). It is expected that the voltage ratings of the VSC converters can rise in future, but will not reach the levels of the LCC-CSC converters. Potential voltage ratings could be achieved by the adoption of modular converters which are series connected and therefore only handle a proportion of the total voltage of the converter. The continued development of MI (mass impregnated) and extruded cable types is needed to improve the capacity of cables in line with converter ratings.

### 4.3 Control and Coordination

Given the complexity of offshore multi-terminal networks it is likely that communications involving a central controller will be required, even if a control philosophy without communication is used, as discussed earlier. The form of this control scheme will need to be defined, particularly when a MTDC network transcends multiple jurisdictions and terrestrial grids.

### 4.4 Protection and Circuit Breakers

The availability of high rating direct current circuit breakers (DCCB) is limited as the requirement for circuit breakers is usually designed with traction applications in mind which operate at low ratings. The inherent problem with any DC protection device is that it lacks a definitive point where the current falls to zero, this phenomena is exploited to allow arcs to be extinguished. Electromechanical devices overcome this problem by superimposing current zeros, however this leads to slow clearing times. Solid state devices obtain faster clearing times by using power electronics to block current; however large losses and high costs are symptomatic of this approach. A comprehensive survey on DCCB's is carried out in (CIGRE-JWG-13/14.08 1997). A possible alternative is to forego the use of DCCB's altogether, in systems without circuit breakers it is necessary for the converter currents on the affected pole to be extinguished and for the pole to be isolated. After a suitable period of time the pole and converters can be restarted and system reestablishment can be coordinated, this approach inevitably leads to disruption and loss of energy transfer. Within HVDC-VSC, the added complication of the continuation of current through the valves free-wheeling diodes means the system remains at fault even after the power electronic switches are blocked. An additional requirement would be to open the AC circuit breakers at converters; this means a reset of the rated voltage is needed before the system is operational once more.

Large and complicated multi-terminal VSC-HVDC systems would make it very difficult to implement a system which didn't use DCCB's to clear faults. The low system impedance allows fault currents to rise very fast thus collapsing the voltage, so a DCCB with a fast clearing time would be an ideal candidate. This criteria is fulfilled by a solid-state circuit breaker, however system design needs to be mindful of the high cost and losses of this technology.

### 4.5 Compatibility of Converter Technology

Currently competing manufacturers have been responsible for complete HVDC projects and so the focus of compatibility has been with the AC grids on either side of the HVDC network. Given the expected increase of projects deploying HVDC it is highly likely that interaction between different converter technologies from different manufacturers will occur in future. The solution may be the use of standardised parameters for a converter's DC side to ensure that seamless interaction occurs, synchronising any two distinct converters.

### 4.6 Redundancy

When comparing AC networks with their HVDC counterparts a particular disadvantage is the lack of redundancy within a HVDC link. Whereas an AC network can typical fall back on a redundancy of N-1 or N-2, the HVDC system does not have this level of security. HVDC bipole schemes are able to become monopole schemes and operate at 50% capacity during a pole failure; however this only gives true redundancy when a link is not running at full capacity.

## 5. Conclusion

This paper reviews the present position of research into multi-terminal HVDC networks with a particular focus on its potential offshore wind farm integration. The features of converters topology and control philosophy are summarised and industrial manufacturer's approaches are detailed. The author has then given his informed opinion on the major challenges for the future implementation of such technology into future energy requirements.

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## 7. References

ABB. website 2010. *HVDC Light* [Online]. Available at: http://www.abb.com/industries/us/9AAC30300394.aspx

Andersen, B. R. ed. 2006. *HVDC transmission-opportunities and challenges*. AC and DC Power Transmission, 2006. ACDC 2006. .

Andersen, B. R. et al. 2002. Topologies for VSC transmission. *Power Engineering Journal* 16(3), pp. 142-150.

Arrillaga, J. et al. 2007. *Flexible Power Transmission: The HVDC Options* Wiley.

Bahrman, M. P. ed. 2008. *HVDC transmission overview*. Transmission and Distribution Conference and Exposition, 2008.

Bahrman, M. P. et al. eds. 2003. *Voltage source converter transmission technologies: the right fit for the application*. Power Engineering Society General Meeting, 2003, IEEE.

Breuer, W. et al. 2004. Application of HVDC for Large Power System Interconnections. In: *CIGRE.*

CIGRE-JWG-13/14.08 1997. Circuit Breakers for Meshed Multiterminal HVDC Systems. *CIGRE*.

CIGRE-SC-B4 ed. 2009. *Which role will HVDC technology have in the Future?* Bergen Colloquium.

CIGRE-WG-B4.37 2005. *VSC Transmission.* Electra. pp. 29-39.

CIGRE-WG-B4.39 2009. Integration of Large Scale Wind Generation Using HVDC and Power Electronics. *CIGRE.*

Cole, S. and Belmans, R. 2009. Transmission of bulk power. *Industrial Electronics Magazine, IEEE* 3(3), pp. 19-24.

Feng, C. et al. 2007. Modified Phase-Shifted PWM Control for Flying Capacitor Multilevel Converters. *Power Electronics, IEEE Transactions on* 22(1), pp. 178-185.

Flourentzou, N. et al. 2009. VSC-Based HVDC Power Transmission Systems: An Overview. *Power Electronics, IEEE Transactions on* 24(3), pp. 592-602.

Haileselassie, T. et al. 2008. Multi-Terminal VSC-HVDC System for Integration of Offshore Wind Farms and Green Electrification of Platforms in the North Sea. In: *Nordic Workshop on Power and Industrial Electronics.*

Haileselassie, T. et al. 2009. Control of Multiterminal HVDC Transmission for Offshore Wind Energy. In: *Nordic Wind Power Conference.* Bornholm (Rinnø), Danmark.

Hongbo, J. and Ekstrom, A. 1998. Multiterminal HVDC systems in urban areas of large cities. *Power Delivery, IEEE Transactions on* 13(4), pp. 1278-1284.

Jih-Sheng, L. and Fang Zheng, P. eds. 1995. *Multilevel converters-a new breed of power converters*. Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS '95., .

Jovcic, D. 2006. Offshore wind farm with a series multiterminal CSI HVDC. *Elsevier*, pp. 747-755.

Kim, C. et al. 2009. *HVDC Transmission: Power Conversion Applications in Power Systems*.

Kreusel, J. and Retzmann, D. 2008. Integrated AC/DC Transmission Systems - Benefits of Power Electronics for Security and Sustainability of Power Supply. In: *Power Systems Computation Conference* Glasgow.

Liang, J. et al. eds. 2009. *Control of multi-terminal VSC-HVDC transmission for offshore wind power*. Power Electronics and Applications, 2009. EPE '09. .

Lianxiang, T. and Boon-Teck, O. 2007. Locating and Isolating DC Faults in Multi-Terminal DC Systems. *Power Delivery, IEEE Transactions on* 22(3), pp. 1877-1884.

McCallum, D. et al. 1994. Multiterminal Integration of the Nicolet Converter Station into the Quebec-New England Phase II HVDC Transmission System. In: *CIGRE.*

Meah, K. and Sadrul Ula, A. H. M. 2009. A New Simplified Adaptive Control Scheme for Multi-Terminal HVDC Transmission Systems. *Electrical Power and Energy Systems*.

Nakajima, T. and Irokawa, S. eds. 1999. *A control system for HVDC transmission by voltage sourced converters*. Power Engineering Society Summer Meeting, 1999. IEEE.

Sakurai, T. et al. 1983. A New Control Method for Multiterminal HVDC Transmission Without Fast Communications Systems. *Power Apparatus and Systems, IEEE Transactions on* PAS-102(5), pp. 1140-1150.

Schettler, F. et al. eds. 2000. *HVDC transmission systems using voltage sourced converters design and applications*. Power Engineering Society Summer Meeting, 2000. IEEE.

SiemensAG. website 2010. *HVDC Plus - VSC Technology* [Online]. Available at: http://www.energy.siemens.com/hq/en/power-transmission/hvdc/hvdc-plus/

Spahic, E. and Balzer, G. eds. 2005. *Offshore wind farms - VSC-based HVDC connection*. Power Tech, 2005 IEEE Russia.

Szechtman, M. et al. 2008. *The Role of SC B4 - HVDC and Power Electronics in Developing the Power Grid of the Future.* Electra. pp. 14-22.

Yao, L. et al. 2008. Large Offshore Wind Farm Grid Integration - Challenges and Solutions. In: *CIGRE.*