Topologies for VSC transmission

The increasing rating and improved performance of self-commutated semiconductor devices have made DC power transmission based on voltage-sourced converters possible. This technology is called VSC transmission. The main components in a DC scheme are depicted and their functions explained. The features of three main categories of converter topology suitable for DC transmission are described. Three specific converters, namely two-level, three-level diode-clamped and four-level floating-capacitor converters for a 300 MW scheme, are compared in terms of costs, DC capacitor volume, commutation inductance and footprint. The floating capacitor converter is shown to yield the lowest system cost.

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High-voltage direct current (HVDC) is often the economic means for delivering electric power over long distances and/or for interconnecting two unsynchronised AC networks, which may be at different frequencies. HVDC schemes totalling 60 GW with individual scheme ratings between 50 MW and 6300 MW have been installed worldwide, and many more installations are being considered.

Until recently all commercial HVDC schemes employed the well-established, line-commutated, current-sourced converters with the thyristor being the present-day switching device. However, voltage-sourced converters (VSCs), which use devices that can be turned off using gate control, are now feasible at ratings suitable for power transmission.1,2,3,6,7 This is a result of advances in the voltage and current ratings of power semiconductors such as the insulated gate bipolar transistor (IGBT). HVDC applications of this technology are referred to as VSC transmission schemes.

A principal characteristic of VSC transmission is its ability to independently control the reactive power flow at each of the AC networks to which it is connected. Reactive power control is also completely independent of the control of real power flow. This is an advantage when the converter is connected to weak AC networks or networks with no other voltage source. However, VSC transmission does have some disadvantages, which include potentially high power losses and high capital costs when compared with conventional HVDC, but the technology continues to evolve.

To enable VSC transmission to compete with conventional HVDC outside a niche market, a number of technical advancements in the VSC technology are required. This article discusses a breakthrough—the use of a floating capacitor, multilevel converter topology. This technology reduces the converter power losses and alleviates the technical difficulties commonly associated with the design of very high-voltage self-commutated semiconductor switches and other equipment.

Fundamentals of VSC transmission

The fundamentals of VSC transmission operation may be explained by considering each terminal as a voltage source connected to the AC transmission network via a three-phase reactor. The two terminals are interconnected by a DC link, as schematically shown in Fig. 1.
The output voltage waveform \( v_2 \) of a VSC may be described by the following equation:

\[
v_2 = \frac{1}{2} V_m \sin(\omega t + \phi)
\]

Variables \( M \) and \( \phi \) can be adjusted independently by the VSC controller to give any combination of voltage and phase shift in relation to the AC system fundamental. As a result, the voltage drop \( AV \) across the reactor \( X \) can be varied to control the active and reactive power flows.

Fig. 2 shows the fundamental frequency phasor representation for a VSC operating as an inverter and supplying reactive power to the AC system. In this case it can be seen that the VSC output has a larger amplitude and is phase advanced with respect to the AC system.

According to Figs. 1 and 2, the active and reactive power exchange (P and Q) as seen from the AC system terminals can be expressed respectively as:

\[
P = \frac{V_1 \sin \phi}{X} V_2
\]

\[
Q = \frac{V_1 \cos \phi - V_2}{X} V_1
\]

(\( \phi \) is the phase angle between \( V_1 \) and \( V_2 \)).

The PQ diagram of VSC operation is shown in Fig. 3. The VSC is able to operate at any point within the circle, the radius of which represents the converter MVA rating.

**VSC transmission implementation**

Fig. 4 shows a more detailed circuit of one half of a VSC transmission scheme comprising the DC link, the reservoir DC capacitors, the VSC, a high-frequency blocking filter, a converter transformer and a shunt harmonic filter. The other half of the scheme would be a mirror image about the mid-point of the DC link.

In a point-to-point transmission scheme, the DC link may be a cable or overhead line having two conductors. VSCs can also be configured as a back-to-back HVDC scheme, interconnecting two adjacent asynchronous AC networks via indoor, DC link busbars. In contrast to line-commutated DC transmission, the polarity of the DC link voltage remains the same at all times, with the DC current being reversed to change the direction of power flow. This characteristic of VSC transmission makes it more suitable for the implementation of multi-terminal HVDC schemes linking several AC systems.

A DC capacitor is connected to the terminals of the VSC providing the DC voltage source necessary for the dynamics of the system and governing the voltage ripple on the DC line. The ground reference for the VSC may be made at the midpoint of the DC capacitor via a high impedance. This has the advantage of limiting current flow during ground faults on the DC side.

In its simplest form, the VSC employs a
generally be arranged to block triplen harmonics produced by the converter.

In order to meet AC system harmonic specifications, AC filters usually form an essential part of a VSC transmission scheme. These filters can be connected as shunt elements on the AC system side of the converter transformer. In this arrangement, the transformer reactance provides the necessary series impedance between the converter harmonic voltages and the filters. Line commutated HVDC schemes typically incorporate additional capacitance in the design of their AC filters to compensate for the reactive power consumption of the converter. Since a VSC can provide reactive power ranging from +1 pu to −1 pu, reactive compensation is not necessary. This constitutes a significant cost saving over thyristor converters where compensating capacitance can be as much as 0.6 pu of the converter rating.

Self-commutated power electronic devices
The maximum feasible rating of VSC transmission schemes is essentially limited by the present-day ratings of suitable semiconductor devices. Until recently, voltage source converters were associated mainly with industrial motor drives using the gate-turn-off (GTO) thyristor, insulated gate bipolar transistor (IGBT) and metal-oxide semiconductor field effect transistor (MOSFET) in the converter circuit. As the ratings of these devices were initially small, it was technically difficult and uneconomical to form the switches suitable for converters in power transmission applications.

A power transmission system has features that are different from those of an industrial drive system. Generally speaking, equipment for a transmission system must continue in service whilst the AC system experiences faults, disturbances and transients. High availability and high efficiency are other requirements that converters of a power transmission system must meet. These requirements are in turn imposed on the semiconductor devices leading to the desire for:

- high blocking voltage
- high turn-off current
- low conduction and switching losses
- short turn-on and turn-off times
- suitability for series connection
good \( \frac{dv}{dt} \) and \( \frac{di}{dt} \) capability
- good thermal characteristics
- low failure rate.

Hitherto, no device has been able to meet all these requirements because optimising one area often renders another area sub-optimal. At best, a device can satisfy only some of these requirements and, in this respect, GTO thyristors and IGBTs have been potential candidates. The relative ease with which it can be controlled and its suitability for high-frequency switching, have seen the IGBT emerge as the chosen device for most VSC applications.

**Converter topologies**
The basic, unrefined AC output waveform of a VSC is determined by the topology of the converter. Three main categories of topology suitable for DC power transmission exist. These are:

- two-level topology
- multilevel diode-clamped topology
- multilevel floating capacitor topology

**Two-level VSC**
The two-level topology has been widely used in many applications at a wide range of power levels. A number of two-level transmission VSCs have also been built with ratings up to 60 MW. The schematic of one phase of a two-level converter is given in Fig. 6(a). As shown, it is capable of generating the two-voltage levels \( +V_k \) and \( -V_k \).

In order to improve the quality of the output, PWM can be used to produce an output waveform with a dominant fundamental component with the compromise that significant high-order harmonics are also produced. A typical PWM switched waveform, using a carrier based control method with an average valve switching frequency of 1000 Hz is shown in Fig. 6(b). For the purpose of this illustration the DC capacitor has been assumed to have an infinite capacitance (i.e. no voltage ripple). A harmonic analysis of the waveform in a 50 Hz application is shown in Fig. 6(c). The advantages of the two-level topology are:

- simple circuitry
- small DC capacitors
- small footprint
- semiconductor switches have the same duty.

The disadvantages of the two-level topology are:

- large blocking voltage of semiconductor switches
- crude basic AC waveforms
- high converter switching loss due to high switching frequency used.

**Multilevel diode-clamped topology**
By using a number of DC capacitors in series and additional diodes, a multilevel diode-clamped converter can be formed. Fig. 7(a) shows one phase of a three-level circuit and the output three voltage levels, i.e. \( +V_k \), \( 0 \), \( -V_k \). For a three-phase unit, the DC capacitors are usually shared by the phases.

Again, PWM can be used to improve the output waveform quality. A typical PWM switched waveform, using a carrier-based control method with an average valve
switching frequency of 500 Hz is shown in Fig. 7(b). A harmonic analysis of the waveform is shown in Fig. 7(c). An infinite DC capacitance has been assumed. The advantages of the diode-clamped topology are:

- reasonably small DC capacitors
- lower switch blocking voltage
- small footprint
- good basic AC waveform
- relatively low converter switching loss.

The disadvantages are:

- inherent difficulty in keeping DC capacitor voltages constant
- complex circuitry for large number of levels; the number of added diodes increases rapidly with the number of levels
- semiconductor switches have different duties.

Multilevel floating capacitor topology
The multilevel floating capacitor topology produces the same AC waveform as the multilevel diode-clamped topology. This topology has no additional diodes but has additional DC capacitors known as floating capacitors. One phase of a three-level floating-capacitor converter is shown in Fig. 8. For a three-phase unit, the main DC capacitors are shared by the three phases but the floating capacitors, marked \( C_c \), are not. The PWM switched waveform and the Fourier analysis are identical to the three-level diode clamped circuit (Fig. 7(b) and (c)). The advantages of the multilevel floating-capacitor topology are:

- semiconductor switches have the same duty
- lower switch blocking voltage
- good basic AC waveform
- low converter switching loss.

With the volume of capacitors largely proportional to the square of their nominal voltages, the disadvantage of this topology is the large footprint incurred by the floating capacitors.

Comparison of topologies
As part of its development work, Alstom has compared in detail several different converter topologies. This work has concluded that, for practical and economic reasons, multi-level topologies with more than four levels are unlikely to be attractive unless the power level is substantially higher than 300 MW. This
section gives the results of a comparison of three systems with different topologies, i.e. two-level, three-level diode-clamped and four-level floating-capacitor converters. Other investigations concluded that the three-level floating capacitor circuit was marginally superior to the three-level diode clamped converter. However, a four-level converter was selected for the floating capacitor topology in this study since it represents the optimum balance of performance and cost at the chosen power level and can be readily implemented. Increasing the number of levels for the diode-clamped example yielded no net benefit, and considerably increased implementation complexity.

The scheme rating considered for this comparative study is 300 MW, ±150 kV DC, representing the higher end of the principal market for VSC transmission. At much lower power levels, the benefits of multilevel topologies are less pronounced and two-level converters may be more economically attractive.

The switching frequencies for each of the three converter models used in the study are selected to achieve a harmonic performance equivalent to that of a two-level converter switching at 1050 Hz. This frequency is chosen as a compromise between two limiting factors. At higher switching frequencies, the converter switching losses become more significant whereas converters operating at low frequencies require the use of larger, more expensive DC capacitors and AC filters. These trends are applicable to all the converter topologies in the study.

In the sections to follow, each topology is analysed in terms of the capital costs, capitalised losses, DC capacitor volume, commutation inductances, and the footprint of the converter station.

Costs and losses
Fig. 9 compares the normalised capital cost, capitalised losses and the total cost, where the capital cost of the two-level converter is defined as 1 pu. The different duty on the semiconductor devices in the different topologies has been taken into account when evaluating the total capital cost. In particular, for the two-level and three-level topologies the higher switching losses, associated with the higher switching frequency for each device, reduce the current capability of the semiconductor necessitating the use of higher rated semiconductor devices. Notwithstanding this, the two-level converter results in lower capital cost than the three-level diode-clamped and four-level floating-capacitor converters.

The high switching power loss, which is capitalised at the rate of 3000 €/kW, makes the two-level converter most costly overall. In contrast, in spite of having the highest capital cost, the low power losses for the four-level floating-capacitor makes this topology the most economically attractive. If the loss capitalisation is reduced to 1000 €/kW, the three topologies yield almost identical total cost.

Capacitor volume
The comparison of DC capacitor volume is shown in Fig. 10. Again the value for the two-level converter is defined as 1 pu. The DC capacitor volume has been calculated to limit the voltage ripple to less than 5%. Fig. 10 shows that the four-level floating-capacitor converter requires much higher DC capacitor
Special Feature: AC/DC power transmission

![Comparison of DC capacitor volume](image)

Volume than the two-level and three-level diode-clamped converters. This is only partly due to the additional floating capacitors. The relatively low switching frequency that can be used with this type of converter requires the use of larger capacitance values to achieve the voltage ripple performance of the other topologies.

In many instances, it may be possible to permit larger levels of voltage ripple with all converter topologies. The effect of this would be to reduce the significance of capacitor volume as a factor in overall scheme design.

**Commutation loop inductance**

One initial concern with the multi-level topologies was whether the commutating loop stray inductance would increase dramatically as the number of levels increased. A large commutating loop inductance would necessitate a significant increase in snubber capacitance, which would increase the switching loss, thereby negating some of the benefits of the multi-level topology. The investigation, which included the creation of 3D drawings of the complete converter circuits, concluded that this concern was unfounded.

Fig. 11 compares the commutation inductances for the three topologies where the commutation inductance of the two-level converter is again defined as 1 pu. It can be seen that the multi-level circuits do not show a significant increase in commutating loop inductance. This is largely due to the fact that the DC capacitor banks used in these circuits consist of many parallel connected capacitor units, which can be arranged to provide low stray inductance between their terminals.

The three-level diode-clamped converter results in lower commutation loop inductance than two-level and four-level floating-capacitor converters. This is because, for the three-level diode-clamped converter, only half the stray inductance of the DC capacitor appears to each valve during commutation.

**Footprint of converter**

The normalised footprints of the converters are compared in Fig. 12 where again 1 pu is assumed for the two-level converter. It can be seen that the four-level floating-capacitor topology has a much larger footprint than the two-level and three-level diode-clamped converters. This is mainly due to the volume of the DC capacitors required. However, the additional capacitor footprint is somewhat alleviated by the fact that a smaller high-frequency blocking filter is required between the four-level VSC and the converter transformer. During each switching, the voltage steps for the two, three and four-level converters are 300 kV, 150 kV and 100 kV, respectively, and so the same divd at the transformer terminals can be achieved using proportionally smaller series blocking reactors with the four-level converter.

It should be noted that the comparison of the footprints is for the converters only. Therefore, when the rest of the power systems equipment associated with the HVDC station is taken into account, the differences in size shown in Fig. 12 become less significant.

**Ease of implementation**

The implementation of a high-voltage DC converter presents a wide range of technical challenges, not least the series connection of

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many semiconductor devices to form a high-voltage switch. This involves controlling the dynamic voltage sharing between series devices without introducing large losses. The multi-level topologies utilise switches with a lower rated voltage than those of the two-level converter thereby facilitating the design process.

Summary of comparisons
Table 1 summarises the findings of the study comparing the three topologies. Only the issues concerning the deliverable VSC scheme are considered, as other technical issues are ultimately reflected in the system cost or converter loss elements.

Every VSC transmission application will have a range of requirements that emphasise different strengths or weaknesses of each converter topology. For example efficiency may be the key factor in an island power link whereas a power trading application may be influenced primarily by capital cost. In a situation where losses are of prime importance, the four-level floating capacitor converter is likely to offer the optimum solution.

300 MW example
As part of the study work described in the previous section, detailed modelling and analysis of a 300 MW floating capacitor VSC transmission scheme has been undertaken. Particular attention was paid to the physical layout of the converter components in this example to achieve a minimum loop inductance with the most compact overall design.

The model assumes a DC link voltage of ±150 kV—a typical value for economic power transmission in a 300 MW point-to-point scheme. With this DC voltage, each of the 18 valves that make up one converter is rated at one-third of the total DC link voltage, i.e. 100 kV. The inner and outer floating capacitors are rated at 100 kV and 200 kV, respectively. Fig. 13 shows the single-line circuit diagram for one converter station.

The valves and high-frequency blocking...
filters would be installed inside a converter building where the connections would also be made to the transformer secondary bushings. The converter transformer itself and the AC harmonic filters would be located outdoors.

A 3D view of one terminal of the 300 MW VSC transmission model is shown in Fig. 14. The size of the valve hall is approximately 22 m by 18 m with an interior clear height of 7.5 m.

Conclusion
The emergence of VSC transmission has opened new markets for HVDC and a number of commercial VSC transmission schemes are now in operation.

Despite the range of advantages that VSC transmission offers over thyristor-based HVDC, practical VSC schemes continue to exhibit significantly higher losses. This factor is due to the large conduction loss inherent with suitable, self-commutating devices and the requirement for relatively high switching frequencies. Nevertheless, new devices are being developed and some of these have promising low conduction loss and reasonable switching loss.

With the introduction of multi-level floating capacitor converters to VSC transmission, efficiency improvements are achievable using existing semiconductor devices. These topologies permit the use of lower switching frequencies resulting in a corresponding reduction in switching losses. As a consequence the application of VSC transmission can be made far more economically attractive.

References