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ON THE SUITABILITY OF MODULAR MULTILEVEL CONVERTER (MMC) IN HIGH VOLTAGE DIRECT CURRENT (HVDC) TRANSMISSION SYSTEM

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ABSTRACT

Transmitting bulk electrical energy over long distance by overhead transmission lines or submarine cables using high voltage direct current (HVDC) transmission system offers more flexibilities such as controllability of power flow and robustness against disturbances. Both current source converter (CSC) and voltage source converter (VSC) configurations have been considered in HVDC system. The former is used in HVDC transmission system involving stiff grid networks of higher ratings while the latter is commonly used in connecting to a weak grid. As such, special applications of HVDC such as connection between two or more weak grids and connection of wind power plants require the VSC configuration. However, in the conventional VSC configuration, the converter arm would have to be designed with large number of semiconductor switches that can block the full DC-bus voltage. However, with the evolution of modular multilevel converter (MMC) as a member of VSC family, sub-module (SM) chopper cells are used. This paper investigates the suitability of MMC in HVDC transmission system. The paper shows that the MMC configuration can generate any desired voltage levels required to synthesize a smooth output waveform, thus eliminating the need of heavy filters, has modularity in both hardware and software and generates very low harmonics.

Keywords: Modular Multilevel Converter, Voltage Source Converter, Current Source Converter, Line Commutated Converter, High Voltage Direct Current

INTRODUCTION

Both industries and academia are considering the modular multilevel converter (MMC) for high voltage applications notably high voltage direct current (HVDC) transmission system owing to its scalability capability to high voltage and power levels, reduced switching frequency, realization of redundancy, nearly sinusoidal output waveform and its ability to operate with weak grids (Patro & Shukla, 2020). The concept of HVDC system can be realized via two basic converter configurations, namely; line-commutated converter (LCC) and voltage source converter (VSC) (Kadandani, 2021a).

The LCC configuration used in HVDC system are typically constructed using thyristors. However, thyristor-based rectifiers depend on the system AC voltage for commutation, hence the name line commutated converters. They also introduce low order harmonics, as such, they require large AC filter for suppression of the low frequency harmonic components (Sánchez-Sánchez et al., 2018). The LCC technology has low switching frequency. Although LCC-based HVDC technology has the capability to control current in the DC side of the system under fault conditions (Elgamasy et al., 2020), but it also suffers some disadvantages such as the need for synchronous voltage for commutation, the need of reactive power compensation devices and the requirement of polarity change to allow reversed power flow.

The VSC configuration initially used for HVDC system are 2-level and 3-level VSCs based on IGBTs which are controllable devices, they can be turned off whenever the need arise. This is possible independently of the system AC voltage. Moreover, VSCs does not need a strong grid and are able to switch at higher frequencies. Unlike LCC technology, the VSC-based systems are self-commutated and capable of full control of active and reactive power independently (Gonzalez-Torres et al., 2020; Han et al., 2018; & Wang et al., 2019).

It is worth noting that there is limitation in the practical realization of the number of voltage and power levels using traditional 2-level and 3-level VSCs such as neutral point clamped converter or flying capacitor converter. To cater for this, the MMC technology have been proposed (Lesnicar & Marquardt, 2003a, 2003b). With the aid of MMC technology, hundreds or thousands of voltage levels can be realized with ease, thus guaranteeing a more close sinusoidal voltage waveform (Franquelo et al., 2008).

MMC is a member of VSC with additional features. The converter has the highest potential for HVDC application than other topologies of switch-mode converters. When used in HVDC system, MMC have proven to respond accurately to the dynamic of the system and other control orders in any situation without any impact on the capacitor voltage balancing (Saeedifard & Iravani, 2010).

The Modular Multilevel Converter (MMC)

The modular multilevel converter (MMC) technology was first presented by (Lesnicar & Marquardt, 2003a). MMC exhibits low harmonic distortion, high fficiency, modular design and ability to scale voltage and power to higher levels qualifying it to be a promising technology for HVDC transmission system.

Structure and Operating Principle of MMC

Figure 1 shows the schematic diagram of a three phase MMC. The structure comprises of two arms per phase-leg. The two arms designated as upper and lower comprises of a number of submodules (SMs) that are identical and a series connected inductor. Each SM has a bank of capacitor, C that is configured to a special switching arrangement. It is the switching arrangement that connects or disconnects the capacitor in series with the arm.

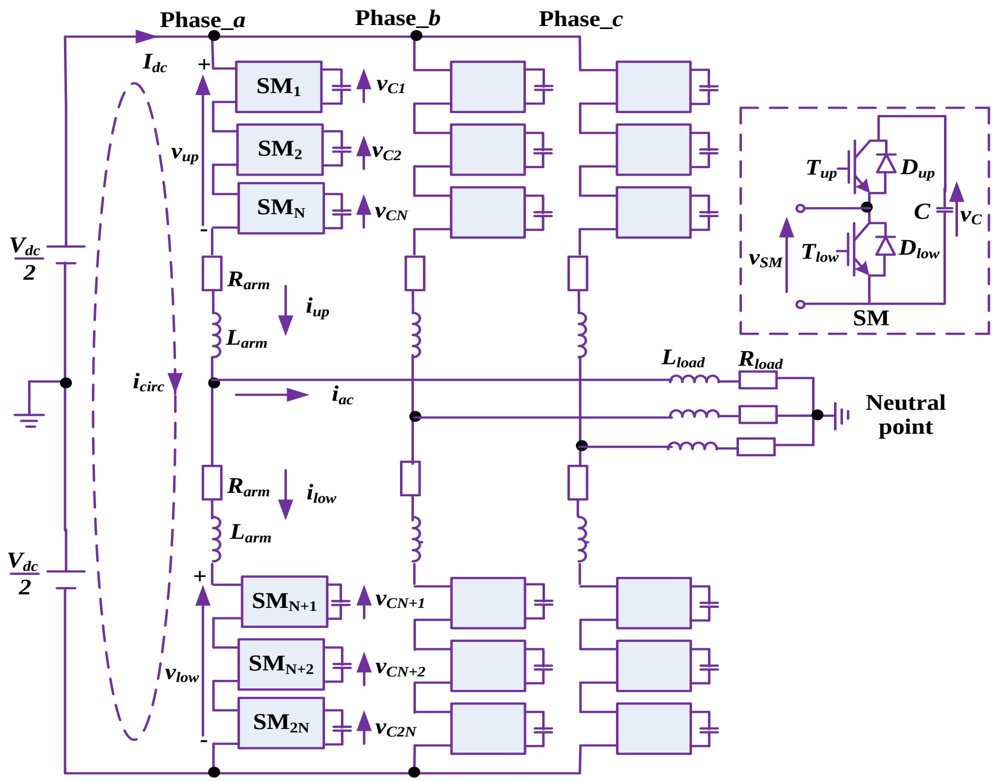

Figure 1: Schematic of a 3-Phase MMC

Capacitor Voltage Balancing Control for MMC

Capacitor voltage balancing in MMC consists of two parts, namely; arm voltage balancing control and individual sub-module (SM) capacitor voltage balancing control (Perez et al., 2015). The aim of the arm voltage balancing control is to alleviate the voltage difference that may exist between the two arms of each phase of the converter (Kadandani, Dahidah, & Ethni, 2019). The individual capacitor voltage balancing control is aimed at mitigating any difference that may exist in the individual SMs within each arm of the converter (Kadandani, Dahidah, & Ethni, 2021)

Modulation Schemes for MMC

The work presented in (Kadandani, 2021b) reviewed the modulation techniques in MMC and classified them into two types, namely; space vector based algorithms and voltage level based algorithms as depicted in Figure 2. The main purpose of the modulator is to synthesise the AC waveform by activating SMs. Each arm of the converter has its own modulator that works independently. Each modulator works in hand with voltage balancing controller in selecting and activating an SM. The modulator is then coupled to the converter control loops to generate the signals required for establishing the desired switching sequence.

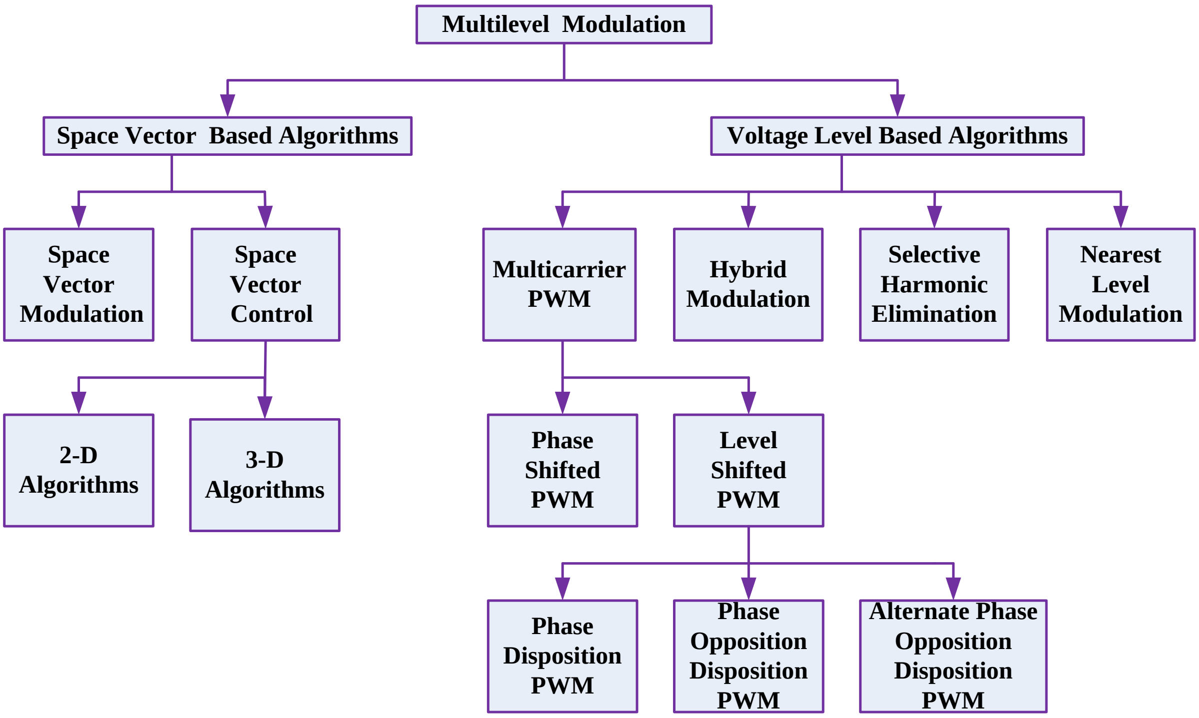

Figure 2: Modulation Techniques in Modular Multilevel Converters

An Overview of HVDC System

The concept of HVDC transmission system involves an interconnection of two or more converter stations within one or several AC power systems located at remote areas through a DC grid. It is a transmission system in the form of DC that employs power electronic based control techniques to improve the system controllability and power transfer capability. Despite extensive use of semiconductors, HVDC system is more efficient means of transmitting bulk electrical energy over long distance by overhead transmission lines or submarine cables than the high voltage alternating current (HVAC) transmission system. The HVDC system has low electromagnetic interference, low acoustic noise and high controllability. It ease the interconnection between two asynchronous power systems and it does not increase the short-circuit level on the connected AC system. Unlike HVAC system, the HVDC system has higher robustness against disturbances and higher controllability of power flow.

Line Commutated Converters Based HVDC System

Figure 3 shows the block diagram of LCC-based HVDC transmisson system using CSC configuration. In this technology, transformers are used to connect the two converters to the AC system. Provisions are made for filters on both AC and DC sides of the system to suppress low frequency harmonic components. It is worth noting that VAR compensators are provided on the AC side to provide the converters with the necessary reactive power compensation needed for proper operation of the system. Phase reactors are also provided to minimise the voltage ripple in the DC side.

LCC-based HVDC technology is generally employed in high voltage transmission between two stiff power stations over long distances that have limited dynamic requirements. In other word, the LCC-HVDC technology is applicable in systems that lacks reversed power flow, reactive power compensation capability or in systems lacking black start (Schönleber et al., 2020).

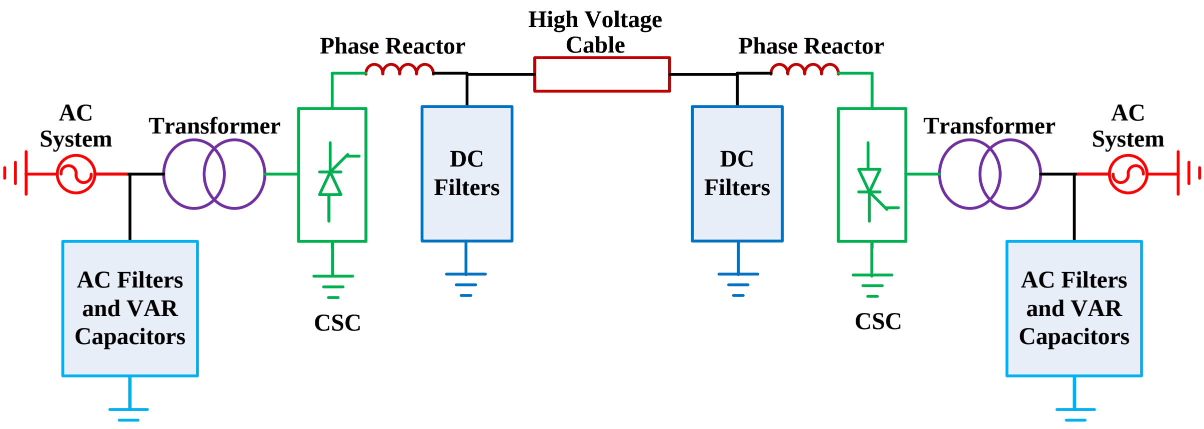

Figure 3: Schematic of LCC-Based HVDC System

Voltage Source Converters Based HVDC System

Figure 4 shows a schematic of VSC-based HVDC transmisson system. It is a two converter station being connected by DC conductors of opposite polarity. Although the DC current path changes with that of the power transfer, the voltage magnitude at the DC terminal remains the same. A DC capacitor is provided on both converter stations to filter the DC voltage. In addition, there are AC filters on both sides to suppress harmonics component from the AC system voltages. The purpose of the phase reactor is to regulate the interchange of power between the converter and the AC system and also to limit the magnitude of fault current.

VSC-HVDC technique is commonly used in special applications such as connection to a weak grid, connection between two or more weak grids and in the integration of wind power plants (Schönleber et al., 2020).

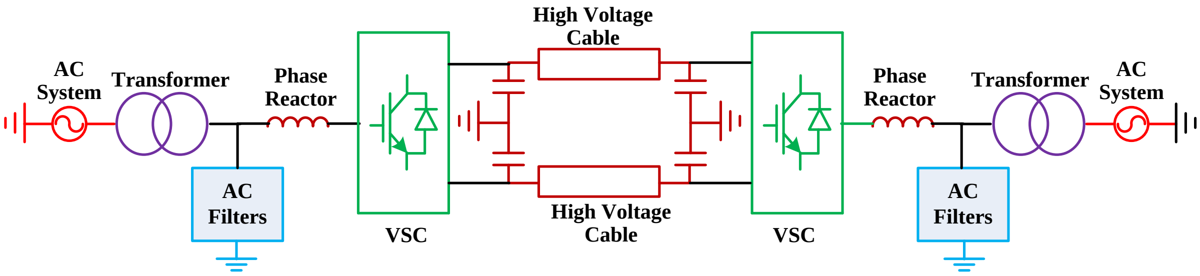

Figure 4: Schematic of VSC-Based HVDC System

Comparison Between LCC and VSC Based HVDC System

The work presented in (Kwon, Kim, & Moon, 2018; Wang et al., 2017; Xue, Zhang, & Yang, 2018; Ye et al., 2018) have outlined the advantages and disadvantages of both line commutated converter and voltage source converter configurations. Table 1 gives a concise comparison between the two configurations.

Table 1: Comparison Between LCC-Based and VSC-Based HVDC Technologies

	LCC-Based HVDC System	**VSC-Based HVDC System**
Commutation	Requires AC voltage to commutate.	Self commutated
Losses	Low	Higher
Harmonic distortion	Higher, requires large filters	Insignificant
Active and reactive power control	Consume reactive power and requires reactive power support from the AC grid.	Able to control active and reactive power independently
Ability to operate in weak grid	No, requires a stronger system	Yes, operate easily
Overload Capability	Higher due to the robustness of the thyristors used in its construction	Limited, depends on the rating of the IGBT
Dynamic response to high PWM frequency	Low	Fast
Fault ride through capability	Not capable	capable
Black start capability	Not feasible	Feasible
Need for special converter transformers;	Yes	No
Site requirements / footprint	Wide area due to reactive power compensation devices	Reduced area
Installation and commissioning	Low	Fast
Multi-terminal HVDC realization	Not easy	Easier
Reliability and efficiency	Higher	Lower

MMC-Based HVDC Transmission System

Figure 5 shows a schematic of MMC-based HVDC transmisson system. This configuration may or may not include AC filters depending on the voltage level and or the required quality of the output voltage. Due to the MMC scalability capability, the use of transformer in this type of HVDC technology become optional. Further, DC capacitors are also eliminated in this configuration due to the availability of DC capacitors in each SM chopper cell of the convrter. The MMC exhibits modularity and ease of control.

Before the evolution of MMC, conventional 2-level and 3-level VSCs were used in HVDC application in which case, an arm would have to be designed with large number of semiconductor devices. Typically, a large number of insulated-gate bipolar transistor (IGBT) are connected in series and are used to block the full DC-bus voltage. However, with the evolution of MMC, the large number of series-connected IGBTs are substituted with SM chopper cells consisting of a set of IGBTs, capacitor, and an arm inductor (Zhang et al., 2018).

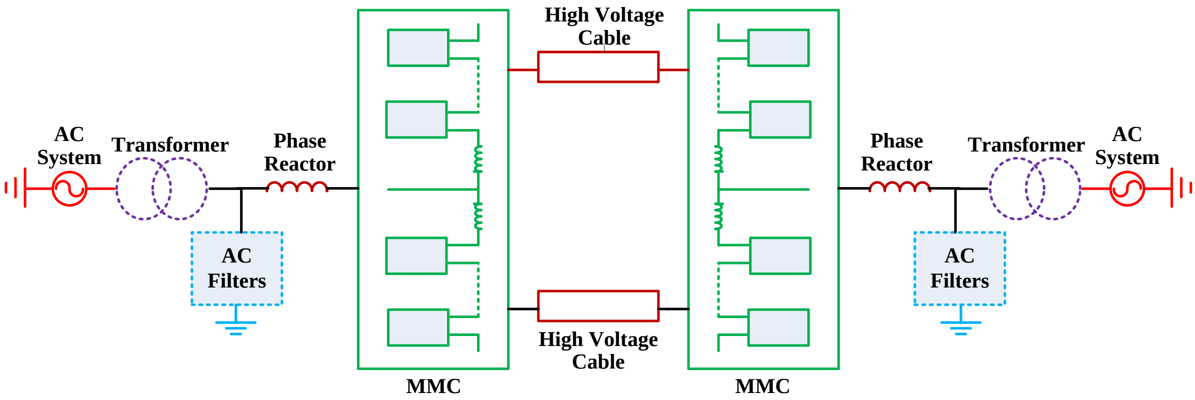

Figure 5: Schematic of MMC-Based HVDC System

It can be observed that the MMC technology in HVDC system offers the following benefits (Ansari, Liu, & Khan, 2020; Hahn, Burkhardt, & Luther, 2016; Liu & Zhao, 2021; Zhang et al., 2018);

i. The MMC technology eliminates the need of connecting series of large number of semiconductor devices required to block the full DC voltage as the case with the traditional 2-level and 3-level VSC technology,
ii. Further, the SM chopper cells in the MMC technology can generate higher voltage levels required to synthesize a smooth voltage waveform, thus eliminating the need of heavy filters,
iii. The MMC technology has a unique switching action involving certain selected IGBTs for each switching cycle unlike the traditional 2-level and 3-level VSCs which all the IGBTs in an arm have to switch simultaneously,
iv. It has minimum switching losses due to the adoption of low switching frequency,
v. High modularity in both hardware and software,
vi. Low harmonic contents,
vii. Generates output waveforms with much more closer approximation to sinusoidal waveform.

Based on the foregoing, MMC is said to be the most preferred technology for high power applications like HVDC transmission system.

CONCLUSION

The paper presented a general overview of high voltage transmission system emphasizing the superiority of HVDC over HVAC technique. The two major converter topologies, namely; LCC and VSC used in HVDC system were discussed. The paper gives a detailed comparison between LCC-based and VSC-based HVDC system. Finally, the advantages of MMC over the traditional 2-level and 3-level VSCs were outlined which qualifies the MMC configuration as the promising choice for HVDC transmission system.

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