

Analysis of HVDC Converter Topologies

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ABSTRACT

This paper represents a review of the evolution in the field of converters for HVDC applications. The different converter topologies starting from Current Source Converter (CSC) or Line Commutated Converter (LCC) up to recent advanced or enhanced Alternate arm Modular Multilevel Converter (AAMMC) with their advantages and drawbacks have reviewed. The Modular Multilevel Converter (MMC) and Alternate Arm Modular Multilevel Converter (AAMMC) topologies are presented with their features such as hybrid combination with reduced number of devices, less losses, DC fault blocking capability, etc. which are most effective and expected features for HVDC applications.

Keywords: Line Commutated Converter (LCC), Voltage Source Converter (VSC), Neutral Point Clamped (NPC) converter, Modular Multilevel Converter (MMC), Alternate Arm Modular Multilevel Converter (AAMMC).

I. INTRODUCTION

The current situation of the power system in case of electricity generation, transmission, energy demand and the control systems are changing rapidly. The depletion of fossil fuels, coal mines leads to more attention on the use of renewable energy sources. Thus the integration of such renewable energy sources to grid can be possible with the help of different types of power electronics converters. The power electronics converters can be designed and implemented as per applications such as HVDC converters, HVAC converters, motor drives etc. The new appearance of designed converter has to capable to operate at the different operating conditions such as normal condition as well as fault condition and drive the all needed power for the conversion. Before advancement of semiconductor devices and microelectronics technologies, the simple power electronics converters have gained more prominence for the industrial, commercial, control systems and information technology applications [1][2]. Since

the last two decades the application of power electronics converters to the power system have gained more importance as power compensator, AC-DC or DC- AC converters, filters and controllers etc [1]. A continuous development in the power electronics converters for high voltage applications still goes on.

HVDC is an economic and reliable way of transmitting bulk power over long distance with two unsynchronized interconnected AC transmission networks which may be operate at different frequencies [3]. The HVDC converter stations generally employed with line commutated converters with thyristor switches [2], [3], [4]. In recent converter technologies the main importance has given to IGBTs and GTOs for system design.

The main purpose of this paper is to present a review of evolution of different HVDC converter topologies to compare the advantages and drawbacks with their different features. Lastly the paper discuss about new advanced

AAMMC topology for HVDC applications. Obviously, this paper cannot explain the operating principle and control strategies of each converter in detail. But the cited literature should serve as references.

II. RELATED WORK

Michaël M. C. Merlin, et al. [23] has explained the newest converter topology as an alternate arm converter with DC fault blocking capability. Yushu. Zhang, et al. [7] have worked on voltage source converter for high voltage application and demonstrated the comparison between the multilevel converter and 2 level converters and conducted power loss estimation in two types of losses such as conduction loss and switching loss. C.C. Davidson and D.R. Trainer [10] have demonstrated the innovative concepts for hybrid multilevel converters for HVDC power transmission.

III. DIFFERENT MULTILEVEL CONVERTER TOPOLOGIES

A. CURRENT SOURCE CONVERTER (CSC) OR LINE COMMUTATED CONVERTER (LCC):

The current source converters are also called as the line commutated converters. The power electronics semiconductor devices operate as switches for turn ON and OFF continuously to change the current flow path. At the time of switching OFF operation the current gets blocked. This procedure is called as 'commutation' and current flows away from switch during commutation. The turn OFF operation of the switches of semiconductor devices are controlled by line so called line commutated converters or by external circuit. The thyristors switching operations may be controlled or uncontrolled.

The LCC consist of semiconductor elements which has the ability to withstand the voltage in either polarity. So the current direction remains same ultimately the power direction does not change. The

LCC has the better advantages over other Voltage Source Converters (VSCs) or Self Commutated Converters (SCC) such as low typical losses per converter (0.7%) [6], high power capability, overload capability, lower cost with higher reliability for high voltage applications. The current source converters have the black start capability, but it does not require additional components for operation and control.

It is now much mature technology for HVDC systems but it has some disadvantages such as it generates the harmonics during low frequency commutation so requires large sized AC/ DC filters which increases the total size of converter station. The reactive power control is not much effective and draws reactive power from grid during the operation. The power and current direction can be reverses by reversing the voltage polarity but which makes difficult operation for DC grid applications and requires the other reactive compensators.

B. VOLTAGE SOURCE CONVERTER (VSC) OR SELF COMMUTATED CONVERTER (SCC):

Since 1990s the thyristor based converters were replaced by IGBTs based converters with two level output also called as first generation of VSCs. The controlling of HVDC system with voltage source converter is now becoming more dominant for high power rating up to 1000MW [5]. The voltage source converters are self-commutated converters controlled by IGBTs or GTOs switching operation of semiconductor devices. The commutation process can take place by self-controlling ON/ OFF action of switches of semiconductor devices. The voltage source converters can be implemented with 2 or 3 level or multilevel converters. The VSCs have some advantages over current source converters such as much compact size of converter station due to elimination of filters, better controllability, insignificant harmonic generation and effective

active as well as reactive power control, so there is no need of any reactive power compensators. The power flow can be reversed by reversing current flow which is suitable for HVDC system. But this topology has some drawbacks over CSC or LCC such as higher cost and large typical converter losses (1.7%) per converter [6]. This technology is not much mature technology as compared to CSC in the field of HVDC.

The VSCs with two level and three level converters have generally designed for high voltage applications which gives low level steps in output voltage which may not be exactly sinusoidal waveforms. Such outputs of converters are not much effective for HVDC transmission or high voltage applications. Thus with such low level output converters the problems of high total harmonic distortion have become an undesirable issue of high voltage power system. The VSCs with two or three level converters are well suited for medium voltage applications [8]. To improve the operating voltage levels, the number of components of semiconductor devices are connected in series with AC filters to eliminate harmonics. But the main limitation of such converters is large rate of change of voltage (i. e. dv/dt) necessitates the interfacing transformer having high voltage withstand property for insulation; it should sustain high switching voltage and high frequency of operation.

C. MULTILEVEL CONVERTERS:

The rapid progress in the power electronics technology leads to maximum use for high voltage transmission and distribution systems, for the applications of high power motor drives etc. In order to obtain desired high voltage and high power having good controllability, the multilevel converters are designed for high voltage applications [15]. In such applications 2 or 3 level converters have some limitations due to switching restriction [6], [7], [9].

The different innovative techniques are applied to multilevel converters and the designs have gained more attention in few years. The different innovative techniques and different control strategies have developed and discussed [10].

The multilevel converters are represented with three different converter topologies: a) Diode Clamped multilevel converter or Neutral Point Clamped multilevel converter. b) Capacitor Clamped multilevel converter or Flying Capacitor multilevel converter.

c) Cascaded H- bridge multilevel converter.

a) Diode Clamped multilevel converter or Neutral Point Clamped multilevel converter:

The diode clamped multilevel converters are also called as neutral point clamped multilevel converters (Fig. 1).

These converters have been employed in practical use with generally 3 level converters and especially diode clamped multilevel converters. The reason behind the maximum utilization of such converters is it requires less number of capacitors with single DC source. The voltage levels vary in 3 steps of $+V_{dc}/2$, 0, $-V_{dc}/2$. The main concern of this structure is how to balance or maintain neutral point voltage at half of the voltage at DC link or input DC voltage [8]. **Advantages:**

- 1) This topology requires only one isolated DC supply for its operation.
- 2) This converter does not require large sized filters to eliminate harmonics.
- 3) It is able to regulate reactive power.

It provides high efficiency due to use of fundamental frequency for all switching devices and simple back to back power conversion system.

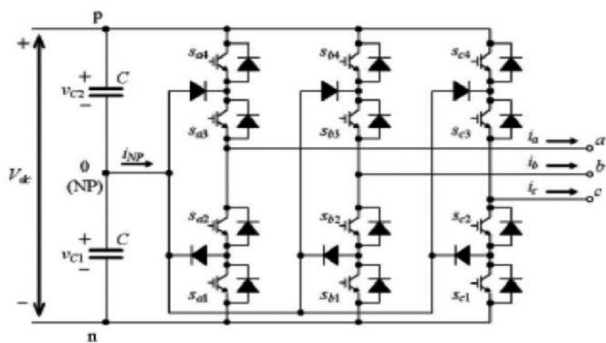


Figure 1. Diode Clamped or Neutral Point Clamped multilevel converter [16]

Disadvantages:

- 1) The converter requires the more number of diodes for increased levels and system becomes impractical.
- 2) The capacitor voltage cannot be maintained as per selected switching pattern.
- 3) The additional neutral point voltage balancing control circuit is required for converter of more than three levels.
- 4) It is difficult to control active power of individual converter levels due to capacitor imbalance.
- 5) This converter topology is not much suited for HVDC applications redundancy.

b) Capacitor Clamped or Flying Capacitor multilevel converter:

It is almost identical topology to diode clamped converter but the capacitors are clamped for sharing the voltage between the switches (Fig.2). This converter also generates similar voltage levels as diode clamped multilevel converter i. e. $(+V_{dc}/2, 0, -V_{dc}/2)$ [8].

Advantages:

- 1) This topology also operates on single DC source.
- 2) It is able to regulate both real and reactive power.
- 3) No filters are required for harmonic elimination.
- 4) The total harmonic distortion is lower at higher levels of converter

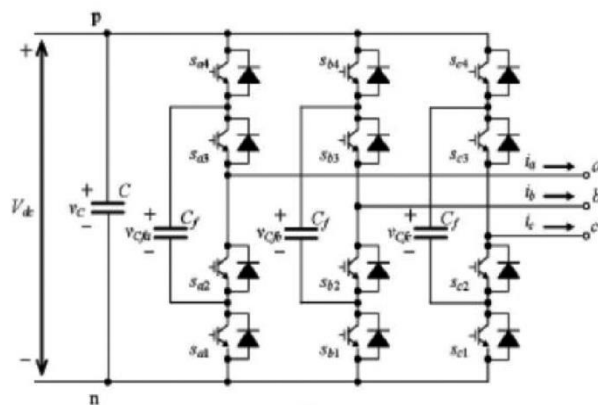


Figure 2. Capacitor Clamped or Flying Capacitor multilevel converter [16]

Disadvantages:

- 1) The number of capacitors increases for more or higher levels of converters; which increase the size and system
- 2) becomes bulky, complex control system and more expensive.
- 3) Switching losses are more due to high frequency switching operation.
- 4) The output voltage is again half of the DC link voltage or input DC voltage which is not well suited for HVDC applications

c) Cascaded H- Bridge multilevel converter:

This converter topology is employed with series connected H- Bridge cells with separated DC source (Figure 3). The each series cell can produce three level output with $+V_{dc}, 0, -V_{dc}$. By N number of cells in series connection can produce $2N+1$ level output. The isolated DC sources easily maintain the voltage sharing between switching devices [8].

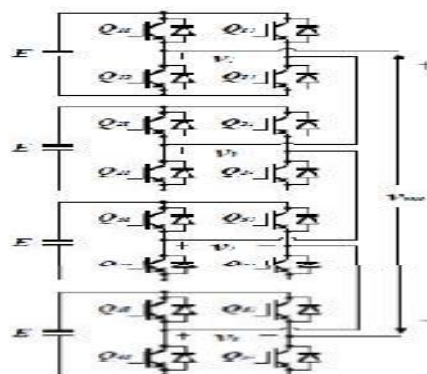


Figure 3. Cascaded H- Bridge multilevel converter [17]

Advantages:

- 1) This converter topology necessitates minimum number of devices or components per levels than neutral point clamped multilevel converter and capacitor clamped multilevel converter.
- 2) This leads to minimize the weight and cost of the converter.
- 3) No need of additional capacitors and clamping diodes.
- 4) The circuit consist the similar structured H- bridge cells connection which makes system more modular and scalable for operation and vmaintenance.

Disadvantages:

- 1) For higher level converters the more number of separate DC sources are required to supply each level which increases the complexity in the transformer connections.
- 2) The higher ripples can generate due to single phase operation of individual cells with large capacitors in each cell.

IV. MODULAR MULTILEVEL CONVERTER

In 2003, the modular multilevel converter was first proposed by Marquardt and Lesnicar and in 2010 [6], [11]; Siemens have employed a new converter design with HVDC PLUS technology. Simultaneously the HVDC Light products have been upgraded by ABB with generally similar technology in the market. The effective switching steps or levels are achieved through number of series connected sub modules. The MMC is composed of similar structured self- controllable submodules, either be two level half bridge or two level full bridge converters with capacitor across the device as an energy storage device (Fig. 4). The output waveforms appear almost sinusoidal which does not require any DC or AC filters. The HVDC system voltage level requirements determine the number of sub modules connected in series. This technology is

well suited for high voltage transmission system with recent advances in technology [18]. The typical losses per converter for MMC are less (1%) per converter as compared to two level (3%) and three level diode/ neutral point clamped converter (2.2%) [6]. Due to low voltage level at each submodule and operating at low frequency, the switching losses are less.

MMC is a prominent VSC topology well suited for many applications especially for HVDC [2], [9], [19]. The MMC has DC fault blocking capability. Thus the main advantage of MMC with two level full bridge sub modules does not require any AC/DC circuit breakers.

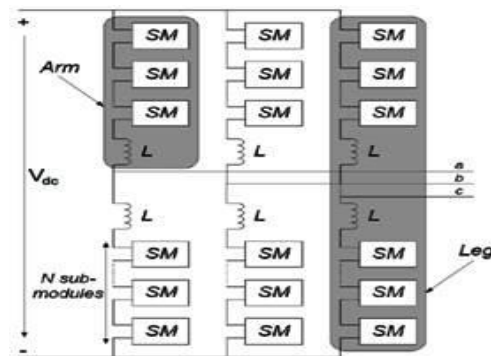


Figure 4. Modular Multilevel Converter (MMC) [13]

There are different modulation techniques to control MMC:

- 1) Conventional PWM
- 2) Phase shifted modulation technique
- 3) Level shifted modulation technique [13]
- 4) Capacitor voltage balancing scheme [14]

Advantages:

- 1) The MMC has better performance as compared to other VSC topologies.
- 2) The main problem with large steps dv/dt in the voltage levels can be reduced with multilevel small steps on AC sides. So this minimizes the transformer insulation high voltage switching requirements [2].
- 3) The MMC has the fault blocking capability which suppresses the fault current [20].

- 4) For medium voltage motor drives the MMC provides low distortion and allow efficient motor operation [12].
- 5) Use of low cost commercially available IGBTs with minimum rating reduces the cost of converters.
- 6) The MMC submodules reduce the harmonic levels which eliminate the need of large sized filters.

Disadvantages:

The complexity in the control strategies increases with high levels of converters and requires more sensors for data processing.

V. ALTERNATE ARM MODULAR MULTILEVEL CONVERTER

The technology is now moved towards a new hybrid multilevel converter known as an Alternate Arm Modular Multilevel Converter (AAMMC). It is composed of the hybrid combination of the two level converter as the director switches and modular multilevel converter as series connected H- bridge cells or submodules (Figure 5). For three phase converters the system consists of the 3 legs, 6 arms each with stack of series connected H- bridge cells which generate the multistep voltage levels. This converter is able to improve the AC voltage level than DC terminal voltage. The director switch is connected in series to determine submodule AC current conduction sequence [27]. The main features of an AAMMC are low typical losses than MMC per converter due to softswitching technique for operation and alternate conduction mode of operation of the arms, it may require less number of cells for its control and operation, less volume of the converter station etc. [21], [22], [24].

This converter has main advantage as it has DC fault blocking capability to isolate fault current [28]. This eliminates the need of AC/DC breakers

of large size and ratings [23]. The problems of high steps dv/dt can be minimized due to its ability to produce relatively fine changing voltage steps. As MMC, it is also able to produce harmonic free AC currents. Thus this converter acts as multilevel, multifunctional converter and can be reliable, modular, and scalable for HVDC applications.

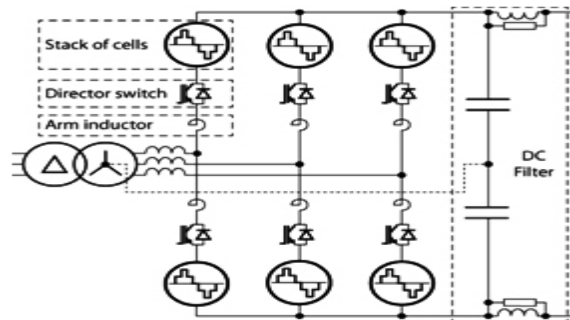


Figure 5. Alternate Arm Modular Multilevel Converter (AAMMC) structure [23]

An Enhanced Equivalent Model (EEM) of the monopole half bridge symmetrical modular multilevel converter has introduced [25], [26] to analyze the electromagnetic transients. The existing model has compared with this enhanced equivalent model and concluded that the EEM has less simulation computational time or burden and more accuracy. The EEM model has tested under various operating conditions such as its startup, AC side 3 phase to ground fault and pole to pole fault at DC side. The study results have demonstrated [25] that the current and voltage waveforms are of lower level EEM model are close to the waveforms obtained by higher level EEM of modular multilevel converter with eliminating high frequency ripples. Thus the enhanced equivalent model has great potential for protection system of HVDC system with multilevel MMCs.

Advantages:

- 1) The AAMMC is modular, scalable converter.
- 2) It has DC fault blocking capability as well as DC side fault management capability, which does not require large rated AC/DC breakers.

- 3) Due to reduced number of components ultimately the size and volume of the converter station reduces.
- 4) Almost negligible or harmonic free pure sinusoidal AC output generation.
- 5) Lower the total harmonic distortion as compared to conventional VSCs.

VI.CONCLUSION

The evolution of the different converter topologies have been presented and discussed comparatively with their advantages and disadvantages. The evolution is based on new trends in the power electronics technology. The recently developed MMC and AAMMC have been discussed with their different features. AAMMC is a newest, scalable and multifunctional converter topology for HVDC applications. The converter station with features like components, minimum size, fast response at normal as well as faulty conditions, no requirement of large rated AC/ DC breakers, negligible harmonic generation, and required pure AC output waveforms etc. are the essential factors for today's HVDC converter system. Thus it has great potential for the projects in the field of HVDC transmission.

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