Future VSC-HVDC converter topologies and their coordination with extruded DC cables

Colin **DAVIDSON**, Antonios **TZIMAS**, Konstantin **VERSHININ,** David **TRAINER;** GE's Grid Solutions Business, (UK), colin.davidson1@ge.com, antonios.tzimas@ge.com, konstantin.vershinin@ge.com, david.trainer@ge.com

ABSTRACT

The Modular Multi-level Converter (MMC) has become established as the most popular VSC topology for HVDC today. The MMC gives low levels of DC ripple voltage and, like most VSCs, a non-reversing DC voltage polarity in normal operation. However, the MMC occupies a large land area, which may become critical in space-constrained applications such as offshore. Two other promising converter topologies include the Alternate Arm Converter (AAC) and Series Bridge Converter (SBC), offering reduced land utilisation and potentially better fault management. The benefits of these topologies are discussed in the paper.

KEYWORDS

VSC, topology, MMC, AAC, SBC.

INTRODUCTION

Voltage Sourced Converters (VSC) started to appear in HVDC systems almost 20 years ago, all previous HVDC systems having used Line-Commutated Converters (LCC). At first, VSC voltage and power ratings were low but the growth of VSCs was ensured by some of their capabilities which exceed those of LCC systems – such as the ability to feed power into a completely dead AC network and to control active and reactive power independently. From the perspective of the DC cable, a further advantage was that power reversal in VSC systems is achieved by reversing the direction of current, not the polarity of voltage. Thus, voltage polarity reversals are avoided in normal operation with VSC systems. Voltage polarity reversals are stressful for any type of cable but were of particular concern for extruded cables because of the perception that extruded cables are unable to withstand such polarity reversals because of space-charge build-up. Hence, the growth of cost-effective extruded DC cables has been aided by the growth of VSCs.

The VSC topologies in use today give very low levels of DC voltage ripple. This is in contrast to LCCs, which produce significant amounts of 12-pulse voltage harmonics superimposed on the DC voltage. This represents a further advantage of VSC systems over LCC systems. However, these present-day VSC systems are not without their disadvantages; 2-level and 3-level converters are relatively compact but generate significant amounts of high-frequency voltage harmonics on the AC side and have very poor efficiency, while Modular Multilevel Converters (MMC) have far superior harmonic performance and losses but occupy a large land area. Hence there is a motivation to explore alternative converter topologies which will give the harmonic performance and losses of an MMC but with reduced land area. This subject takes on particular significance in offshore applications where space is very expensive.

REVIEW OF HVDC CONVERTER TOPOLOGIES FOR CABLE APPLICATIONS

From the birth of commercial HVDC in the 1950s to the late 1990s, all HVDC systems used LCC. LCC systems result in significant harmonic distortion on both the AC and DC connections, chiefly in the form of current harmonics injected into the AC grid and voltage harmonics applied to the terminals of the DC system. With the commonly-used 12-pulse connection, the main DC voltage harmonics are of order 12n (12^{th}, 24^{th}, 36^{th} etc). In applications involving overhead lines, adequate filtering of these DC voltage harmonics is necessary in order to avoid problems with telephone interference. However, in HVDC systems where the entire transmission route uses underground or submarine cable, it is usually not necessary to add DC filtering because the capacitance of the cable insulation acts as an efficient high-pass filter and its screen limits the coupling between the cable and nearby telephone lines.

The first VSCs used in HVDC systems were based on the "2-level" converter (Fig. 1), familiar from more mainstream applications such as motor drives.

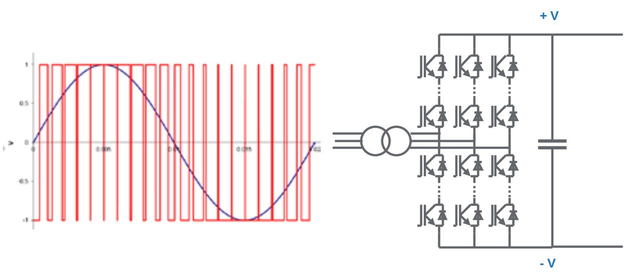

Fig. 1: 2-level converter for HVDC

Although the AC output voltage contains a high harmonic content, the DC voltage is well smoothed because of the large DC-link capacitor. Using IGBTs, it is possible to switch the valves at quite high frequency (>1kHz) to reduce the harmonic content of the AC output voltage, but this leads to a level of power losses (>2% per end) that is unacceptable for many applications and despite this, harmonic filters are still essential on the AC side. Today, 2-level converters are used only in relatively low-power applications, normally below 100 MW.

Some HVDC schemes were also built with 3-level converters, offering a small improvement in harmonic performance, but at the price of greater complexity, both in converter layout and control.

The Modular Multi-level Converter (MMC), first published in 2003 [1], has transformed the VSC-HVDC industry with its excellent harmonic performance and efficiency (Fig. 2).

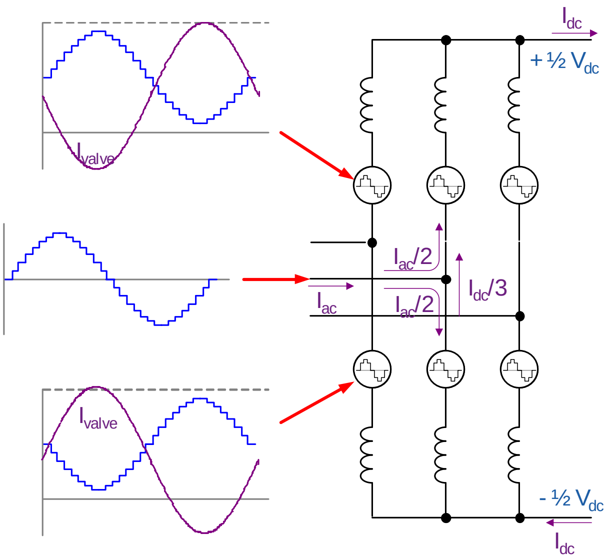

Fig. 2: Modular Multilevel Converter (MMC)

In the MMC, the six switches of the 2-level converter are replaced by six controllable voltage sources. Being composed of tens or hundreds of discrete voltage steps, the AC output voltage of an MMC is a very close approximation to a sinewave and thus, in many applications, AC harmonic filters are not required. Where they are needed, harmonic filters are only installed to avoid magnifying existing harmonics.

Normally there is no overall DC capacitor in an MMC and the DC voltage is formed by the summation of the upper and lower arm voltages for each phase, the three phases being connected in parallel. Valve reactors are needed in each arm in order to limit the circulating current resulting from a mismatch between the ordered DC voltages of the three phases. The valve reactors can be connected at the DC terminals (as in Fig. 2) or the AC terminals.

The waveform quality on the DC side is also very good. The MMC allows the AC and DC voltages to be controlled independently and thus there exists the possibility for a ripple component of voltage to be present on the DC bus, either as a result of deliberate control action or an incorrectly tuned controller. But in the absence of such effects the only ripple voltage that should be present is a high-frequency "white noise" component resulting from the instantaneous errors between the ordered and achieved DC voltages of the three phases. This ripple voltage has low magnitude – of the order of one submodule's worth of voltage - and is applied behind the inductance of the valve and/or DC reactors, which provide further filtering. With GE's converter design and modulation strategy, this means the maximum ripple voltage is about ± 2 kV on a total of typically 640 kV, although other manufacturers may have different modulation strategies.

Despite its advantages, the MMC topology suffers from one significant drawback – its physical size. The size is dominated by the DC submodule capacitors, which in total have a stored energy of many tens of kilojoules per megawatt rating. As a result, the MMC requires a large building (Fig. 3) which can be challenging to accommodate in urban areas and adds considerably to the cost of the platform topside for those applications where HVDC is used to import power from far-offshore wind farms.

A further shortcoming of the MMC (and 2-level) topologies is that in their most common form, they are not capable of suppressing the fault currents that arise from DC pole to pole short-circuits. A refinement of the MMC, the "Full-Bridge" MMC, is capable of doing this, but only at a considerable penalty in terms of efficiency. These limitations have motivated a serious research effort [2] to find better topologies that can give the same harmonic performance as the MMC but in a more compact layout and with the ability to clear DC faults.

Fig. 3: A commercial MMC installation

ALTERNATE ARM CONVERTER (AAC)

The large physical size of the MMC arises from the fact that all six valves need to contain enough submodules to construct the entire DC terminal-to-terminal voltage at certain points on the voltage waveform. For much of the cycle, the current in the valve is quite low, but the submodules must still be there so that they can contribute to the valve voltage waveform at the correct time (Fig. 4).

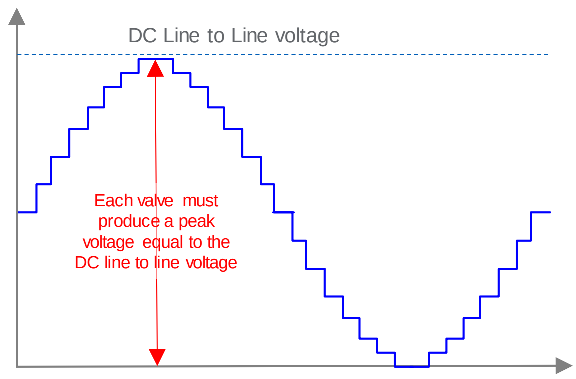

Fig. 4: MMC valve voltage rating

It is this limitation that inspired the "Alternate Arm Converter", or AAC.

In the AAC (Fig. 5), each valve still contains large numbers of submodules, but these submodules are of the "Full-Bridge" type (which confers the ability to block DC-side faults) and are reduced in number compared with the MMC. In addition, each valve contains a series-connected IGBT valve referred to as a "Director Switch" whose function is to isolate the submodules from the DC terminals of the converter for parts of the cycle – those times at which the valve would need to produce the largest voltages. As a result, fewer submodules are needed to generate the highest parts of the converter voltage waveform, and since the capacitors in these submodules dominate the overall size, the overall size is reduced despite the addition of the IGBT director switches. The power losses are also reduced compared with the Full-Bridge MMC (although they are still higher than the Half-Bridge MMC).

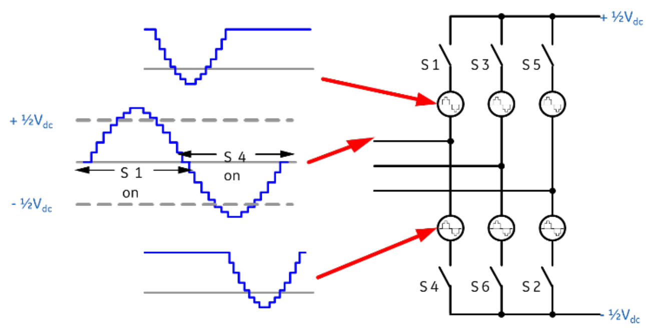

Fig. 5: Basic concept of Alternate Arm Converter

Theoretically, the AAC can be operated with each "director switch" closed for exactly 180° every cycle. In this mode, the number of submodules required is exactly half of that required by a comparable-rated MMC. However, operating in this mode is not practical for a real system because there is no mechanism by which energy can be balanced between valves (energy balancing between the six valves of an MMC is a very important aspect of the design and one that has a large effect on the design of its control system).

In order for energy balancing between valves to be possible, there needs to be some "overlap" between the closing times of the director switches in the upper and lower valves of each phase. The presence of such overlap means that the number of submodules required per valve increases to more than 50% of that of a comparable MMC. For this reason, initial development work on the AAC was concentrated on relatively short overlap periods of up to 30°.

The AAC, in common with the Full-Bridge MMC, is able to suppress DC terminal-to-terminal faults electronically (and very quickly – microseconds for the IGBTs to be blocked and a few milliseconds for current to be driven to zero) without opening any switchgear. However, the AAC has significantly better losses than the Full-bridge MMC and is more versatile because the presence of the director switches allows the Full-Bridge cells to be isolated from one or other DC terminal, allowing several distinct STATCOM operating modes to be used transiently during DC line faults [3].

The AAC, like its MMC cousin, gives near perfect waveform quality on the AC side. However, the short-overlap version of the AAC does not give perfect waveform quality on the DC side: there is a residual 6-pulse harmonic current injected onto the DC network, which requires filtering.

Later [4] it was realised that by extending the overlap period to 60° (i.e. ±30° either side of the voltage zero crossing point), the operation of the circuit is fundamentally changed. In this "Extended Overlap" mode (EO-AAC) there are always at least two phases capable of conducting the DC current. This gives an additional degree of freedom to the design of the controller and means that it is possible to null the DC-side harmonic currents that are present in the short-overlap mode, thus achieving AC and DC waveform qualities comparable with the MMC while still giving a useful reduction in the number of submodules and physical footprint compared with an MMC.

It has been shown [4] that, for a given submodule capacitor ripple voltage, the total stored energy requirement of the AAC is dramatically lower than that of the MMC, shown on Fig. 6.

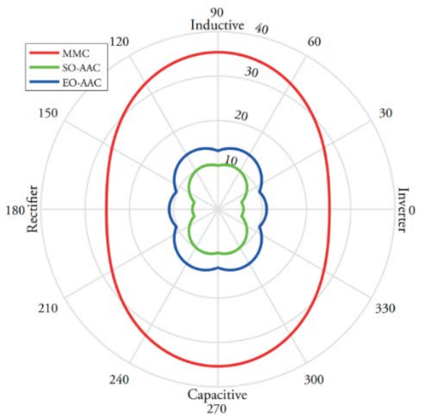

Fig. 6: Stored energy requirement for MMC versus AAC, in kilojoules per megawatt of rating.

The AAC in both short- and extended-overlap modes has been tested on small-scale demonstrators at the University of Nottingham and Imperial College London, both in the UK. Its main expected application is for multi-terminal DC networks where its inherent DC fault-blocking capability and significantly lower power losses than a Full-Bridge MMC would be of greatest benefit.

SERIES BRIDGE CONVERTER (SBC)

While the AAC appears and behaves very much like a variant of the MMC, another alternative converter topology, the "Series Bridge Converter" (SBC) behaves in a fundamentally different way.

The SBC was inspired by the method of operation of a single-phase "H-bridge" converter, one of the simplest and most widely used of all power electronic converters.

<u>Basic Series Bridge Converter topology</u>

In a standard H-bridge converter, the DC capacitor provides a steady voltage source which is then "unfolded" to produce a square-wave voltage on the AC side, as illustrated on Fig. 7. Normally, it is considered desirable for the ripple content of the DC link voltage to be as low as possible, since any ripple voltage present is "unfolded" onto the AC side as shown on the red curves on Fig. 7.

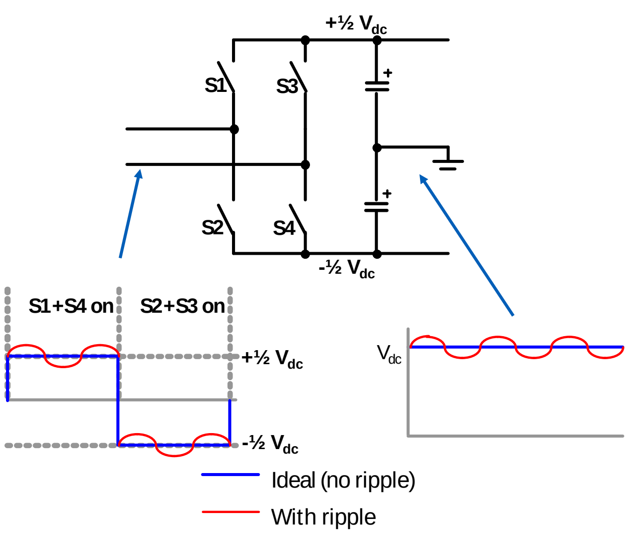

Fig. 7: H-bridge showing effects of DC ripple voltage on output voltage

However, it was realised that if the DC capacitor of Fig. 7 is replaced by a waveform generator (constructed from Half-Bridge submodules, similar to those used in the MMC topology), this effect can be turned to an advantage. By arranging for the "DC" voltage to be a rectified sinusoid (Fig. 8), the unfolding action of the H-bridge results in a perfect sinewave on the AC side. The waveform generator becomes, in effect, an "active DC capacitor".

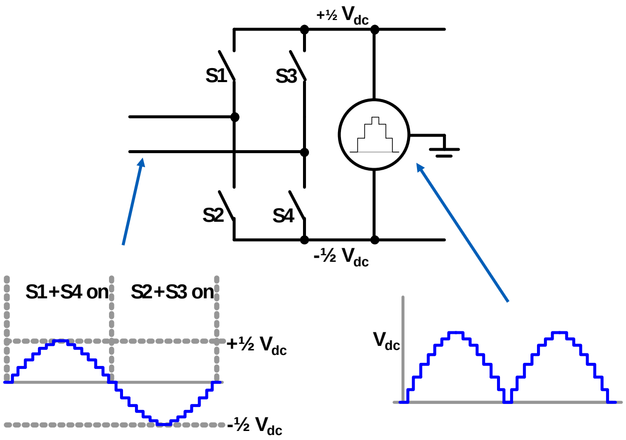

Fig. 8: Basics of operation of one phase of the SBC

For a power system application, of course three phases are required, but this can be achieved by simply connecting three of the phase modules of Fig. 8 in series on the DC side, as shown on Fig. 9.

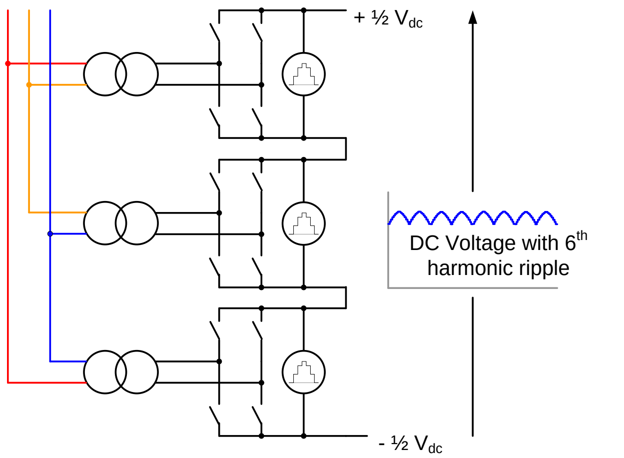

Fig. 9: Basic three-phase SBC

One of the notable advantages of this topology is that the total voltage rating of the Half-Bridge submodules (waveshaping circuits) is dramatically lower than in the MMC. In the MMC, six valves are needed, each required to produce a peak voltage equal to the DC terminal-to-terminal voltage. In the SBC, only three valves are required, each required to produce a voltage of half the DC terminal-to-terminal voltage. Hence, only one quarter of the total voltage rating is needed.

Moreover, since the waveshaping circuits are outside the main current path, their DC capacitors can be much smaller than in an MMC. Thus, not only are fewer submodules needed, those submodules are smaller. The

SBC topology therefore results in an impressive reduction of footprint, which could be very important for offshore or inner-city applications.

The basic three-phase SBC shown on Fig. 9 gives excellent voltage and current waveform quality on the AC side but results in a significant 6-pulse DC voltage ripple, comparable to what would be obtained from a 6-pulse diode rectifier.

In an overhead line application, such a level of DC voltage ripple would generally not be acceptable because of the risk of interference with telephone lines, and harmonic filtering would need to be added in such cases. However, in an HVDC system involving only cable transmission, the cable itself (as noted above) acts as a good high-pass filter as noted already, and a moderate level of voltage ripple may well be acceptable from the perspective of interference to external systems, the only constraint being the ability of the cable itself to withstand such a ripple voltage without degradation.

The SBC topology could, of course, be extended to a 12-pulse arrangement which would give a similar level of voltage ripple to that which has been accepted for decades on LCC HVDC schemes. However, because of other shortcomings of the basic SBC topology of Fig. 9, further research work has led to an improvement allowing perfect harmonic cancellation.

SBC with Series Full-bridge cells

One of the disadvantages of the topology shown in Fig. 9 is that the AC and DC-side voltages are not easy to decouple. Such decoupling is necessary so that reactive power can be controlled, otherwise the magnitude of AC voltage (the parameter that must be controlled if reactive power is to be varied) is determined from the DC voltage.

The solution to this problem is to add a small number of Full-Bridge submodules in the connection between the waveshaping circuit and the H-bridge, as shown on Fig. 10.

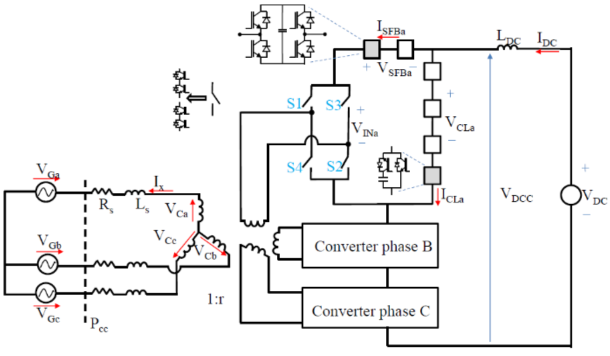

Fig. 10: SBC with Series Full-bridge cells added

Adding only a small number of Full-Bridge cells allows the AC voltage to be raised or lowered enough with respect to nominal to allow reactive power to be controlled. A relative voltage rating of about 10% (compared to the rating of the Half-Bridge waveshaping cells) is sufficient to achieve this. However, by adding a slightly larger (but still small) number of Full-Bridge cells (with a relative voltage rating of about 30%), not only can reactive power be compensated fully, but the Full-Bridge cells can act as a series active filter, completely removing the DC voltage ripple. Figs 11 and 12 illustrate the idealised voltage waveforms for a 20 MW demonstrator installation using active filtering.

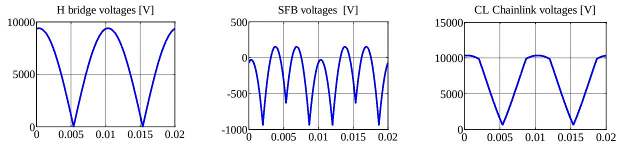

Fig. 11: Left to right: DC-side input voltage to H-bridge, voltage across Series Full-Bridge cells, voltage across waveshaping circuit.

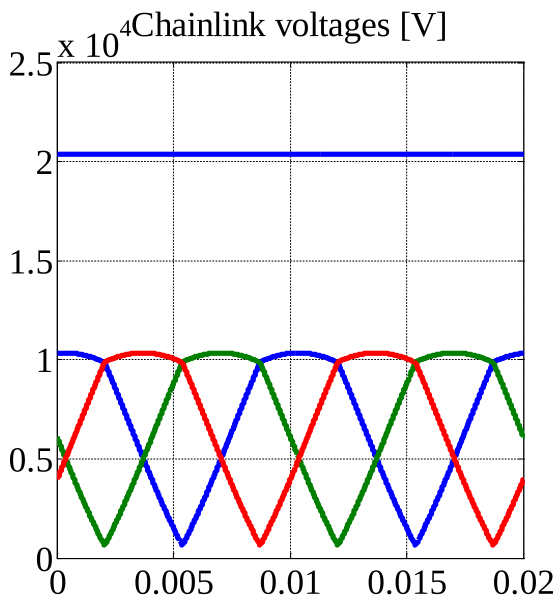

Fig. 12: DC voltage (top) and voltages of the three waveshaping circuits

Unlike the Half-Bridge waveshaping cells, the Full-Bridge cells are in the main current path and need to be dimensioned accordingly. Nevertheless, a more cost-effective solution can still be achieved if the number of Series Full Bridge cells is reduced (for example, to only the number needed for reactive power control). There is therefore a motivation to try and optimize better the complete (cable+converter) system, using the inherent ripple voltage capability of the cable.

Further refinements of the SBC are possible, for example to include a small number of inverse-series IGBTs in the arms of the H-bridge, which allows the converter to block DC-side faults like the AAC or Full-Bridge MMC.

COORDINATION WITH EXTRUDED CABLES

Line-Commutated HVDC converters have been successfully applied with Mass-Impregnated DC cables for decades, usually without any DC harmonic filters. The Mass-Impregnated DC cables have shown themselves well able to withstand the (relatively small) ripple voltage applied to the cable by the converter.

However, with Voltage Sourced Converters and extruded DC cables, an expectation has developed within the industry that there is negligible ripple voltage – mainly because the VSC topologies in use today produce little or no ripple voltage (depending on the modulation strategy adopted).

However, the time has come to re-examine some of the assumptions of the last 20 years. Although VSC-HVDC has found a niche in the importing of offshore wind power to the mainland, with some 10 DC-connected offshore wind systems built or under construction in Germany, this offshore market sector has not taken off as quickly as might have been expected because of the very high cost of building an HVDC station on a platform in the sea. This high cost is dominated by the cost of the platform topside. The topside structure is many times more expensive than the converter itself, but is influenced very much by the physical size of the converter. As noted above, Modular Multilevel Converters are bulky, so a well-optimised converter for offshore wind needs to be substantially more compact than an MMC.

One manufacturer [7] is proposing the use of Diode Rectifier Units (DRU) as a cost-effective means of importing power to the mainland. While DRUs are undoubtedly smaller and simpler than MMCs, they require a special hybrid cable containing two DC conductors and a medium-voltage AC “umbilical” cable. Moreover, being a type of LCC, harmonic performance is poor, the DC cables will be subjected to voltage ripple and since a diode rectifier is a completely passive system, this approach loses much of the flexibility that is present with a VSC – for example, the ability to use the VSC as a reference signal for the wind turbines to lock onto.

A better alternative is to continue using a VSC, but make it a more compact VSC. The SBC does this. The footprint occupied by the converter is about half that of an MMC of the same rating, and this will lead to dramatic reductions in the cost of the topside.

It is possible to design the SBC such that both the DC and AC waveforms are of excellent quality (like an MMC) but a more compact and cost-effective solution can be achieved by using fewer Series Full-Bridge cells (sufficient only to compensate reactive power) and tolerating the resulting voltage ripple on the DC cable.

Today there is very little published information or understanding of the level of voltage ripple that an extruded DC cable can actually tolerate. In part this is because the physical mechanisms involved are not too well understood, but a variety of techniques are now available to probe the internal space charge distribution of the cable while it is running [8]. Further research work in these areas is strongly recommended.

In addition to consideration of steady-state effects such as DC voltage ripple, proper consideration must also be given to the transient stresses to which a cable may be subjected in operation, for example as a result of a single-phase fault on one of the connected AC systems.

CONCLUSIONS

The Modular Multi-level Converter (MMC) is well-established as the most popular type of VSC for HVDC transmission. It gives excellent AC and DC waveform quality and low losses, but its large physical size is a drawback in some applications, particularly for offshore wind.

Several other converter topologies are also possible, offering the same advantages as the MMC but with smaller footprint. These include the Alternate Arm Converter (AAC), which also has additional capabilities for DC fault clearing, and Series Bridge Converter (SBC). Both of these can be designed to have equivalent harmonic performance to the MMC, and the SBC in particular has dramatically smaller footprint. However, even more cost-effective solutions can be achieved if the DC voltage waveform quality can be compromised. For submarine cable applications there is no technical need to limit DC-side harmonics, other than the ripple capability of the cable itself. For extruded DC cables the ripple capability is poorly understood today, and further research work is strongly recommended to understand better the amount of ripple the cable can actually tolerate. This will allow a better overall optimization of the (cable+converter) system, which in turn will stimulate the far-offshore-wind generation and transmission market.

REFERENCES

[1] A. Lesnicar and R. Marquardt, 2003, “An innovative modular multilevel converter topology suitable for a wide power range”, IEEE Power Tech Conference, Bologna, vol. 3, Jun. 2003.

[2] C.C.Davidson and D.R.Trainer, 2010, “Innovative Concepts for hybrid multi-level converters for HVDC power transmission”, IET 9th International Conference on AC and DC Power Transmission, London.

[3] R.Feldman et al, 2013, “DC fault ride-through capability and STATCOM operation of a HVDC hybrid voltage source converter”, IET Gener. Transm. Distrib., 2014, Vol. 8, Iss. 1, pp. 114–120.

[4] M.M.C. Merlin et al, 2017, “The Extended Overlap-Alternate Arm Converter: A Voltage Source Converter with DC Fault Ride-Through Capability and a Compact Design”, IEEE Transactions on power electronics, accepted for publication 2017.

[5] R. Feldman et al., "A Hybrid Modular Multilevel Voltage Source Converter for HVDC Power Transmission," Industry Applications, IEEE Transactions on, vol. 49, pp. 1577-1588, 2013.

[6] E.Amankwah et al, 2016, “The Series Bridge Converter (SBC): A Hybrid Modular Multilevel Converter for HVDC Applications”, EPE-ECCE conference, 2016.

[7] T.Hammer et al, 2016, “Diode-Rectifier HVDC link to onshore power systems: Dynamic performance of wind turbine generators and Reliability of liquid immersed HVDC Diode Rectifier Units”, CIGRÉ Session 2016, Paris.

[8] A.Tzimas et al, 2017, “Extruded DC cables experience during a VSC ageing programme with online monitoring techniques”, INSUCON 2017.

GLOSSARY

HVDC: High-Voltage Direct Current
VSC: Voltage-Sourced Converter
LCC: Line-Commutated Converter
MMC: Modular Multilevel Converter
AAC: Alternate Arm Converter
SO-AAC: Short-Overlap AAC
EO-AAC: Extended Overlap AAC
SBC: Series-Bridge Converter
SFB: Series Full-Bridge