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Abstract. The continuous increasing progress in high power and high voltage semiconductor devices leads to have a substantial impact on optimization and effective management of electric grids. These developments have great influence on High Voltage Direct Current (HVDC) and flexible ac controller technologies. This article gives an outline of the innovations in Voltage source Converter (VSC) based HVDC technology. VSC based HVDC technology offers decent advantages which includes interconnection of asynchronous networks, bulk power transmission and voltage stability support. VSC based HVDC technology niche utilities to grab opportunities in incorporating large scale renewable energy sources to the grid, especially on shore /offshore wind energy to the grid. Furthermore, VSC-based HVDC technology is essential for maintaining voltage stability in networks of interconnected grids. In the face of changing loads and the incorporation of renewable energy, these systems help to maintain grid dependability and resilience by offering dynamic voltage management and wattless power support. This article highlights the transformative potential of VSC-based HVDC technology in modernizing and future-proofing electric grids. By leveraging the latest innovations in semiconductor devices and control technologies, VSC-based HVDC systems empower grid operators to overcome existing challenges and embrace the opportunities presented by the evolving energy landscape.

Keywords. VSC, HVDC, Control Strategy, Electric grid, Semiconductor.

1 INTRODUCTION

Perpetual growth in electrical energy demand and enhancement progress of high power, high voltage semiconductor devices has resulted in massive development in electrical power sector especially in transmission and distribution sector. Few of these developments include flexible ac transmission system, HVDC transmission and Supervisory Control and Data Acquisition (SCADA). HVDC transmission became first choice of the utilities due to its advantages like interconnection of asynchronous AC systems, bulk power transmission
over long distances, power control and integration of renewable energy sources [1-10]. More than 100 HVDC installations are in operation, transmitting nearly 90GW of power in the world. These installations majorly employ the technologies as given below.

Current Source Converters (CSCs) employs conventional thyristor along with natural commutation. This technology is called as CSC-HVDC or Classical HVDC and it’s block diagram is shown in Figure 1. This technology is entrenched, typically around 1000MW. Itaipu HVDC transmission line with Power transfer capacity of 6300MW in Brazil utilizes this technology only [11-13]. VSCs utilises Gate Turn Off thyristors (GTOs) or Insulated Gate Bipolar Transistors (IGBTs) as switching devices and uses forced commutation. This technology is called as VSC-HVDC and its block diagram is shown in Figure 2. This concept is well-known and reliable for medium power applications around 400MW. Estlink, Estonia-Finland HVDC transmission line with transmission capacity of 350MW is an example of VSC-HVDC[14-17].

![Fig. 1. HVDC Scheme with CSC concept using thyristor](image1)

![Fig. 2. HVDC Scheme with VSC concept using IGBTs](image2)

**2 FUNDAMENTALS OF VSC-HVDC**

VSC-HVDC scheme utilizes two power converters with DC link is shown in Figure 2. The simplest VSC circuit utilizing three-phase bridge is shown in Figure 3. To gain higher voltage blocking potentiality for the converter, each IGBT shown in Figure 3 are replaced by series connected IGBTs. This ensures higher DC bus voltage level of the HVDC converter. For proper four quadrant operation, IGBT is shunted by an anti-parallel diode. Apart from providing filtering of DC harmonics, DC bus capacitor also serves as energy storage device. The other circuits of VSC HVDC are presented in section III.
Fig. 3. Three-Phase VSC circuit

The converters can be controlled by any of the PWM techniques. Sinusoidal PWM technique is mostly preferred due to its ease of implementation. The switching frequency of power switches is directly allied to the harmonics of the system generated. A simple sinusoidal PWM for a two-level inverter is shown in Figure 4. To reduce the harmonic content on ac side, filters are connected at ac side also.

Fig. 4. Two-level Sinusoidal PWM method

The true and watt less powers transferred from VSC to the grid at fundamental frequency assuming a lossless inductor are characterized by the equations shown below.

\[ P = \frac{V_s \sin\theta}{x_L} V_R \]  
\[ Q = \frac{V_s \cos\theta - V_R}{x_L} \]

Where \( V_s \) and \( V_R \) are generated voltage of VSC and voltage and \( V_R \) is voltage at receiving end.

HVDC transmission employing VSCs can offer several advantages over CSC based HVDC transmission systems. Few of them are presented below.

1. Average and wattless power utilized or injected by the VSC converter can be made to control completely independent of each other.
2. Failures developed by the ac networks due to commutation can be avoided completely.
3. Week AC networks can also be connected to the VSC-HVDC system. The networks with no generation source can be tied to VSC-HVDC system.

4. Reduced filter size and faster dynamic response due to higher switching frequency PWM compared to fundamental frequency.

5. Converter transformers are not required since switches used in converters are completely controlled.

ABB supplies VSC-HVDC technology with a trade name of HVDC-Light, while Siemens with trade name HVDC-Plus. Alstom-Grid supplies VSC-HVDC technology with trade name of HVDC-MaxSine.

Some of the VDC-HVDC installations in the world are listed in table I.

**Table 1.** Few VSC-HVDC projects.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Location</th>
<th>Characteristics</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Power in MW</td>
</tr>
<tr>
<td>Transbay</td>
<td>USA</td>
<td>400</td>
</tr>
<tr>
<td>Caprivi link</td>
<td>Namibia</td>
<td>300</td>
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<td>Skagerrak 4</td>
<td>Norway</td>
<td>700</td>
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<td>EWIC</td>
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<td>1000</td>
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<td>Borwin 1</td>
<td>Germany</td>
<td>400</td>
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</tbody>
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3 **Emerging Applications**

There are many key areas in which VCS-HVDC technology can be effectively utilized. The applications are listed below

1. Power supply to Islands
2. Infeed to Densely populated load centres
3. Isolated remote loads
4. Off shore generation
5. Multi terminal systems

Wind power plants and especially, offshore wind plants are well matched for VSC-HVSC transmission. Transmission of power from offshore power plants by overhead transmission lines is neither economic nor practically feasible. Requirement of capacitor banks for commutation of thyristors is a limitation to transmit the power by classical HVDC system. Hence VDC-HVDC is a best choice in such cases. VSC-HVDC system with 4 terminals employing PWM technique exclusively used for wind parks is shown in Figure 5. In this configuration three wind generators can pump power to DC micro grid through VSCs. From DC grid the DC power is inverted and fed to AC grid through fourth VSI.
Advent of Doubly Fed Induction Generators (DFIGs) in wind parks with VSC-HVDC technology associated with coordinated control strategy is most current research in this field. Integration of DFIG wind farm with transmission system using VSCs is depicted in Figure 6. Three-level NPC converters used as VSC in this application.

4 VSC-HVDC PROJECTS

Few of the VSC based HVDC installations in the world, which are currently in operation are listed in Table I. Generally, each VSC based HVDC installation serve one specific characteristic for which it is specially designed. For example, Eagle pass, VSC-HVDC installation in USA is designed as back-to-back system. This installation is operating at 138KV AC voltage at both ends with transmission capacity of 36MW. Gotland HVDC installation in Sweden is designed for providing voltage support. This project is transmitting the power generated by a wind power plant located in the sea through underground submarine cables over 70 Km Murray Link, Australia VSC-HVDC connection.
was established to control asynchronous connection for trading. Trool A offshore, Norway VSC-HVDC connection was established to reduce the CO2 emissions and to feed offshore Plants. Caprivi link, Namibia VSC-HVDC transmission is designed to connect two synchronous week systems. This installation is transmitting 300MW of power over 950km using overhead conductors.

There are many HVDC installations presently operation in India. All these installations are Line Commutated Converters. Biswanth-Agra Bipolar HVDC transmission line is in operation with transmission capacity of 400MW and operating Voltage of ±500kV. The Pugalur-Thrissur VSC HVDC is part of Power Grid Corporation of India Limited (PGCIL) to reduce the deficit of power in southern India. PGCIL gave this order to a consortium of Siemens and Sumitomo Electric industries limited. This project will operate with transmission capacity of 2000MW at an operating voltage of 320kV. Electric trade analysts believe that Pugalur-Thrissur project will open doors to new VSC-HVDC Projects in India.

5 FUTURE TREND

VSC based HVDC systems are technically superior compared with LCC HVDC systems. The future trend in Research and Development (R&D) may likely make VSC-HVDC more cheaper and reliable. Implementation of Multilevel VSC technology at higher switching frequencies may likely reduce the switching losses in the converter. Forthcoming research in the design of cables which can withstand high leakage currents and better voltage rating may also make VSC-HVDC, a better alternative in bulk power transmission.

6 VSC-HVDC MULTILEVEL TOPOLOGIES

In this section, various VSC configurations suitable for the employment of VSC-HVDC system are presented. Recent multilevel inverter configurations extend their popular advantages to converters with high power rating and can with stand high voltages for power system applications such VSC-HVSC and forced commutated FACTS devices. There are various multilevel converter topologies described in literature and most of them are practical serving industrial applications. Most commonly used topologies are

- Diode-Clamped or Neutral-Point (NPC) clamped converter
- Flying Capacitor Converter
- Cascaded H-Bridge Converter

Multi-level converters with three and five levels using PWM technique are commonly used in power system applications. Hence Line-Neutral voltage of these PWM techniques is depicted in Figure 7 and Figure 8 respectively.
The semiconductor switches used in these converters are fully controlled unlike thyristors used in Classical HVDC systems. Since these switches can be commutated by using low power pulses, no separate source of reactive power is required [18-19]. Most used switches are IGBTs and GTOs. Semiconductor switches which are completely controlled are suitable for high voltage, high power applications.

Modular approach combined with phase shifted PWM bids number of advantages, especially harmonic performance of overall VSC-HVDC system. MMC using half bridge with cascaded structures are more suitable for synthesizing different voltage levels [20]. As the voltage level increases, the output voltage is nearer to the sinusoidal waveform thus reducing the harmonic content. A modular multilevel converter with its half bridge form is shown in Figure 9. Redundancy and compact size of the converters are greatest advantages of these converters.

A hybrid VSC which cartels the concept of two level and modular multilevel converter is shown in Figure 10 [20-21]. Hybrid VSC consists of soft switched H bridge converters along with M2C cells. Major function of this M2C cells is for wave shaping of line current. The objective to design hybrid VSC is to reduce power loss and enhance controllability. Additionally, the compact design is achieved along with enhanced harmonic performance. Voltage control can be enabled by implementing tripole harmonic modulation scheme to achieve true power and wattless power regulation [22-23]. When full H bridges are used in hybrid VSC, inductor current control is possible in DC faults. The hybrid VSC can be made
more compact by replacing full H bridges by half bridges. The advantages achieved are reduced power loss and reduced switching devices [24]. Voltage converters connected end to end with common DC link find applications not only in HVDC but also in Wind energy conversion systems with Doubly Fed Induction Generator (DFIG) and in co-generation applications such as solar-wind energy [25-26].

![Diagram of a hybrid VSI topology with three-phases]

Fig. 10. A hybrid VSI topology with three-phases

7 CONTROL METHODS FOR VSC-HVDC BASED PROJECTS

Performance of VSC-HVDC systems connected to grid depends exclusively on control methods adopted. A suitable design of controller along with suitable parameter selection have greater impact on system stability. Few important control strategies are discussed.

7.1 Voltage Controller

This method is very commonly used to control VSC-HVDC system. The specialty of this method is its ability to have direct control over power angle controller and wattless power controller. The true power between VSC and the given AC system is controlled using phase angle shift $\delta$. The wattless power is controlled by the magnitude of voltage across VSC and modulation index. The difference between reference and actual wattless powers is processed to wattless power controller and the output obtained becomes magnitude of modulating signal. To synchronize the VSC voltage and grid voltage this controller utilizes a Phase Locked Loop (PLL) [27-31]. Average power along with wattless power cannot be controlled independently in voltage controller. Another limitation is that this controller is not capable of limiting the converter currents.
7.2 Vector Current Controller

This controller is considered to overcome the limitations of voltage controllers which cannot control true power and wattless power independently. In this method, three phase rotating vectors are converted into two-phase stationary axis to achieve independent control of true and wattless powers [32-33]. Fast dynamic response with good power quality are major advantages of this scheme. Impact of grid disturbances and harmonics is less on converters. However, the performance of VSC-HVDC is poor when tied to week AC networks or very week AC networks. Inner current control is affected by the low frequency resonance which may effect the performance of VSC based HVDC System.

7.3 Advanced Vector Current Controller

Advanced vector current controller is designed to seize the limitations of vector current controller. Advanced vector current controller can have better performance even when a week AC network is connected to VSC-HVDC. This is achieved by taking the system non-linearities into account. By incorporating four blocks of decoupling gains, the outer loop of conventional VCC is enhanced to obtain better voltage regulation along with increased average power [34-36].This method suffers from the limitations of ignoring sudden changes during the normal operation of grid and asymmetrical faults [37-39].

7.4 Fuzzy Adoptive PI Controller

This controller is best option when a passive AC network is to be connected to VSC based HVDC system. At rectifier side, constant wattless power and constant DC link voltage controls are adopted and at inverter side AC voltage control is used [40-41]. In this method, synchronously rotating three phase output voltages are converted to α-β reference to generate reference voltage vector. Altering this vector, frequency and magnitude of AC voltage can be controlled. This method is capable of adapting changes within system and automatically controlling the PI parameters. Agility of the controller needs to be verified when large range of disturbance are generated [42-43].

8 KEY ISSUES AND CHALLENGES

VSC has several advantages when compared to LCC type converter, but it suffers from several limitations that is necessary to be attended. Firstly, voltage restrictions and peak current limitations of power converters. Secondly, voltage stability and angle limitations when VSC is connected to grid. Apart from above mentioned problems, there are a few more issues when a week AC network is connected to VSC-HVDC. The major issues are high dynamic overvoltage, voltage instability and harmonic resonance. The watt less power consumed by the converter will decrease to zero if DC power transfer is interrupted. As a result, the AC voltage of the inverter increases. To withstand this enhanced AC voltage, the equipment should be highly insulated otherwise the equipment may get damaged [44-45]. In this situation to maintain commutation margin, the delay angle of the inverter is increased. The inverter draws high watt less power which results in fall in AC voltage and hence voltage instability issues may rise. Further research is recommended in VSI to reduce the commutation loss. Stability enhancement and reduction of overall loss of VSC based HVDC system are the key areas to be focussed especially when working with higher voltages.
9 CONCLUSION

Recent developments of the VSC based HVDC technologies are discussed in this article. Continuous growth in the high power and high voltage semiconductor technology has led the utilities to exploit maximum benefits of the HVDC systems with VSCs which includes faster dynamic response, independent control of average and watt less power and compact converter stations. Control methods for VSC based HVDC configurations have been analysed. VSC based HVDC systems undeniably will continue to offer better solutions in the transmission sector of power systems. As the energy landscape continues to evolve, with a growing emphasis on renewable energy integration, grid modernization, and interconnection of regional power networks, VSC-based HVDC systems are poised to play an increasingly vital role. The inherent advantages of VSC technology, including its ability to provide precise voltage control, mitigate power quality issues, and facilitate grid stabilization, make it an indispensable tool for addressing the challenges and complexities of modern power systems. Moreover, the compact footprint and modular design of VSC-based HVDC converters make them well-suited for deployment in diverse environments, including offshore wind farms, remote areas, and urban centres where space is limited. VSC-based HVDC systems are a revolutionary technology that provide unmatched advantages and capabilities in the power systems transmission industry. VSC-based HVDC systems are well-positioned to handle the changing demands and difficulties of the contemporary energy landscape, paving the way for a more effective, dependable, and sustainable future for power transmission and distribution. This is due to their demonstrated performance, adaptability, and scalability.

References


