HVDC Transmission using Modular Multi-Level Converter for Offshore Wind Farms

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Abstract- *In recent technology improvement, Modular multi-level converters are in high raise with better results and applications in HVDC transmission systems. It has a very easy adaptation to the voltage conversion from AC to DC with extension capability with increase in levels. In this paper we introduce a Modular Multi-Level Converter (MMC) with different level comparison converting three phase AC to DC for transmitting wind energy generated at offshore wind farm. High voltage three phase AC is converted to high voltage DC for HVDC transmission with reduced ripple in accordance with number of levels. Output of five level and nine level MMC is compared and both are simulated in Matlab/Simulink along with offshore wind farm transmission network.*

Keywords- Offshore wind farm, HVDC, Modular multi-level converters (MMC), Insulated-Gate Bipolar Transistor (IGBT) sub-module, Pulse Width Modulation (PWM)

I. INTRODUCTION

Wind energy converting systems generating electricity are subject to a growing interest as they render a secure, clean and competitive option for conventional sources of energy. Most European countries have plans for increasing the generation of electricity by wind energy. However, wind farms occupy a large space compared to conventional power plants and create noise which is major concern. Therefore, planning the wind farms offshore is the best option, even gaining advantage over onshore wind systems as with higher annual wind speeds offshore a more and more energy yield is obtained. Countries like Germany, the Netherlands, United Kingdom, Denmark and Sweden are currently operating offshore wind farms or have offshore wind farm projects in development.

The trend for offshore wind farms to move further offshore, combined with the falling cost of power electronics has resulted in an increase in the number of wind farms using HVDC systems for power transmission to shore [1], [2]. The HVDC converters in use today however, are not optimized for the offshore wind industry, offering little in terms of system redundancy and accounting for roughly 11% of their capital costs [3], [4].

Recently, Marquardt and Lesnicar have proposed a new converter topology referred to as the 'modular multi-level converter' for the VSC converter [5]. In the MMC, several elementary switching sub-modules are stacked together to attain the required dc operating voltage. Unlike other HV Voltage Source Converter (VSC) topologies, the MMC avoids the difficulty of connecting semiconductor switches in series. The voltage rating can be scaled by simply adding additional sub-modules to the stack. Thus, it becomes easier to construct VSCs with very high power and voltage ratings. The MMC arrangement additionally has considerably lower switching losses. In previously proposed multi-level topologies such as neutral point clamped or flying capacitor converters, only a limited number of levels, usually 3 or 5, can be practically realized [6]. The MMC on the other hand, typically uses a hundred or more levels and creates an essentially sinusoidal ac waveform without the need for any additional filtering. Moreover, the balancing of capacitor voltages in an MMC is easier than in previous multilevel topologies [7]. It is also claimed that in comparison with two-level VSC topologies, with the MMC, the probability of dc bus short circuits is reduced, as is the magnitude of the short circuit current [8].

Therefore, the MMC is considered to be a highly attractive candidate in high voltage and high power transmission applications. The first application of this technology was for the ±200 kV, 400 MW Trans Bay HVDC cable project in California [8].

Compact converter topologies with high power capabilities are good candidates for HVDC applications. Multi-level converters have higher voltage quality compared with two or three level converters that greatly eliminate the need for filtering. Among multi-level converters, modular multi-level converter (MMC) is a relatively new and promising topology for high voltage applications and it is the only multilevel converter commercially available for HVDC applications. MMC is a scalable voltage source converter topology that uses identical modules. The modules are switched at different points of time and the effective switching frequency of the converter is high which results in low harmonic distortion.

The aim of this paper is to develop a suitable model to represent an offshore power transmission network, to validate the power transmission line model. Design a complete modular multilevel converter based HVDC system using IGBT with body diode. Propose a new MMC configuration to improve harmonic performance and to incorporate minimal Total Harmonic Distortion (THD) modulation technique with the proposed MMC configuration to obtain a better output voltage quality. To this end, the proposed hybrid HVDC transformer modelling in Matlab Simulink using configurations of the MMC topology.

II. SYSTEM OVERVIEW

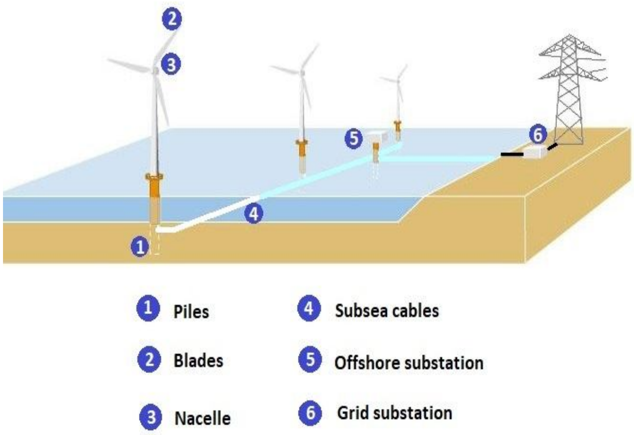

Fig. 1 Simplified version of an offshore wind farm

The electrical energy generated at an offshore wind farm needs to be transported to a connection point at an onshore grid. Generally, AC is used for production and transmission by the wind farm as well as the onshore grid. Cables or wires are the possible solutions for the transportation of electricity. Overhead transmission lines are not considered in this study as the reasonable span between masts is an average of 700 to 1200m, resulting in the need of several offshore structures, which are shown in Fig. 1.

Modular multi-level converters are the replacement for the conventional voltage source converters connected in series for voltage amplification. The modular multi-level converter comprises of several modules connected in series. For better results and efficiency, we consider a half-bridge converter module with only two switches in each module. These modules are connected in series with the number of levels denoted by a number of modules connected in series. The formula for the number of levels is given as 2n+1, where n is the number of modules. A simple model of multiple module modular multi-level converter is seen in Fig. 2.

As it can be seen that each module is connected in series with a submodule capacitor connected on the DC side of each converter with equal capacity for balanced voltage. The both IGBTs (Insulated Gate Bipolar Transistor) in the same leg operate complimentarily with an anti-parallel diode connected to the IGBT. The anti-parallel diode is connected to IGBT for freewheeling operation for an inductive load to conduct during switch OFF state of IGBT. If the diode is not connected to IGBT sudden ceasing of current occurs, generating high peak voltages at the AC side and DC side of the converter.

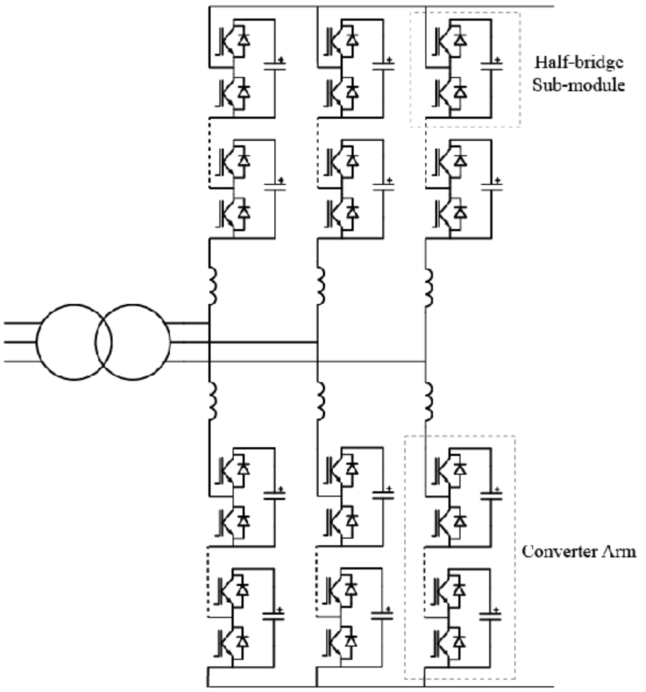

Fig. 2 Three-phase half bridge modular multi-level converter

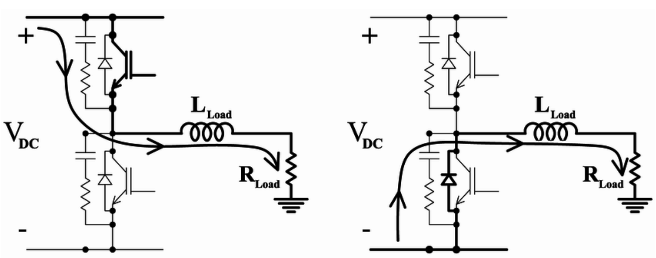

Fig. 3 Freewheeling of the anti-parallel diode of IGBT for RL load

During the upper switching conduction state, the submodule capacitor is inserted inside the converter and it is charged with the input voltage, as shown in Fig. 3. And when the lower switch switches ON the capacitor charges or discharged depending upon the flow of current through the submodule capacitor. There are four switching states for each module comprising of two IGBTs, which is given in Table I.

Table I
Switching states for a sub-module

Switching state	S1 Positive half cycle	S2 Negative half cycle	D1 Negative half cycle	D2 Positive half cycle	Voltage across submodule capacitor
1	ON	OFF	OFF	OFF	V_{cap}
2	OFF	ON	OFF	OFF	0
3	OFF	OFF	ON	OFF	V_{cap}
4	OFF	OFF	OFF	ON	0

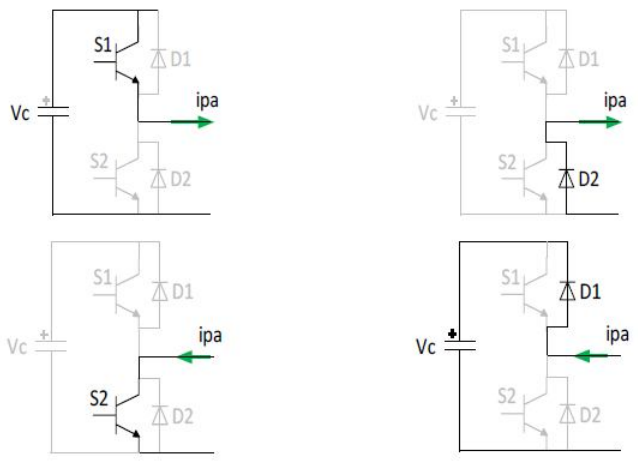

Fig. 4 Switching states of each half bridge module

The module is divided into two regions, upper arm, and lower arm. An upper arm is considered to be S1 and D1 with the lower arm as S2 and D2, as shown in Fig. 4. Considering a single phase operation, the control structure of the modular multi-level converter has to maintain the capacitor voltage with a specific voltage amplitude. The voltage of each capacitor connected to each half bridge module has to be the same to avoid circulating currents. The active power and reactive power transfers need to be tuned by adjusting the amplitude and phase of the reference sinusoidal waveform for the generation of pulses for the power electronic devices.

III. SIMULATION MODELLING OF MODULAR MULTI-LEVEL CONVERTER

In order to analyse the performance of modular multi-level converter the modelling is done in MATLAB software R 2016a (9.0.0.341360) version with updated toolbox. The model is run for a specific simulation time with outputs shown in graph with respect to time. A comparison of voltage regulation and amplitude are taken from five level modular multi-level converter and nine level modular multi-level converter. At first considering a three phase five-level modular multi-level converter the MATLAB Simulink design.

For convenience the converter is divided as upper region and lower region. The upper region consists of two power electronic switches in each leg of one phase and the lower region also consists of two power electronic switches (IGBTs) in each leg of one phase.

A three phase programmable source is taken from Library browser – Simscape – Sim Power systems – Specialized technology – Electrical sources. The value of the source is set to (440 V phase to phase) a lower voltage level at first to check the performance of the five-level converter.
The source has an internal impedance of 0.1 Ω and 1mH attached from a three phase RLC branch block taken from Library browser – Simscape – SimPowersystems – Specialized technology – elements.

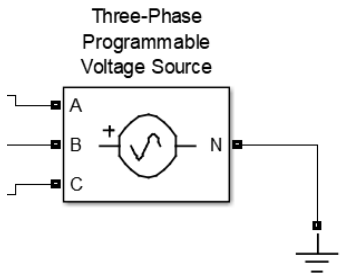

Fig. 5 Three phase programmable source block

After the internal impedance block the phase line split into two branches of upper region and lower region. Both the upper region line and lower region line has a current harmonic filter inductor of 5mH which is single phase RLC branch. In the half bridge the DC side capacitor is also modelled from the single phase RLC branch block with the branch type changed to C and the value is set to 10uF.

The half bridge with two IGBTs and anti-parallel diode are connected in series are found in Library browser – Simscape – SimPowersystems – Specialized technology – Power electronics.

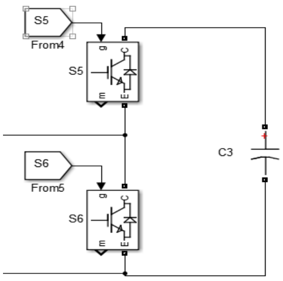

Fig. 6 Half bridge with IGBT/diode power electronic device

With all these components the modelling of the proposed topology can be done as shown in Fig. 7.

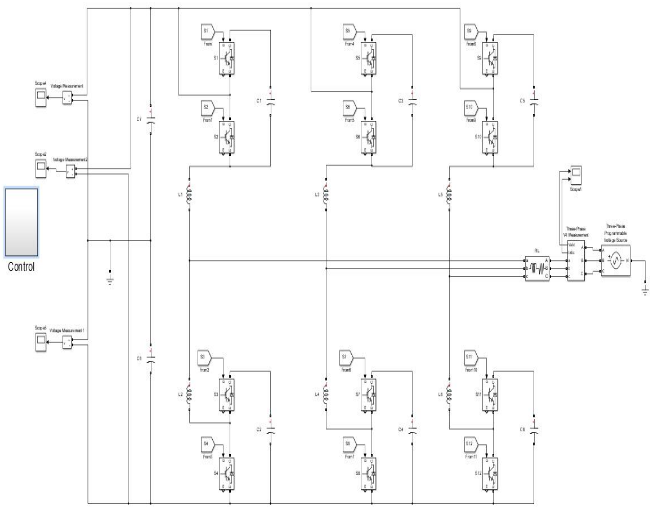

Fig. 7 MATLAB Simulink modelling of three phase five level modular multi-level converter

IV. LEVEL SHIFTED PWM CONTROL

The pulses for the IGBT are given from a central control unit where four triangular waveforms are compared to a sinusoidal waveform (level shifted phase disposition sinusoidal pulse width modulation technique) generating pulses for all the four IGBT/diode switches. The internal modelling of control unit is shown below as in Fig. 8.

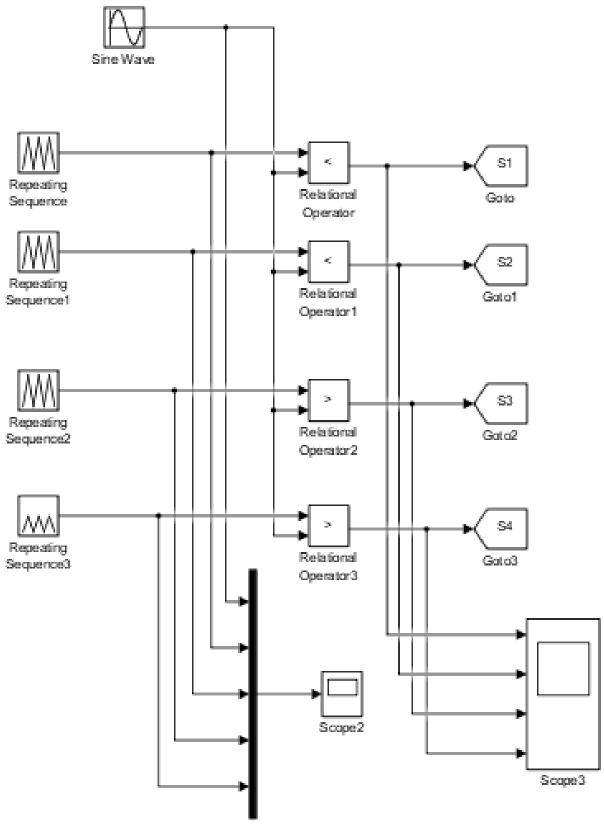

Fig. 8 Pulse generation using level shifted PD modulation technique

The upper two relational operators compare the positive side triangular waveforms with sinusoidal wave and generated pulses for S1 and S2. The lower two relational operators compare the negative side triangular waveforms with sinusoidal waveforms generating pulse for S3 and S4. The comparison and pulses for the four switches of phase A is shown below in Fig. 9.

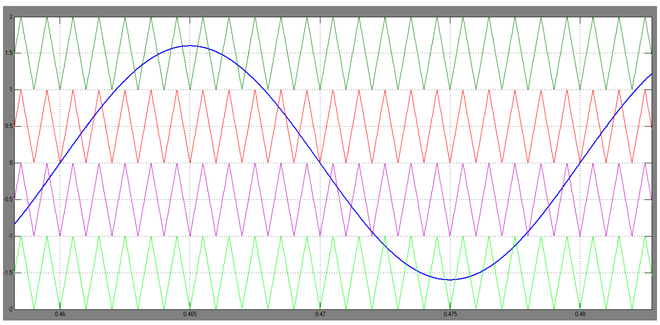

Fig. 9 Waveform comparison of level shifted PWM for five-level MMC

When the above pulses are fed to the five-level converter the output DC voltage across the converter is recorded and a graph is generated with respect to time, as shown in Fig. 10.

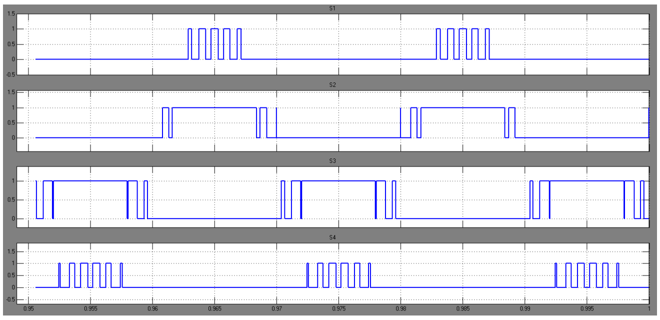

Fig. 10 Pulses for all the four switches of Phase A

The same analysis is carried out on nine level converter with total eight half bridges in each phase. Four in upper region and four in lower region for the same input voltage of 440Vrms and 50Hz. The filter and source impedance values are set as same as five-level converter. The Fig. 11 below is the Simulink modelling of nine-level converter.

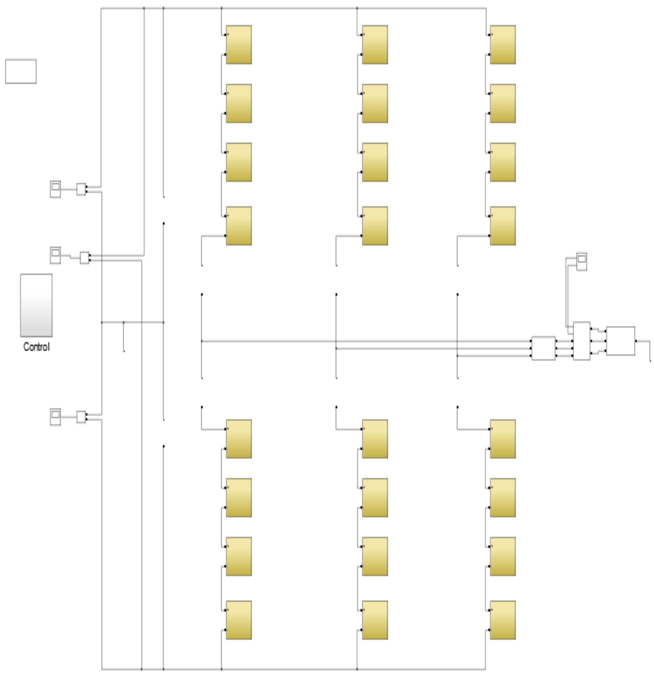

Fig. 11 Half bridge nine-level converter

For eight bridges eight triangular waveforms on upper region and eight triangular waveforms in the lower region are taken and compared to a single sinusoidal wave generating pulses for all the 16 power electronic switches.

V. RESULTS

When the pulses are fed to the five-level converter the output DC voltage across the converter is recorded, as shown in Fig. 12.

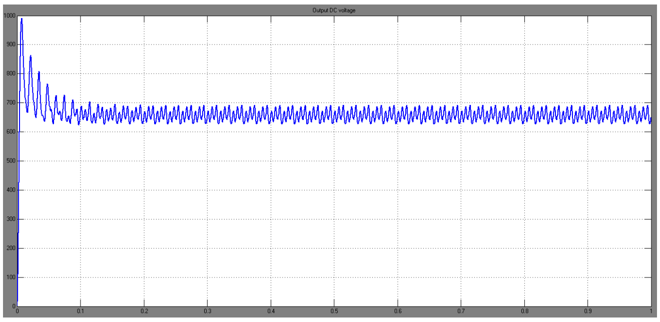

Fig. 12 Output DC voltage of five level converter

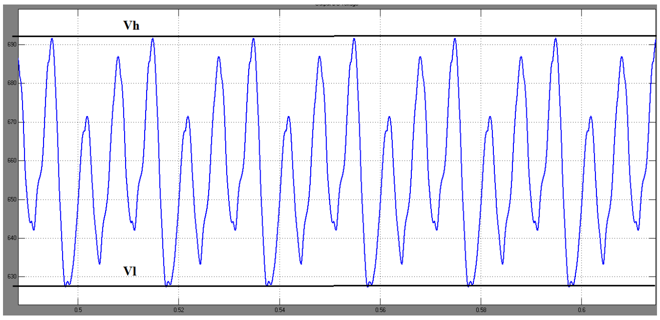

Fig. 13 Limit values for output DC voltage for five-level converter

The DC ripple percentage can be calculated as given by eq. (1),

$$\% R = \frac{V_h - V_l}{V_h} \times 100 \qquad (1)$$

Therefore,

$$\%R = (690-630)/690 \times 100 = 8.69\%$$

Thus, the ripple factor for a modular five-level converter is high at 8.69%. The same analysis is carried out on nine level converter with total eight half bridges in each phase. The output DC voltage of the nine-level converter measured is shown below in Fig. 14.

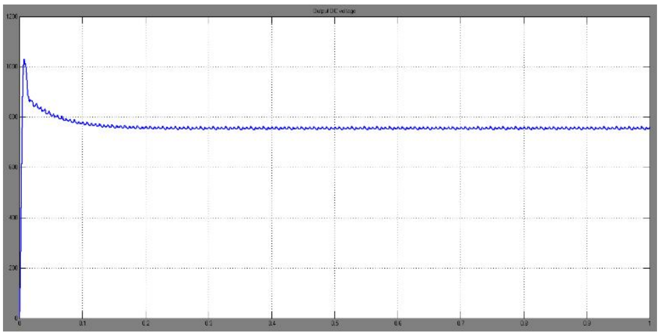

Fig. 14 Output DC voltage of nine level converter

Therefore,
%R=(763-750)/763×100=1.7%

It can be compared that the ripple of the nine level converter us much more less than the five level converter and also there is an improvement in the output voltage amplitude.

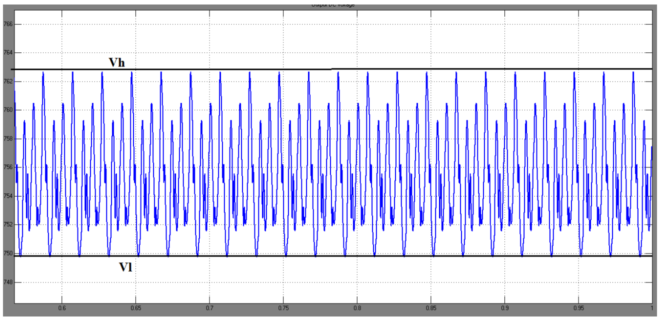

Fig. 15 Limit values for output DC voltage for nine-level converter

Table II
Comparison between five-level and nine-level converter outputs

Number of levels of MMC	Output voltage (V)	THD
5 Level	690	8.69 %
9 Level	763	1.7 %

VI.DISCUSSION AND CONCLUSION

The HVDC transmission is a good solution for connecting offshore wind farms to the mainland. The results have proved the technical feasibility of the connection of an off-shore wind farm by means of a IGBT based MMC-HVDC link with an onshore grid.

With the above results comparison from the graphs and value calculations it is clear that with the increase in number of levels in the modular multi-level converter the voltage amplitude increases and ripple decreases. The converter will be more balanced with phase disposition technique with no switch failures. Higher voltage beyond 1000kV can also be converted to HVDC and transmit to longer distances. In the five-level modular multi-level converter the output voltage of the converter has a ripple of 8.69% which is more than IEEE standard level (5%). The ripple in the DC voltage is reduced to a very low value of 1.7% when a nine-level modular multi-level converter is used with eight modules in each phase. There is also an improvement in the voltage amplitude from 690V to 763V which is a rise of 10%. The same rise can be noted for a 1500kV HVDC line which can be increase to a value of 1650kV when an eleven level modular multi-level converter is used.

MMC with half-bridge sub-modules has minimum number of devices among multilevel converters commercially used for HVDC applications but the control system is more complex than two or three level converters hence improving the design and control of MMC without making the system more complicated is very important. MMC uses several sub-modules for high power applications such as HVDC.

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