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Modelling and control of LCL voltage source converter-based hybrid high voltage alternating current/high voltage direct current system

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ABSTRACT

Voltage source converters (VSCs) have revolutionized high voltage direct current (HVDC) transmission, offering numerous advantages such as black start capability, absence of commutation failure, and efficient control of bidirectional power flow. This study introduces a comparative analysis of advanced VSC technologies, focusing on a novel series hybrid converter incorporating an inductor-capacitor-inductor (LCL) passive circuit. This configuration is explored for its potential to enhance both high voltage alternating current (HVAC) and high voltage direct current (HVDC) side fault suppression capabilities and improve DC output voltage quality, addressing critical drawbacks of traditional VSCs. Through comprehensive simulations in MATLAB/Simulink, this research evaluates and compares three different converter topologies: the three-level neutral point clamped converter, the hybrid converter with AC side cascaded H-bridge cells, and the LCL hybrid converter. The comparison is based on key performance metrics such as DC output voltage quality, fault suppression capabilities, and system efficiency during normal and fault conditions. The study finds that the LCL hybrid converter outperforms traditional converters by significantly improving DC output voltage quality and enhancing fault suppression capabilities in HVDC systems. It effectively reduces ripple and maintains stability during faults, making it a superior choice for future HVDC converter designs and applications, offering valuable insights for advancing HVDC technology.

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1. INTRODUCTION

An efficient power transmission and distribution system is a fundamental requirement to fulfill customers with essential energy needs. For many decades electricity networks have provided the vital links between producers and consumers with great success. Power grids have been designed to serve the needs of large predominantly carbon-based generation located remotely from demand centers. However, the electricity generation landscape is faced with new challenges.

The energy sector is being challenged by limited fossil energy resources, climate change and growing energy consumption. It is estimated that by the year 2040, electricity consumption will be grown by 40% [1]. Undoubtedly, these major obstacles show that there is a need for new energy strategies. Great attention has been given to new energy strategies based on renewable technologies and power trading. Today there are over 500,000 km of power lines across the globe enough to stretch 12 times around the earth [1]. The current transmission and distribution system has served the purpose extremely well but will not be sufficient in the future [2].

By the end of the 19th century due to ease of alternating current (AC) voltage level transformation, AC technology was selected to transmit electric power. Even though high voltage alternating current (HVAC) transmission suffers from some technical restrictions, nowadays most electrical power is transmitted using HVAC. The main limitations of AC transmission are reactive power generation/consumption, the impossibility of asynchronous ties, challenges in offshore wind farm integration, and the limitation in transmission distance. To overcome these limitations and to develop the transmission capability high voltage direct current (HVDC) transmission was suggested. HVDC is no new solution, but the adoption of direct current (DC) transmission was limited due to the lack of reliable high voltage power conversion equipment. The revolution in the power semiconductor industry managed to reduce the complexity and size of the power converters. HVDC grew in a remarkable manner making it an attractive alternative to conventional HVAC transmission [3].

Recent advancements in HVDC systems have revolutionized power transmission, offering significant benefits over traditional HVAC systems, especially in long-distance and high-power applications. HVDC systems, particularly those employing voltage source converters (VSCs), have emerged as a superior alternative due to their efficiency, stability, and ability to integrate renewable energy sources. These systems enable the seamless integration of offshore wind farms and other renewable energy sources into existing grids, facilitating the transition towards more sustainable energy systems. However, the complexity of multi terminal direct current (MTDC) systems introduces new challenges in control and protection, which are critical research areas [4].

In the context of MTDC systems, the role of advanced converters such as VSCs has been highlighted in study [5] emphasizing the importance of robust control strategies in ensuring voltage stability across interconnected grids. The introduction of fractional order proportional-integral controllers represents a significant improvement over traditional proportional-integral (PI) controllers, offering enhanced stability and adaptability in multi-infeed voltage source converter-high voltage direct current (VSC-HVDC) systems. This innovation addresses the limitations of conventional control methods, particularly in handling nonlinearities and dynamic changes in power systems, thereby improving the overall reliability of HVDC networks.

Furthermore, the integration of offshore wind power into weak grids via VSC-HVDC transmission systems has been thoroughly explored in study [6]. This study highlights the effectiveness of VSCs in maintaining voltage stability and supporting grid operations under fluctuating load conditions. The ability of VSC-HVDC systems to provide dynamic reactive power support is crucial for enhancing the resilience of weak grids, which is increasingly common in remote and offshore locations.

The emergence of advanced protection methods for DC faults in HVDC systems is another critical area of research, as in [7]. In which, a comprehensive review of DC fault protection techniques underscores the importance of fast and reliable fault detection and isolation mechanisms in preventing cascading failures in HVDC networks. These advancements are essential for the safe and efficient operation of future DC grids, particularly as the deployment of HVDC systems continues to expand globally.

The development of hybrid feedforward control schemes for inductor-capacitor-inductor (LCL) grid-connected inverters, as demonstrated in [8], further contributes to the enhancement of HVDC system performance. Their work focuses on mitigating the challenges associated with LCL filters, such as resonance and stability issues, by employing advanced control techniques that improve the dynamic response and reduce harmonic distortion. This is particularly relevant in the context of HVDC systems, where maintaining power quality and stability is paramount.

In conclusion, the ongoing research, and technological advancements in HVDC systems are addressing the complex challenges associated with modern power transmission. The integration of novel control strategies, improved converter technologies, and advanced protection mechanisms are crucial for realizing the full potential of HVDC systems. These developments not only enhance the performance and reliability of HVDC networks but also pave the way for more resilient and sustainable energy infrastructures.

In this research, the performance of an LCL hybrid voltage source converter is investigated. A hybrid LCL voltage source converter based multi-terminal direct current (VSC-MTDC) transmission system was modeled and simulated. The performance of LCL hybrid voltage source converters was then compared to traditional voltage sources converters during normal and abnormal conditions. The LCL circuit was also compared to the H-bridge cells in their respective effectiveness in improving a three-level neutral clamped converter.

In this research, a comprehensive comparative analysis of advanced HVDC converters was conducted. The comprehensive analysis conducted focuses on the performance of a novel LCL hybrid converter in comparison to traditional converters such as the three-level neutral-point clamped (NPC) converter and the hybrid converter with H-bridge cells. While the LCL hybrid converter approach is not entirely new, our study provides a detailed evaluation of its performance under various operating conditions, which has not been thoroughly explored in previous studies.

The comparative analysis revealed that the LCL hybrid converter offers distinct advantages in fault suppression and DC output voltage quality, particularly when integrated into multi-terminal HVDC systems. By systematically comparing different topologies, we were able to identify the strengths and limitations of each approach, providing valuable insights for the design and implementation of HVDC systems. Although the concept of the LCL hybrid converter has been proposed before, our work contributes to the field by validating its effectiveness through rigorous simulation and analysis. Moreover, our findings highlight practical considerations for deploying such converters in real-world applications, addressing key challenges such as cost, complexity, and scalability. This study not only enhances the understanding of the LCL hybrid converter's capabilities but also offers practical recommendations for its integration into future HVDC systems. By providing a balanced assessment of different converter technologies, our research contributes to the ongoing development of more resilient and efficient power transmission solutions.

The LCL hybrid converter showed significant improvement over the traditional three-level neutral clamped converter in normal and abnormal conditions. The H-bridge cells have a better effect than the LCL circuit in improving the three-level neutral clamped response. Adding the LCL circuit to the hybrid converter has a minor effect in improving the hybrid converter performance. It was demonstrated that the LCL hybrid converter has the ability to suppress DC as well as AC faults. In two terminal and multi-terminal HVDC systems, the LCL hybrid converter proved to have a superior operation behavior.

Following this introduction, section 2 presents a review of the relevant literature, establishing the theoretical and practical context for this study. After that section 3 discusses the converter topologies adopted in this research. It provides an overview of VSCs and justifies the adoption of VSC opposed to line commutated converters (LCC). Then section 4 describes the methodology of this research. Section four presents the methodology adopted for the simulation and analysis of the VSC topologies. It details system layout, converter modeling, design, and control. It also presents the criteria for comparison and evaluation. Section 4 presents the simulation and results of the comparative analysis, discussing the performance, advantages, and limitations of each topology. Section 5 concludes the paper, summarizing the key findings and proposing directions for future research.

2. LITERATURE REVIEW

In HVDC systems, power is converted from AC to DC and then transmitted via overhead lines, cables, or a combination of both, before being converted back to AC at the destination. This conversion process is facilitated by power converters, typically operating as inverters or rectifiers, depending on the power flow direction. Key components of an HVDC station include the AC switchyard, equipped with harmonic filters and reactive power compensation devices; converter transformers, designed to connect converters to the AC system while providing isolation and voltage transformation; HVDC converters, composed of thyristors or transistors; and transmission mediums accompanied by DC filters to mitigate harmonic disturbances. Additionally, auxiliary systems support the cooling, control, and internal power supply requirements of the station.

HVDC transmission systems offer significant advantages over HVAC systems, including efficiency, lower environmental footprint, and improved power system stability. With the capacity for higher power delivery per conductor and longer transmission distances, HVDC decreases overall costs and losses. Its advantages extend to eliminating the necessity for reactive power compensation, reducing line losses, and allowing for asynchronous connections and ground return usage. HVDC technology also enhances power quality within AC systems by controlling power flow and providing a damping torque, which contributes to system stability. These systems are characterized by smaller transmission towers and the absence of issues like charging current at steady state, skin effect, corona, and radio interference [9].

HVDC systems offer further improved performance in terms of power flow management, loss reduction, and integration of distributed generation compared to AC systems. Losses in HVDC systems are reduced significantly due to the absence of reactive power components. The reduction of losses and the absence of reactive components simplifies power flow management and enhances efficiency [10]. Optimization algorithms for distributed generation (DG) placement further enhance the performance of DC systems by determining the optimal locations for DGs, thereby minimizing losses, and improving voltage profiles across the network [11].

In HVAC systems, extensive reactive power compensation and harmonic filtering are required to maintain stability and power quality. Multi-objective optimization techniques for reactive power management in AC systems highlight the need for such compensations to address issues like voltage deviation and power loss [12]. In contrast, DC systems inherently avoid these issues due to the unidirectional nature of DC power flow, which offers efficiency and stability advantages, particularly with high integration of renewable energy sources [13].

Advanced optimization techniques and algorithms can be effectively applied to HVDC systems to improve their performance. These methods have the potential to enhance voltage stability and reduce losses, contributing to better overall system efficiency. Integrating distributed generators in DC systems using such optimization algorithms further improves system performance, including enhanced voltage stability and reduced power losses [14].

Despite these benefits, HVDC systems introduces some challenges such as the high cost of power converters. Some converters require reactive power and have limited overload capacity. Additionally, HVDC converters introduce harmonics, necessitating the use of filters. The complexity of multi-terminal operations also presents operational challenges. Nonetheless, the benefits of HVDC outweigh these drawbacks, making it a preferred choice for long-distance power transmission.

Since its initial commercial implementation in 1954, HVDC technology has significantly matured. It is becoming indispensable for a variety of transmission challenges, notably in integrating offshore wind farms, enhancing long-distance bulk power transmission, facilitating connections between asynchronous grids, and supplying power to densely populated urban areas. HVDC's superiority stems from its ability to transmit power over vast distances with significantly lower losses compared to AC transmission, making it economically viable for connecting remote renewable energy sources—such as hydro, wind, and solar—to distant load centers.

In urban settings, utilization of older less efficient generation units is constrained by environmental regulations. In such situations, HVDC proves advantageous by enabling the integration of new, more efficient generation units located far from cities. Compact HVDC stations, utilizing underground transmission circuits, address the challenges posed by right-of-way and land use limitations, ensuring reliable power delivery without compromising system stability. For cable transmissions, HVDC eliminates the need for reactive power compensation, allowing for longer transmission distances without the physical restrictions imposed by AC systems' higher capacitance and inductance. This attribute is also of particular interest for submarine cables, where HVDC's absence of capacitive charging current and higher rating make it a practical and cost-effective option.

Moreover, HVDC links serve as a robust solution for connecting asynchronous AC grids, supporting energy trading and system stabilization. These links act as buffers to prevent the propagation of disturbances and aid in damping power oscillations following disturbances, enhancing the overall reliability and economic operation of interconnected power systems. There are various configurations of HVDC systems. The four main configurations investigated in this research are back-to-back, monopolar, bipolar, and multi-terminal HVDC system configurations.

The simplest configuration is the back-to-back HVDC system. In this configuration both converters are placed in the same station therefore no transmission line is needed. A back-to-back system is used to connect two adjacent AC grids with same or different frequencies. Moreover, to achieve a defined power flow this topology is used within a meshed grid.

A monopolar HVDC system is a configuration where the two converter stations are connected with a single pole line. The voltage polarity can be either positive or negative. The ground serves as the return path. This configuration is widely used in undersea transmission especially for very long sea cable transmission.

In a bipolar HVDC system the two converter stations are connected with two conductors. One conductor is positive while the other is negative. A mid-point is connected to ground. It is mainly used in applications where overhead lines are used to transmit power. Bipolar systems can be considered as two monopolar systems. The main advantage of such topology is that if one pole is out of service, the other one can still have the ability to transmit power meaning that each side of this topology can operate independently if the neutral point is grounded at both stations.

In multi-terminal HVDC systems there are more than two sets of converts. Connecting more than two converter stations can be done with parallel multi-terminal HVDC stations, series multi-terminal HVDC stations or hybrid multi-terminal HVDC system. Since the converter stations are physically separated in the multi-terminal HVDC transmission a DC circuit is needed to connect them. The inherent fault suppression capabilities of modular multilevel converters (MMCs) have spurred the development of innovative hybrid converter topologies for HVDC applications. These topologies aim to combine the fault-ride-through advantages of MMC-based designs with the operational simplicity and reduced component count of traditional two-level VSCs [15].

A notable strategy involves incorporating H-bridge cells on the AC side of a two-level converter. These cells have been shown to function effectively as active filters, thereby improving output voltage quality, and enhancing the converter's ability to manage DC faults. However, the H-bridge cells add complexity and increase switching losses within the system [16], [17].

Alternatively, the LCL circuit offers a different approach to fault management and power quality improvement in HVDC converters. Traditionally employed in grid-connected converters for their superior high-frequency harmonic attenuation, LCL filters are now being explored for their potential in enhancing both AC and DC fault suppression when integrated with conventional VSCs [18]–[21]. Despite the recognized benefits of both H-bridge cells and LCL circuits, comprehensive comparative analyses of their performance within a unified system are lacking. This research seeks to fill this gap by directly simulating and evaluating the effects of LCL circuits alongside a traditional three-level NPC and an existing hybrid configuration employing H-bridge cells. Our findings contribute to optimizing hybrid HVDC converter designs, balancing specific performance metrics against cost considerations.

3. VOLTAGE SOURCE CONVERTERS VS LINE COMMUTATED CONVERTERS

The converter station is considered the most important element of an HVDC system. Based on the type of power conversion process used in the station, the HVDC system is identified. Two main power converter technologies have been utilized in the conversion stations, current source converter (CSC) and VSC. Figure 1 shows the classification of power converters. Thyristor based CSC HVDC (conventional HVDC) circuits are termed as LCC since the converter valves rely on the system line AC voltage to perform the commutation action. Voltage source converters that employ turn off semiconductor devices are known as self or forced commutated converters. LCC based HVDC is a mature technology with DC power levels and voltages higher than VSC based systems. On the other hand, VSC based systems which originally come from motor drive applications are presented with a power rate of 400 MW.

The three-phase full wave bridge, also known as the 6-pulse or Graetz Bridge is the basic building block used for HVDC conversion [22], [23]. It is called six-pulse, since the DC output voltage will have a harmonic ripple of six times the fundamental frequency, due to the six commutations or switching operations per period. The six-pulse bridge consists of six semiconductor switches or thyristor valves. In order to achieve the required DC voltage rating, the valves are composed of a number of series connected thyristors. Connecting the DC terminals of two six-pulse bridges in series while the AC voltage sources phase displaced by 30^{o}, will increase the DC voltage and some of AC current and DC voltage harmonics will be eliminated. This configuration is referred to as 12-pulse converter. It is the most classical and most used scheme in HVDC. In the 12-pulse converters the fifth and seventh harmonics are cancelled out in the converter transformer [22], [23].

Transferring of DC current from one valve to another in the same row in a synchronized firing sequence of the thyristor valves is called commutation. To commutate from one switching device to its neighbor, line commutated converters depend on the line voltage of the AC system to which the converter is connected. In LCC, the flow of the DC current is unidirectional, and it is considered constant since it flows through a large inductance. As a result, to reverse the direction of power flow, the polarity of DC voltage at both stations is reversed. Behaving like a current source, the converter on the AC side injects both grid frequency and harmonic currents into the AC network [24].

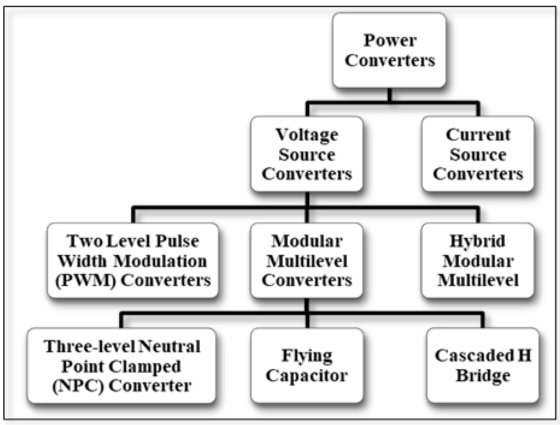

Figure 1. Classification of power converters

One important property of an LCC is that it can only operate if the ac current lags the voltage. Consequently, reactive power is needed to complete the conversion process. As the transmitted power increases, the reactive power required increases in a nonlinear manner. It is estimated that the consumption of reactive power in a conventional HVDC converter is around 0.5 p.u. of the active power [25]. On the AC side, AC filters are installed to fulfill two requirements; to filter the current harmonics and to supply the reactive power required. The need for filtering increases nonlinearly in the same manner as for reactive power absorption, but in the opposite way. Any excess or shortage in reactive power from the local sources should be adjusted by the ac system [26]. On the DC side, filters are needed to minimize harmonic voltages; also, reactors are present, so the ripple of the DC voltage is reduced. Moreover, reactors can reduce the peak current in case of a fault on the DC connection [27].

LCC-based systems are well-established and reliable technology with the lowest losses among converters schemes available. These converters have an economic advantage, since they are thyristor-based converters and thyristors can handle two to three times the power than any other semiconductor devices which also means that LCC has good overload capability. Up to now LCC technology has the highest voltage and power levels and there is a significant research effort to increase it furthermore. However, LCC technology suffers from drawbacks, like its dependence on the connected network voltage, special transformers are required to withstand DC stresses and extra shunt reactive power sources are needed due to large consumption of reactive power also the ability to control reactive power is limited.

In an attempt to address some of LCC disadvantages, capacitor commutated converters (CCC) and controlled series capacitor converters (CSCC) were proposed [22], [28], [29]. By connecting series capacitors between the valves and the transformers, the demand of shunt reactive compensation as well as strength requirements of the connected ac system can be reduced. These added capacitors provide some of the voltage required to commutate, thus improving voltage stability and reducing the probability of commutation failure in case of a fault. Nevertheless, the higher cost of the converter, the protection needed for the capacitors against over-voltages and the negative impact of the energy stored in the series capacitor on the dynamic response in unbalanced conditions are some of CCC configuration disadvantages.

Developments in semiconductor device ratings made it possible to build high voltage valves hence, making VSC applicable to HVDC. Based on self-commutating, fully controlled valves (*i.e.* insulated-gate bipolar transistor (IGBT)) VSC's offer a more flexible solution for HVDC transmission. Absence of commutation failure, fast and decoupled control of bidirectional active and reactive power and small filter requirements are some of VSC attractive features [30]. With VSC, compact site area is achieved, the strength of AC network is not critical, voltage and transient stability are improved, and power direction is reversed by changing the direction of current. One important feature although is missing, the ability to clear faults on the DC side. A comparison of LCC and VSC technologies is provided in Table 1.

Table 1. Comparison of LCC and VSC technology

Item	CSC-LCC technology	VSC technology
1	Mature, with 50 years' experience	Developing
2	Thyristor based, dependent on external circuit for commutation	IGBT based, self-commutating
3	Good overload capability	Limited overload capability
4	Commutation failure can occur	Commutation failure does not occur
5	Requires strong AC systems at both end of the system ($SCR > 2$)	Can operate into weak AC systems silicon-controlled rectifier (SCR) is not critical
6	"Black start" capability requires additional equipment to generate voltage source	"Black start" capability is inherent
7	Minimum DC power is typically 5-10% of rated power	No minimum DC power
8	50% of active power transmitted	Independent control of active and reactive power
9	Reactive compensation required	No reactive compensation
10	Generates harmonic distortion on the AC and DC systems	No significant harmonic generation
11	Switchable AC and DC filters required	Less filtering needed
12	Needs special designed converter transformers	Conventional transformers can be used
13	For reversal of power flow, DC voltage polarity reversal required	Controllable in both directions no reversal of DC voltage polarity required, by changing current direction
14	Polarity reversal requires the use of mass impregnated (MI) cable	Lack of polarity reversal means that both XLPE and MI cables can be used
15	Multi terminal schemes are difficult to engineer due to the polarity reversal issue	Multi terminal systems are simpler to engineer
16	DC grids are not considered feasible	DC grids become possible
17	Large site required, dominated by AC side harmonic filters, 200×120×22 m (100%)	More compact site area, 120×60×22 m (~40%)
18	Low losses 0.7% to 0.8% of transmitted power	Higher station losses 1% of transmitted power
19	Store energy inductively	Store energy capacitively

VSC topologies used in HVDC are classified into two main categories. Those categories are two/three level pulse width modulation (PWM) converters and modular multilevel converters. The two/three level converter is the most VSC HVDC scheme used. The magnitude and phase of the voltage are controlled using PWM as a switching technique.

Even though the two/three level converters offer some solutions to the difficulties in pervious topologies, they have some drawbacks. High switching losses and high $\frac{dv}{dt}$ at relative high switching frequency lead to worst efficiency than LCC. Moreover, complex gate drive circuits are required to ensure equal voltage sharing under all conditions for the large series connected IGBT's. Limiting the voltage levels to two or three levels increases the chances of having an output voltage with high total harmonic distortion (THD).

To overcome these shortcomings, MMC are presented. Having a large number of voltage levels and eliminating the need for PWM, the waveform is generated by discrete voltage steps. By implying a switching frequency of 100-150 Hz, losses and harmonics are decreased. The converter valve is formed from a number of identical, isolated simple single-phase VSC called cells or sub modules [31].

With its own small capacitor installed, each cell is composed of series connected IGBT's and a diode forming a half bridge converter. Although, the ability to suppress DC faults is lost, unless it is a full bridge based, but that means more semiconductors. Nevertheless, comparing the MMC with the conventional VSC, twice the number of IGBT's are needed, bulky and heavy DC capacitor are required which means more stored energy and it is less compact.

A new family of converters is emerging combining the advantages of both MMC and 2-level converters. These hybrid converters depend on a combination of IGBT valves using series connected IGBTs, and to perform a wave shaping task, multi-level converters based on individual and isolated half bridge and full bridge are used. Therefore, fewer cells are required minimizing the number and rating of DC capacitors and reducing switching losses [16], [32].

A hybrid converter topology is based on using a two-level converter being the switching component with low switching frequency, combined with a multi-level converter working as a wave shaping circuit so the harmonics generated by the two-level converters can be eliminated. The hybrid converters can be classified into main classes, series, and parallel circuits. In the series circuits, the wave shaping circuit can be connected either on the AC side or the DC side.

In series circuits topologies, the output voltage is an almost perfect sinusoid. The output voltage of series circuits topologies is a significant improvement over that of the conventional 2-level circuit. However, placing the wave-shaping circuit on the AC side of 2-level converters means that two-level converters are hard switched, which increases the switching losses. In addition, the series IGBT valve should be carefully designed to guarantee voltage sharing under dynamic conditions. Moreover, to avoid high voltage spikes showing in the output voltage, careful synchronization is required between the two-level converter and wave-shaping circuit.

On the other hand, putting the wave-shaping circuit on the DC side will reduce the switching losses and will simplify the design of the valve since the requirements for dynamic voltage sharing become less effective. Both series arrangements share some advantages such as the fact that it needs nearly half the number of cells required for the equivalent MMC. This is because the necessary voltage rating of each converter branch is shared between the switch and wave-shaping circuit. In addition, since the full bridge cells are used in this topology it can suppress the fault currents.

A parallel topology uses an H-bridge in each phase connected in parallel with a wave shaping circuit that consists of half bridge sub modules. Unlike the normal multi-level converter, in the parallel configuration there is no balancing current flow since from the DC side it is seen that the three phases are connected in series. Moreover, the number of sub modules is reduced by almost 25% in comparison with normal multi-level because the wave shaping circuit is placed outside the main circuit path. As the number of cells in the wave shaping circuit increases the harmonic content in the AC voltage is minimized. However, the DC output voltage has a significant component of 6^{th} harmonic and that can be removed by using passive filters.

3.1. Control of HVDC converters

The control system of the hybrid LCC HVDC system is meticulously designed to maintain stable DC current and voltage. This is achieved through a pole-control strategy that dynamically selects the optimal control mode based on the lowest output from the constant current, constant voltage, and constant extinction angle controls, as illustrated in Figure 2. Figure 2 presents two essential PI control block diagrams. The upper diagram manages DC current control, while the lower one governs the extinction angle control. A selection mechanism, not depicted in the figure, determines which of the two firing angle commands should be implemented, choosing the one with the smaller angle.

Additionally, a voltage dependent current limit block is incorporated to reduce the current output if the DC voltage drops below a certain threshold. Typically, the inverter operates in constant extinction angle mode, while the rectifier functions in constant current mode. During transitions between these control modes, a current error signal adjusts the extinction angle reference. This current signal, which feeds into the extinction angle control diagram, originates from the power error signal produced by the current control block.

The precise control of the extinction angle is crucial to prevent commutation failures. Such failures occur when the commutation process is not completed within the required time frame. It is potentially leading to thyristor malfunctions by returning to a forward-biased state prematurely during inverter operation.

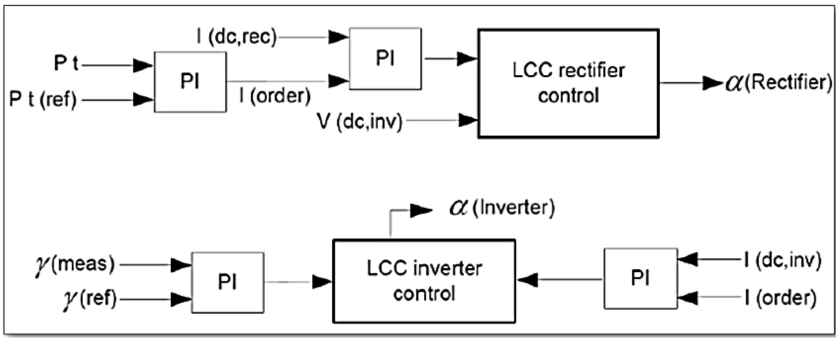

Figure 2. Control blocks for LCC converters

On the other hand, the control of a VSC HVDC should fulfill the purposes of controlling the transferred power and the independent control of active and reactive power. In the literature, there are different control methods for the control of VSC-HVDC. Two known strategies for control of VSC are the direct power control (DPC) method and the vector control method. The basic control principle of DPC is based on the instantaneous active and reactive power control loops. In DPC, based on the instantaneous differences between commanded and reactive power, a switching table selects the converter switching states as a result, the internal current loops and PWM modulator block are not required. Variable switching frequency and the need for fast conversion and computation are some this method's disadvantages that limit its use [33], [34].

The control strategy utilizes field-oriented vector control, enabling the independent management of active and reactive power. This separation is essential for the precise regulation of these power components, ensuring efficient and adaptable operation of the VSC. The control system transforms three-phase currents and voltages into a two-axis d-q reference frame that rotates synchronously with the AC system frequency, simplifying the control of AC quantities as they become DC quantities in this frame. The control scheme comprises two primary controllers: the current controller and the DC-link voltage controller.

Current control loop: This inner loop functions in the synchronous reference frame, transforming the three-phase AC currents into two orthogonal components (d and q axes). This conversion simplifies control by making these components DC signals under balanced conditions. The PI controllers in this loop guarantee zero steady-state error and robust performance. They manage the d-axis current, representing active power, and the q-axis current, representing reactive power. To achieve decoupled control, feed-forward compensation is used to counteract the cross-coupling terms resulting from the inductive nature of the AC system, allowing independent control of active and reactive power.

The mathematical representation of the converter's three-phase currents and voltages in a 2-axis d-q reference frame, rotating at the AC frequency, ω, can be described as (1) and (2):

$$L\frac{di_d}{dt} = V_d - Ri_d + L\omega i_q - V_{d,conv} \quad (1)$$

$$L\frac{di_q}{dt} = V_q - Ri_q + L\omega i_d - V_{q,conv} \quad (2)$$

here, V_d and V_q are the d-axis and q-axis voltages, i_d and i_q are the currents in the d and q axes, R and L represent resistance and inductance, and $V_{d,conv}$ and $V_{q,conv}$ are the converter voltages in the d-q frame.

The power balance between the AC input and DC output is given by (3):

$$P = \frac{3}{2}\left(V_d i_d + V_q i_q\right) = V_{dc} I_{dc} \quad (3)$$

where V_{dc} and I_{dc} are the DC output voltage and current, respectively. The control system decouples i_d and i_q by compensating for the terms $\omega L i_q$ and $\omega L i_d$ through feed-forward control.

DC voltage control loop: This outer loop regulates the DC link voltage to balance the power between the DC and AC sides. It generates reference signals for the current control loop based on the desired DC voltage and operates at a slower dynamic response than the current control loop. The DC voltage controller ensures stable power flow between the VSC and the connected grid or load.

The DC link voltage dynamics can be expressed as:

$$C_{dc} \frac{dV_{dc}}{dt} = I_d - I_L \quad (4)$$

where I_d is the current on the DC side and I_L is the load current. The minimum required DC-side voltage is determined by (5):

$$V_{dc,min} = 2 * \sqrt{\frac{2}{3}} V_{LL,rms} = 2 * V_{peak,ph} \quad (5)$$

where $V_{LL,rms}$ is the line-to-line RMS voltage and $V_{peak,ph}$ is the AC side voltage peak. The reference value for I_d is calculated using feed-forward terms to accurately compensate for load variations.

$$I_{d,ref} = \frac{3}{2} * \frac{V_d I_d + V_q I_q}{V_{dc}} \quad (6)$$

This hierarchical control strategy, with faster inner current control and slower outer voltage control, optimizes the system's dynamic response and stability.

Discrepancies in the VSC's capacitor voltage (V_{dc}), terminal voltage mismatch, and the direct and quadrature axis components of voltage generate the VSC's magnitude and angle controlling signals. The dq-transformation simplifies the three AC quantities to two DC quantities. Voltages V_q and V_d are determined using d and q errors through a decoupled controller block. The modulation index magnitude (m) and phase (θ) signal are then calculated. A phase-locked loop (PLL) synchronizes with the AC network to produce the firing pulses for the IGBTs in the VSC. Figure 3 illustrates the vector control principle [33].

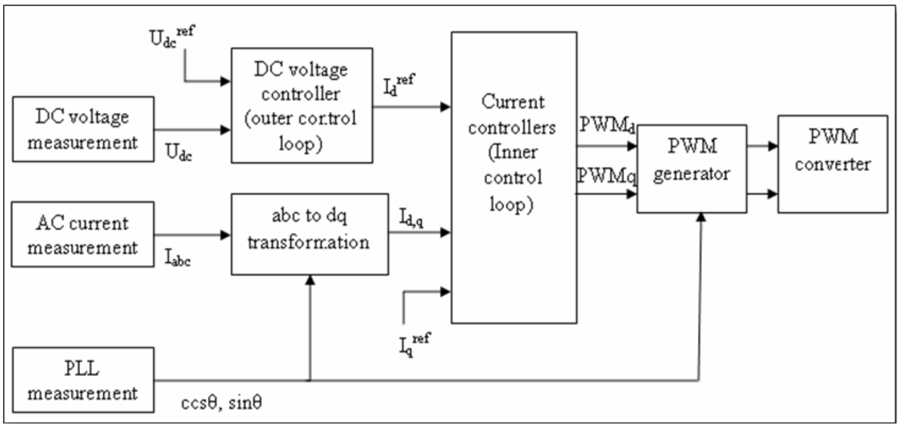

Figure 3. Vector control principle [33]

4. METHOD

In this section, system layout and models are presented. Details of implemented VSC control is discussed as well. After that more details are presented about converter modeling and design. Three-level neutral point clamped converter, hybrid three-level bridge converter, and LCL hybrid three-level bridge are included in the converter modeling and design.

The computational complexity of the MATLAB/Simulink simulations used in this study is straightforward and manageable. Given the standard nature of the simulations, which focus on evaluating the performance of different converter topologies under various operating conditions, the computational demands remain within the capabilities of typical MATLAB/Simulink environments. All simulated topologies the three-level neutral point clamped converter, hybrid converter with AC side cascaded H-bridge cells, and the LCL hybrid converter simulations were all efficiently executed on standard computational hardware. The complexity primarily involves basic control algorithms and standard simulation practices, which do not necessitate advanced computational resources. This aligns with common practices in power system simulations, where MATLAB/Simulink is widely used due to its robust and user-friendly interface for modeling and simulation of electrical systems.

4.1. System layout and model

A two terminal HVDC link is used to interconnect two HVAC systems. The system is model is presented Figure 4. In this system, the HVDC link is represented by a 200 MVA +/-100 kV VSC-HVDC transmission link. The AC systems, 1 and 2, in the model are 400 kV, 2000 MVA AC systems. These two AC systems are demonstrated by L-R equivalents at fundamental frequency 50 Hz. In order to transform the voltage level to a suitable level for the converter a wye grounded/delta transformer is utilized. In this model the VSC converters used are three-level neutral point clamped converters using IGBT/diodes. The converters are connected through a 100 km cable (2 pi sections).

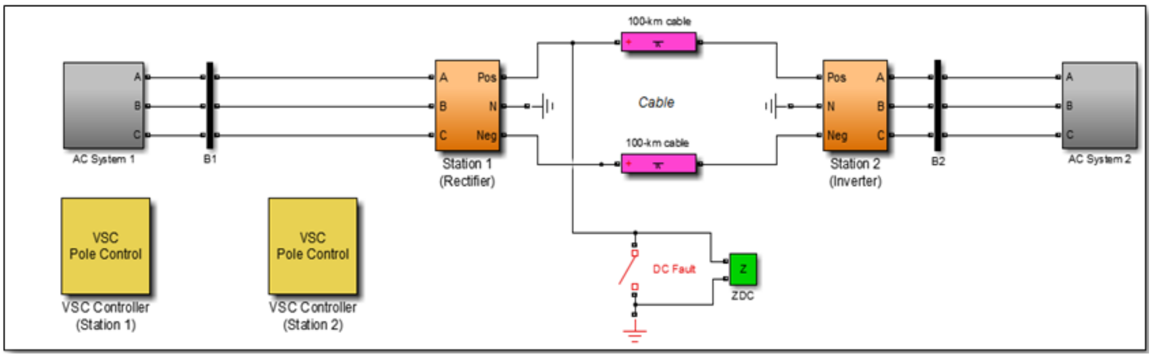

Figure 4. VSC-HVDC transmission system model

The two main transmission line models utilized in time domain simulations are PI sections line model and distributed parameters line model. In a PI sections line model, the resistance, inductance, and capacitance are uniformly distributed along the line. An approximate model of the distributed parameters line is obtained by cascading several identical PI sections. The PI sections line model has a finite number of sections. The number of sections to be used depends on the frequency range to be represented.

Although for frequency domain studies PI sections line models can be precise, in the time domain, particularly for long lines (where propagation travel time spans many time steps), accuracy is compromised. The calculation step time of any simulation should be less than the propagation time. PI line sections are more useful for very short transmission lines where the propagation travel time is less than simulation step time. For studying interactions between HVAC and HVDC system, a simple PI sections line model would be insufficient [35].

Unlike the PI sections line model, the distributed parameters line model effectively has an infinite number of sections. The distributed transmission line model operates on the principle of traveling waves. A voltage disturbance progresses along a conductor at its propagation speed (close to the speed of light) until it reflects back at the line's end. Any signal introduced at the sending end will arrive at the receiving end following a delay, possibly with some minor alterations.

The distributed parameters line model utilizes Bergeron's traveling wave method. This approach employs a traveling wave line model characterized by distributed LC parameters and integrated lumped resistance. It generates a constant surge impedance and essentially operates as a single-frequency model. The Bergeron method is suitable for fundamental frequency impedance studies across various applications. In the Bergeron Model, the inductance and capacitance components are distributed, unlike in PI sections where these parameters are lumped. Effectively, it simulates having an infinite number of PI sections [36].

In This research, the transmission line model used in the simulations utilized the Simulink PI Section Line block. The Simulink PI Section line block provides a realistic approximation of a distributed parameter line by cascading several PI sections. This method captures the essential physical properties of the transmission line, such as resistance, inductance, and capacitance distributed along the line. It also allows for the customization of the number of sections to accurately represent the frequency range of interest. Most importantly, the model implements hyperbolic corrections for RLC elements based on the line length and specified frequency, which is crucial for long transmission lines where these corrections significantly affect the impedance and admittance calculations. This level of detail ensures that our simulations reflect more accurate and practical responses of the HVDC system under study. In This research two PI sections were used. In this study, two PI sections were utilized to draw a balance between accuracy and computational efficiency. This configuration sufficiently captures the key electrical properties and transient behaviors without the computational burden of additional sections, ensuring our simulations are both precise and practical for the intended analyses.

4.2. VSC control

The rectifier controller and the inverter controller in stations 1 and 2 respectively are identical. The rectifier and the inverter controllers are designed to work independently. The controller in station 1 is responsible for controlling the real and reactive power. On the other hand, the second controller is designed to control the DC voltage and reactive power. The switches in the converters are controlled via PWM approach. To control the PWM controller an error signal is generated by comparing the DC voltage across the load with a reference value. A converter works as a rectifier when the DC current is positive and when the DC current is negative it acts as an inverter. The DC source charges the capacitor of the VSC, and the firing angle will be modified by the system to ensure the converter act as an inverter. The block diagram for the control system of the VSC demonstrated in Figure 5.

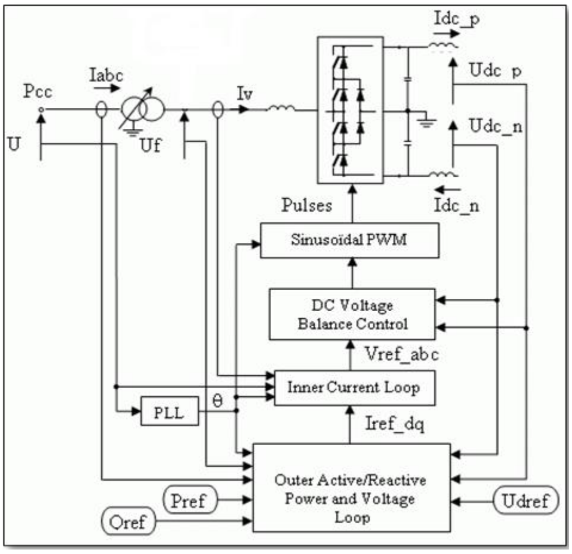

Figure 5. Block diagram for VSC control system as implemented in MATLAB/Simulink

The control system of VSC depends on inner current control loop that controls the AC current. The outer controllers are responsible for supplying the AC current references. The outer controllers are formed of the AC and DC voltage controllers, active and reactive power controllers. From the DC voltage controller or the active power controller, the reference value of the active current is obtained. The AC voltage controller or the reactive power controller supply the reactive current reference value. To eliminate the steady state errors, integrators are implemented in all the controllers. The schematics for the MATLAB/Simulink implementation of the VSC control are shown in Figure 6 and Figure 7.

The system frequency is measured by the phase locked loop block and then the output, the phase synchronous angle is provided to the dq transformations block. The sine of the phase synchronous angle, the fundamental of α component and phase A of the point of common coupling voltage are all in phase in steady state. In steady state, the DC side of the converter should be controlled to keep the pole voltages balanced. As a result, the difference between the DC sides voltages is controlled by the DC voltage balance control.

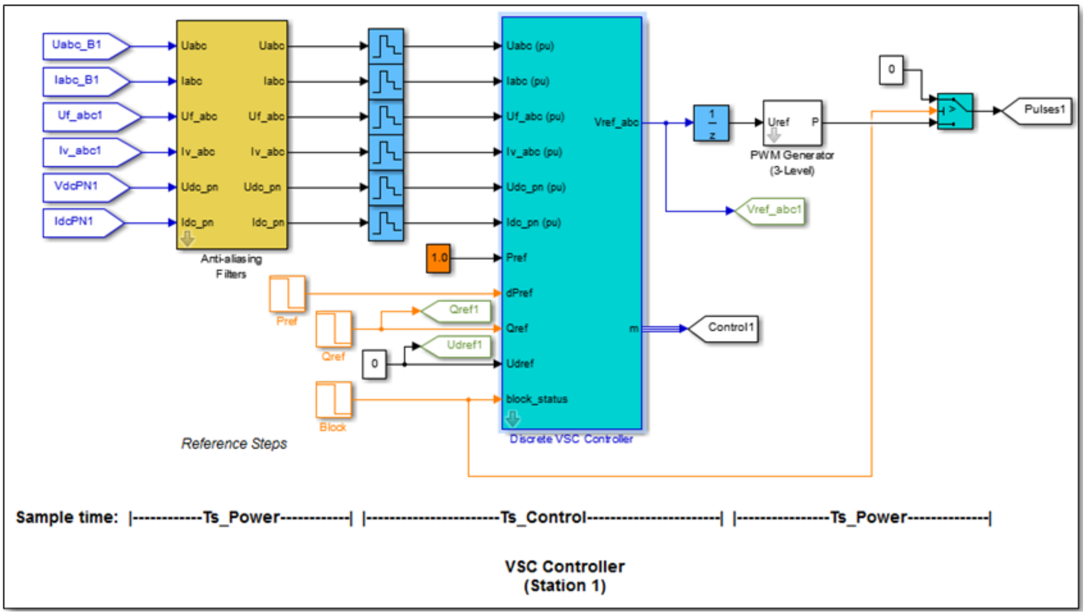

Figure 6. VSC control station

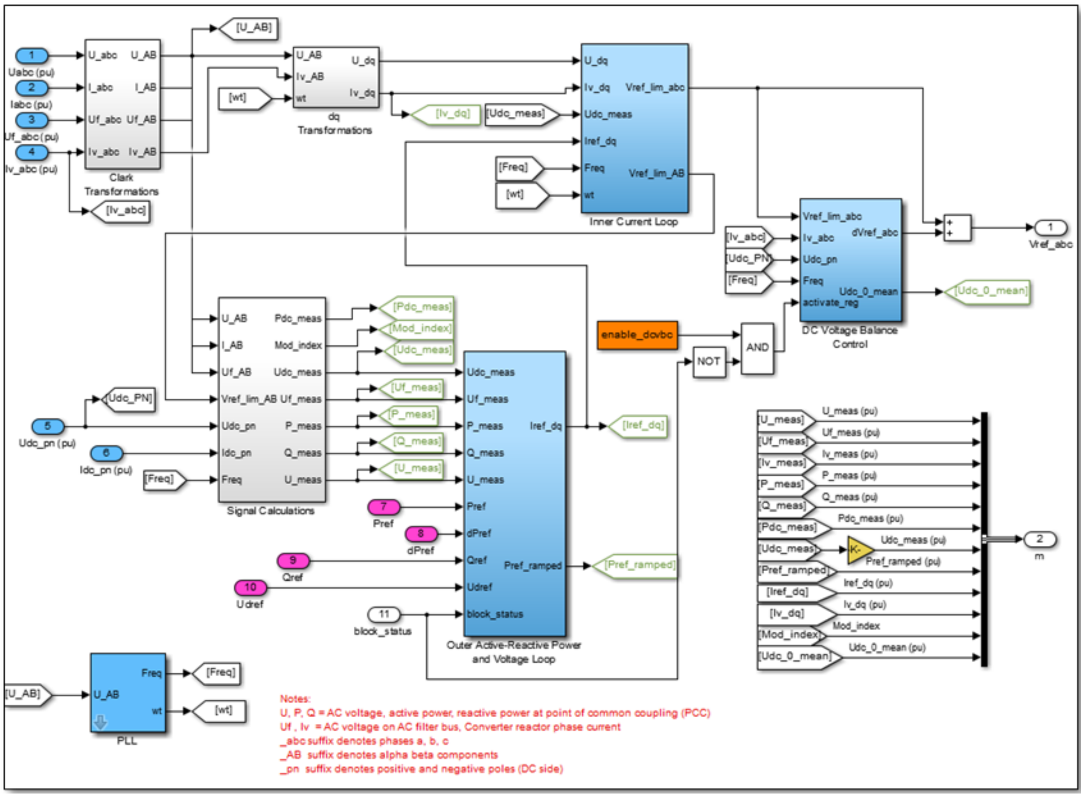

Figure 7. The detailed layout of VSC controller

4.3. Converter modeling and design

Three converter topologies were investigated and included in the comparative analysis of the HVDC link. The three converter topologies are; the three-level bridge VSC, the hybrid three-level bridge and the LCL hybrid three-level bridge. The comparison is mainly based on key performance metrics such as DC output voltage quality and fault suppression capabilities.

4.3.1. Three-level neutral point clamped converter

In the three-level neutral point clamped converter, two series-connected capacitors split the DC bus voltage into three levels. The neutral point is defined as the midpoint of the two capacitors. In that manner, this topology will be able to synthesis an output voltage with three levels: $V_{DC}/2$, 0 and $–V_{DC}/2$. The main task of the diodes in the same leg is to clamp the switch to half the level of the DC bus voltage. If these diodes were not added the output voltages levels could not be defined. Sustaining a voltage balance between the capacitors is vital for the proper operation of this circuit. The key advantages of this circuit are that it has less harmonic content in the output waveforms than the two-level converters and the fact that one isolated DC supply is needed.

There are two main concerns for this topology. As the number of voltage levels increase, the circuit becomes more complex. The other concern is that it is difficult to keep the capacitor voltage levels constant. Figure 8 illustrates the basic schematic of three-level neutral point clamped converters. Figure 9 illustrates the MATLAB/Simulink implementation of the three-level neutral point clamped converter.

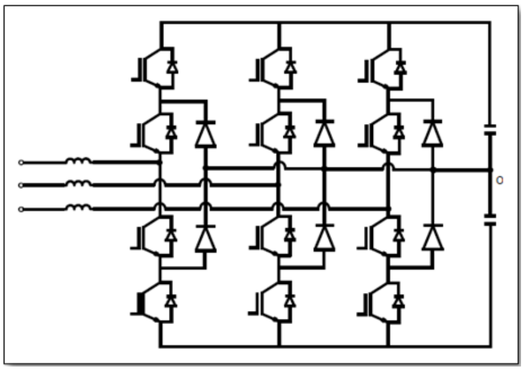

Figure 8. Three-level neutral point clamped converter [15]

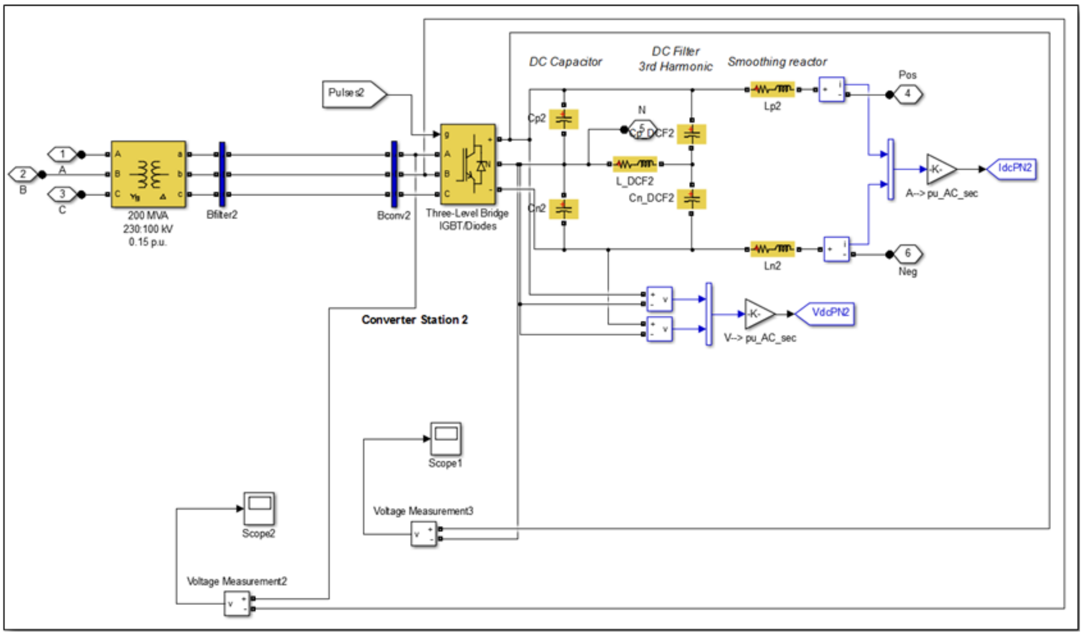

Figure 9. Three-level (NPC) converter circuit

4.3.2. Hybrid three-level bridge converter

The proposed hybrid three-level bridge converter is shown in Figure 10. The block diagram for the controller of the H-bridge cells is presented in Figure 11. A two-level converter H bridge cell is added at each phase of the AC side of the three-level converter. The proposed converter provides many advantages. The

H-bridge cells in each phase will act as an active filter improving the output waveform. Unlike the three level (NPC) converter the proposed topology will have the ability to suppress DC faults. The contribution of AC grid to the DC fault will be eliminated. Consequently, the risk of converter failure due to an uncontrolled over-current in case of a DC fault will be minimized. The magnitude and duration of the DC fault current will be reduced and as a result the DC circuit breaker design will be simplified. The AC networks voltage stability is improved since the converter reactive power consumption is minimized in case of a DC side fault. It will show controlled recovery without the disturbance of VSC-HVDC system from DC-side without the need for AC breakers to open.

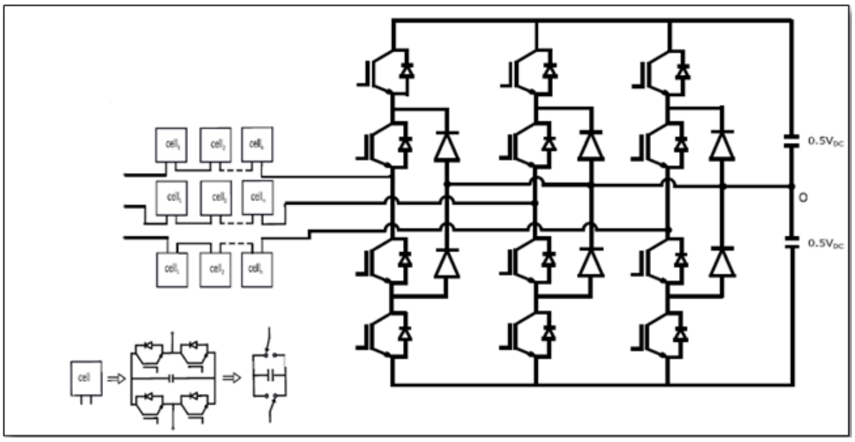

Figure 10. Three-level (NPC) with AC side h-bridge cells

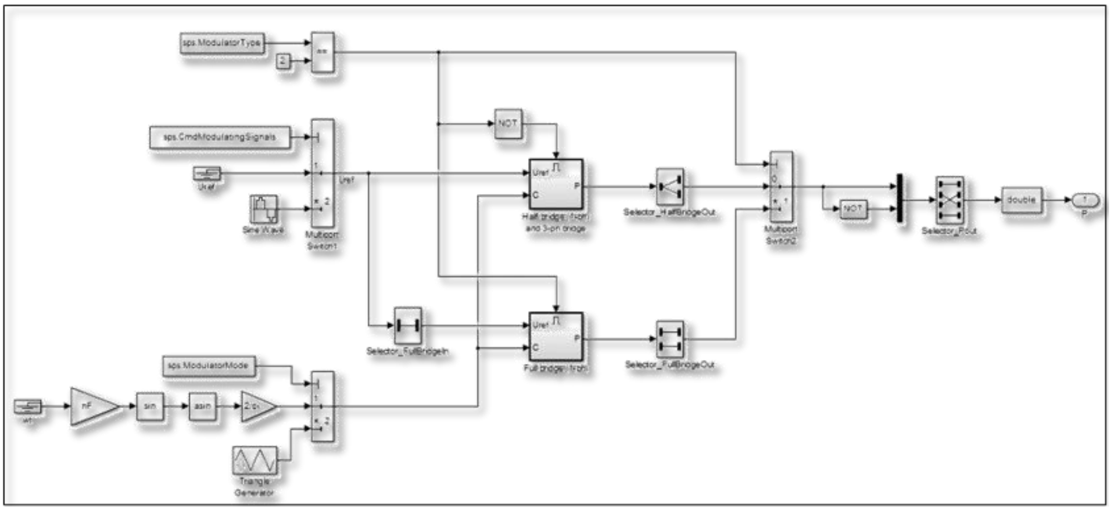

Figure 11. Controller for H-bridge cells

4.3.3. LCL hybrid three-level bridge

The LCL hybrid three-level bridge shown in Figure 12. The MATLAB/Simulink implementation of the LCL hybrid converter circuit is presented in Figure 13. The proposed LCL hybrid three-level bridge is a hybrid three level (NPC) bridge converter with a passive inductor-capacitor-inductor LCL circuit. A well-designed LCL filter has the ability to automatically regulate the power in the manner where the current will be reduced on one side because of voltage depression on the opposite side. There are three vital advantages that are achieved by this approach. The power decline is a built-in feature and does not depend on any protection circuits. The cost of LCL components is considerably lower than semiconductors', which will reduce the overall cost of the converter. And finally, the converter control is maintained even during the most severe faults.

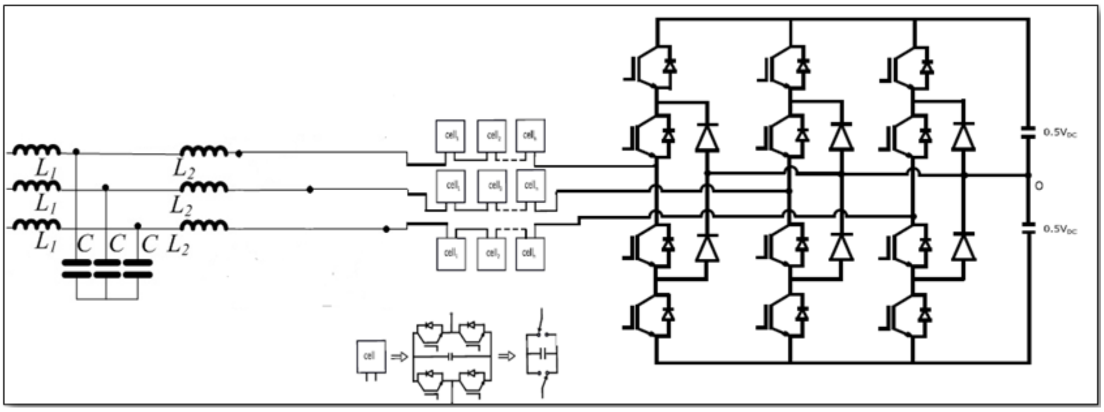

Figure 12. LCL hybrid three-level bridge

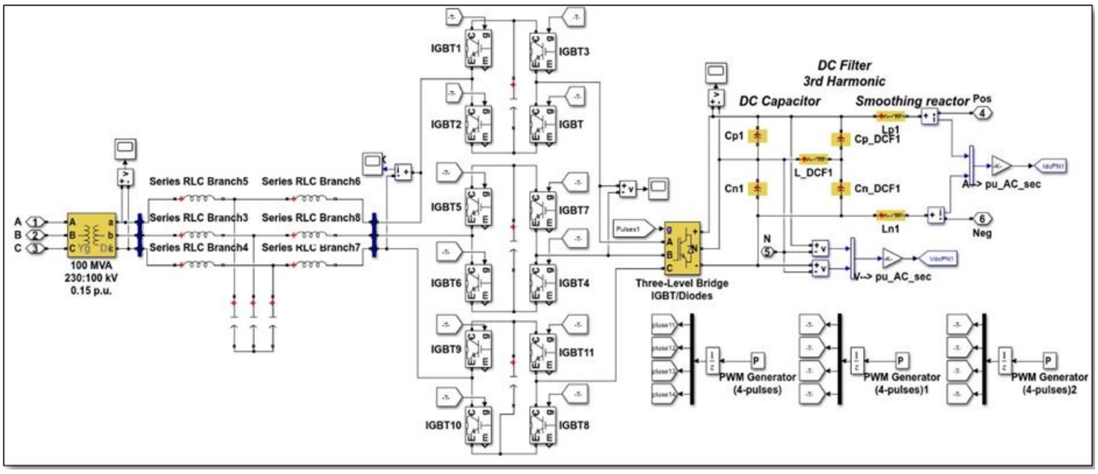

Figure 13. LCL hybrid converter circuit

The LCL circuit can be seen as a power network with input voltage V_{1ac} and input current I_{1ac} and output voltage V_{2ac} and output current I_{2ac}. V_{1ac}, V_{2ac} can be expressed in vector form as (7) and (8).

$$\vec{V}_{1ac} = V_{1acd} + jV_{1acq} \tag{7}$$

$$\vec{V}_{2ac} = V_{2acd} + jV_{2acq} \tag{8}$$

The subscripts d and q stand for the corresponding phasor components. In the topology used, the converter voltage V_{2ac} is the only controllable component and the converter line-neutral rms voltage can be expressed as (9) to (11):

$$V_{2acd} = M_{2d}\frac{V_2}{\sqrt{2}} \tag{9}$$

$$V_{2acq} = M_{2q}\frac{V_2}{\sqrt{2}} \tag{10}$$

$$M_2 = \sqrt{M_{2d}^2 + M_{2q}^2} \tag{11}$$

M_{2d}, M_{2q} represents the dq parameters of the PWM modulated control signal and V_2 is the pole DC voltage. The main circuit are:

$$j\omega L_1\overline{I_{1ac}} = \overline{V_{1ac}} - \overline{V_c} \quad (12)$$

$$j\omega C\overline{V_c} = \overline{I_{1ac}} + \overline{I_{2ac}} \quad (13)$$

$$j\omega L_2\overline{I_{2ac}} = \overline{V_{2ac}} - \overline{V_c} \quad (14)$$

$\omega = 2\pi f$ and $f = 50$ Hz. The capacitor voltage and currents can be represented as (15) to (17):

$$\overline{V_c} = \frac{L_2V_{1acm}+L_1V_{2acd}+jL_1V_{2acq}}{L_2+L_1-\omega^2L_1L_2C} \quad (15)$$

$$\overline{I_{1ac}} = \frac{V_{1acm}(1-\omega^2L_2C)-\overline{V_{2ac}}}{j\omega(L_1+L_2-\omega^2L_1L_2C)} \quad (16)$$

$$\overline{I_{2ac}} = \frac{\overline{V_{2ac}}(1-\omega^2L_1C)-\overline{V_{1ac}}}{j\omega(L_1+L_2-\omega^2L_1L_2C)} \quad (17)$$

Then rewriting (16) and (17) as:

$$\overline{I_{1ac}} = \frac{V_{1acm}k_1-\overline{V_{2ac}}}{j\omega\cdot k_3} \quad (18)$$

$$\overline{I_{2ac}} = \frac{\overline{V_{2ac}}\,k_2-V_{1acm}}{j\omega\cdot k_3} \quad (19)$$

where,

$$k_1 = 1-\omega^2L_2C \quad (20)$$

$$k_2 = 1-\omega^2L_1C \quad (21)$$

$$k_3 = L_1+L_2-\omega^2L_1L_2C \quad (22)$$

The converter behavior can be studied through the above variables K_1, K_2, and K_3. The three parameters: L_1, L_2 and C can be determined from the (20) through (22). The power transfer level determines the coefficient K_3 which is a positive nonzero constant. In the design stage the coefficients K_1 and K_2 are manipulated to be found. Because ω>0, L_1>0, L_2>0, C>0 based on (20) through (22), it can be determined that:

$$K_1 < 1,\ K_2 < 1,\ K_3 < L_1+L_2 \quad (23)$$

based on the system rating the values for K_1 and K_2 are assumed by taking into account the allowed range. Then M_{2acd} and M_{2acq} are determined using (24):

$$\frac{P_{1ac}}{Q_{1ac}} = \frac{M_{2acq}V_2/\sqrt{2}}{V_{1acm}K_1-M_{2acd}V_2/\sqrt{2}} \quad (24)$$

to calculate K_3.

$$P_{1ac} = -3V_{1acm}\frac{V_{2acq}}{\omega K_3} \quad (25)$$

The values for the LCL filter in our system were adopted based on the methodology detailed in [21]. LCL filter parameter selection followed a systematic process to ensure optimal performance and reliability during both normal operations and fault conditions. The inductances L_1 and L_2 were chosen to limit the fault current to values below the rated level, thereby protecting the converter from potential damage during faults. Capacitance C was selected to minimize reactive power flow under normal operating conditions, enhancing the overall efficiency of the system.

The inductance and capacitance values were calculated accounting for various operational and fault scenarios using (7)-(17). The design ensures that the converter maintains good controllability and minimizes losses. The equations (7)-(17) were adopted from [21] to determine the optimal values for L_1, L_2, and C.

These equations take into consideration factors such as the desired power transfer level, the need for fault current limitation, and the requirement to keep the converter's operational losses to a minimum.

In this system, the LCL filter parameters were carefully chosen based on these guidelines. The selected values are demonstrated in Table 2. These values align with the optimized parameters proposed by [21], ensuring that our converter operates efficiently, remains stable, and can withstand faults without significant performance degradation. By adhering to this established methodology, we have ensured that the LCL filter design is robust and effective for high-power VSC HVDC applications.

While the LCL hybrid converter demonstrated promising fault suppression and power quality improvements, it is important to acknowledge that electromagnetic interference (EMI) considerations were not explicitly addressed in this study. High-frequency EMI, particularly in the differential and common modes, can be a significant issue in VSCs. The LCL filter, while designed to suppress switching frequency harmonics, may offer some mitigation at higher frequencies depending on the inductor construction. However, dedicated EMI filters are often necessary for comprehensive EMI management across a wider frequency range [37].

Table 2. Values adopted for LCL filter

Variable	Value
K_1	0.9
K_2	0.7
L_1	0.35 H
L_2	0.117 H
C	8.6727 μF

5. RESULTS AND DISCUSSION

The three converter topologies discussed above were modeled in MATLAB/Simulink, simulated and a comparative analysis has been carried out. The three converter topologies were compared based on the DC output voltage. The ripple factor was calculated for the DC output voltage of the three converters. In addition, the operation of the converters during a DC fault is presented and compared.

5.1. System performance during normal conditions

The converters operation in steady state is shown in Figure 14 to 16. The figures illustrate the DC output voltage of the three-level neutral point clamped converter, the hybrid converter with AC side cascaded H-bridge cells, and the LCL hybrid converter, respectively. Figure 14 illustrates the DC output voltage in volts of the three-level neutral point clamped converter. The figure shows the output DC voltage reaching steady state at approximately $t = 1$ s. The maximum value of the voltage before it reaches steady state is almost 150 kV. The DC output voltage reaches a steady-state value of 105 kV which is near the DC link rated value of 100 kV.

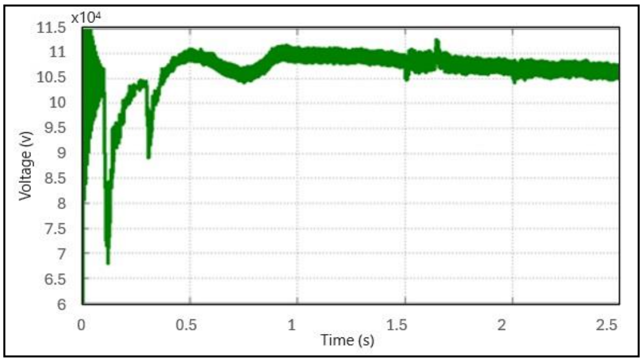

Figure 14. DC output voltage of three level neutral point clamped converter

Figure 15 shows the DC output voltage in volts for the hybrid converter (with AC side cascaded H-bridge cells). It can be observed that there is a significant improvement over three-level neutral point clamped converter in the DC voltage output since the ripple is less and it reaches steady state at approximately $t = 0.6$ s. It is clear from the DC output voltage of the converters that the output is improved after adding the full bridge cells to the three-level neutral clamped converter as can be seen in Figure 15. The maximum value of the voltage before it reaches steady state is almost 150 kV. The DC output voltage reaches a steady-state value of around 100 kV. However, adding the LCL circuit to the hybrid converter has a minor effect in improving the output voltage as shown in Figure 16. Since it also reaches a steady state at approximately $t = 0.6$ s.

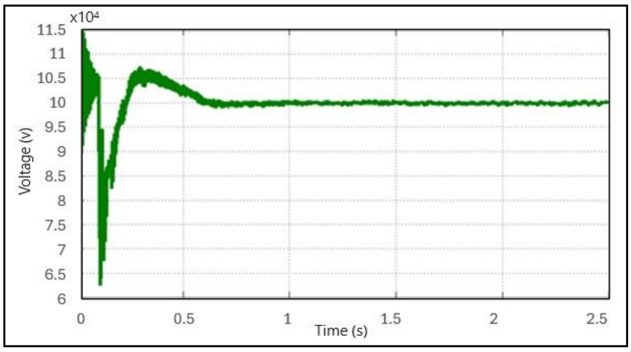

Figure 15. DC output voltage of hybrid converter

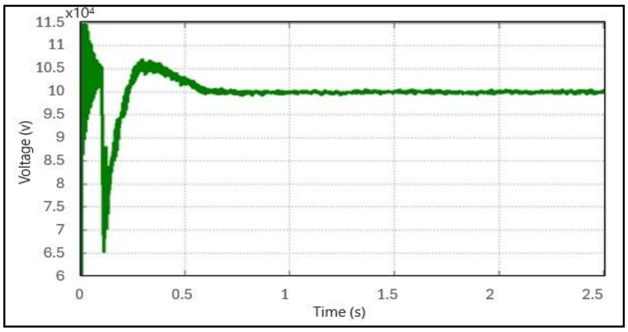

Figure 16. DC output voltage of the LCL hybrid converter

To check the effect of the LCL circuit alone on the three-level (NPC) converter without the full bridge cells, the LCL circuit was added to the three-level (NPC) converter alone and the DC output voltage is presented in Figure 17. It can be observed that the LCL circuit managed to improve the DC output voltage. By comparing the DC output voltage of the hybrid converter shown in Figure 15 with the DC output voltage in Figure 17, it can be observed, that the full bridge cells have the ability to improve the DC output voltage of the three-level (NPC) converter in a better manner. It can be observed that the difference in the output is because of the added capacitors in the LCL circuit.

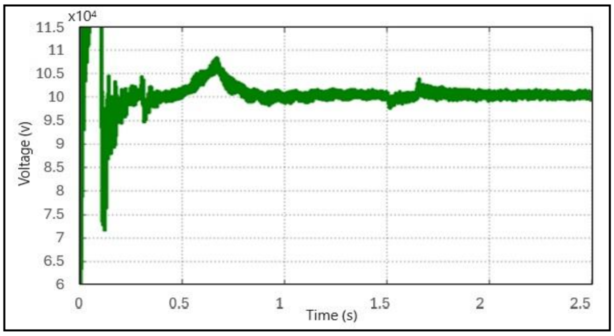

Figure 17. DC output voltage of three-level (NPC) with LCL only

To compare the DC output voltage of the four topologies without the DC filters and 3rd harmonic smoothing reactors, which are used to smooth the output of the converters, a ripple factor analysis of the DC outputs was carried out. The results obtained from ripple factor analysis are tabulated in Table 3. The ratio of ripple magnitude to the mean value V_d is known as ripple factor as in (26).

$$Ripple\ factor = {}^{\delta V}/_{V_d} \tag{26}$$

Where V_d is the direct voltage which is the arithmetic mean of the voltage expressed as in (27):

$$V_d = \frac{1}{T}\int_0^T v(t)dt \tag{27}$$

The deviation from the voltage value periodically is the ripple. The ripple voltage magnitude is:

$$\delta V = \frac{1}{2}(V_{max} - V_{min}) \tag{28}$$

According to the IEEE-4, 1978 standard, the ripple should be less than 3%.

Table 3. Ripple factor of the different converter topologies used

Converter type	Ripple factor
3 level (NPC) converter	3%
Hybrid converter with H-bridge cells	1.4%
LCL hybrid converter	≈1.4%
LCL 3 level (NPC) converter	2%

5.2. System performance during DC fault conditions

In this section, the performance of the three converters during a DC fault is presented. The worst-case DC fault ($V_{dc} = 0$) was applied for the three topologies then, the responses were compared. In Figure 18 and Figure 19, the response of the three-level (NPC) converter during DC fault is presented. Figure 18 shows the DC output voltage of the converter in volts, the DC output voltage mean in pu. Figure 19 shows the power mean of the converter. Although the DC side is short circuited, the DC output voltage mean is considered high and unstable, and the power mean is also unstable and have high values that reaches 1 pu.

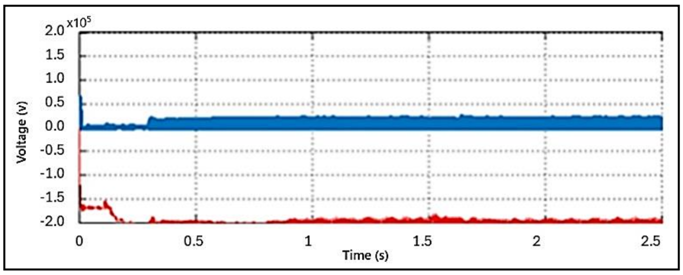

Figure 18. Voltage response of the three-level (NPC) converter during DC fault

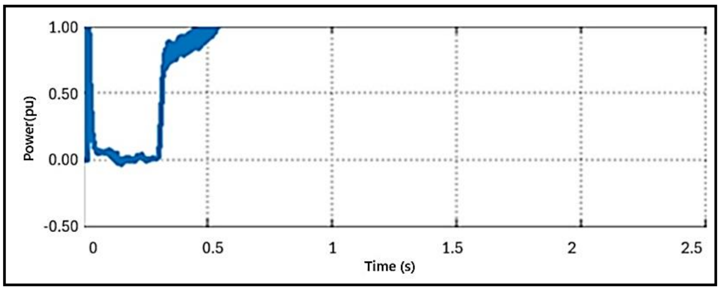

Figure 19. Power response of the three-level (NPC) converter during DC fault

Figure 20 shows the AC input current of the three-level (NPC) converter under the worst-case fault at the DC link ($V_{dc} = 0$). The converter AC current has a high over-current value during the DC fault. It is apparent that the IGBTs have tripped after few μs. If the current values continue at the same base the diodes should be overrated. Due to the fact that the converter failed to keep the AC current near the rated value and to keep its sinusoidal waveform, clearly indicates that did not manage to limit the DC fault and the DC fault was transferred to the AC side. Figure 20 shows the AC input current of the three-level (NPC) converter. Clearly the AC input current exceeds the rated value.

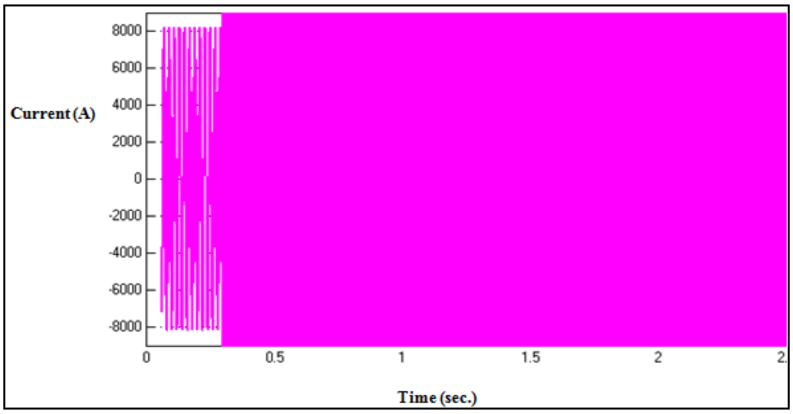

Figure 20. AC input current of the three-level (NPC) converter during DC fault

In Figure 21 and Figure 22, the performance of the LCL hybrid converter during DC fault is illustrated. Figure 21 shows the DC output voltage of the converter in volts, the DC output voltage mean in pu. Figure 22 shows the power mean of the converter. Unlike the three-level (NPC) converter, the LCL hybrid converter shows a more stable response during the fault since the power and voltage means have lower values.

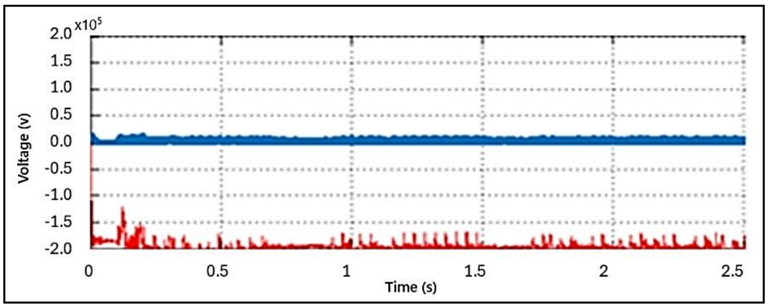

Figure 21. Voltage response of the LCL hybrid converter during DC fault

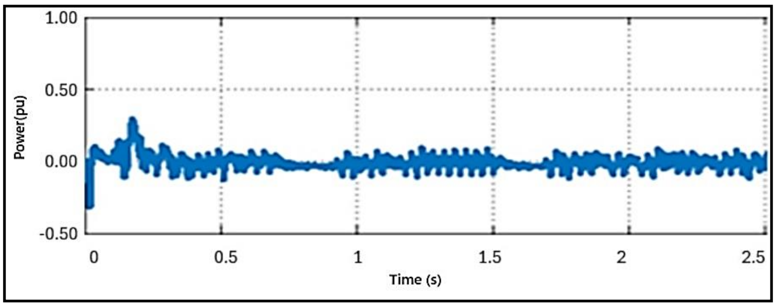

Figure 22. Power response of the LCL hybrid converter during DC fault

The AC input current of the LCL hybrid converter under the worst-case fault at the DC link (V_{dc}= 0) is shown in Figure 23. The figure shows clearly that LCL hybrid converter succeeded in keeping the AC input current within the rated values. Therefore, the DC fault was not transferred to the AC grid and by achieving that, the LCL hybrid converter has the ability to suppress faults.

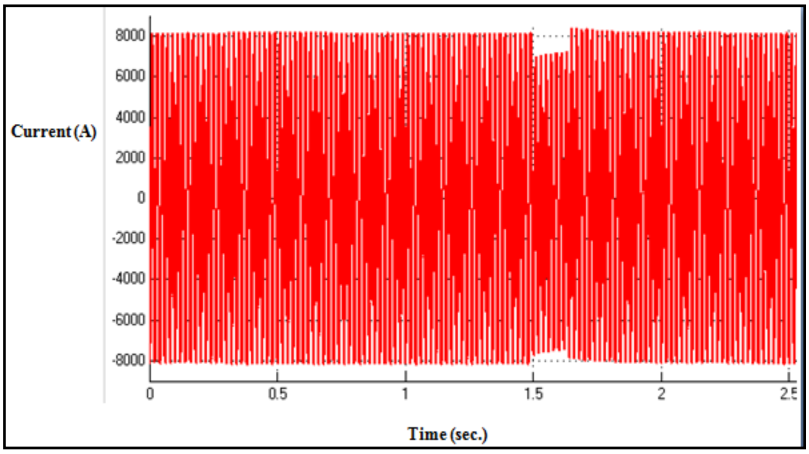

Figure 23. AC input current of the LCL hybrid converter during DC fault

5.3. Summary and discussion

The DC output voltage was found for the three converter topologies. The ripple factor was determined for the DC output voltage of the three converters. In order to study the LCL effect alone, the DC output voltage of an LCL three-level (NPC) converter was found and the ripple factor was also calculated. Moreover, a DC fault was applied at the DC link and the performance of the three-level (NPC) converter, and the LCL-hybrid converter was presented.

Based on the results, the DC output voltage of the three-level (NPC) converter reached steady state at approximately $t = 1$ s. The ripple factor of its DC output voltage was found to be 3%. The DC output voltage reaches a steady state value of 105 kV which is near the rated value of the DC link 100 kV.

However, after adding the H-bridge cells at the AC side of the three-level (NPC) converter, the DC output voltage has improved since the steady state is reached at approximately $t = 0.6$ s and ripple factor was calculated to be 1.4% also the DC output voltage reaches steady state around 100 kV which shows a significant improvement over the traditional three-level (NPC) converter. The results determined for the Hybrid converter coincide with the expected features and with what was found in the literature, that the H-bridge cells will work as an active DC filter.

On the other hand, adding the LCL circuit to the hybrid converter has a minor effect in improving the DC output voltage of the hybrid converter since the LCL hybrid converter DC output voltage almost reaches steady state at the same time as the hybrid converter. In addition, the ripple factor of the DC output voltage did not change after adding the LCL circuit to the hybrid converter. For this reason, the LCL circuit was added to the three-level (NPC) converter to investigate the effect of this passive circuit on the output. It was found that the LCL circuit managed to reduce the ripple factor of the DC output voltage of the three-level (NPC) converter from 3% to 2%. Comparing the effect of the H-bridge cells with the effect LCL circuit in improving the DC output voltage of the three-level (NPC), it can be observed that the H-bridge cells are more advantageous.

The performance of the three-level (NPC) converter and the LCL hybrid converter was tested during a DC fault at the DC link. According to the results, the three-level (NPC) converter failed to suppress the DC fault. The three-level (NPC) converter did not prevent the DC fault from transferring to the AC side. During the DC fault, the three-level (NPC) converter AC input current was unstable, higher than the rated value and lost its sinusoidal waveform. In contrast, the LCL hybrid converter was successful in maintaining the converter AC input within rated values and was able to keep its sinusoidal waveform meaning that the DC fault was unsuccessful in transferring to the AC side as expected.

The LCL converter configuration plays a pivotal role in hybrid HVDC/HVAC systems during severe faults. Primarily, the LCL filter decisively damps oscillations and harmonics, specifically PWM carrier and side-band voltage harmonics, ensuring system stability. It also mitigates resonance risks across the entire harmonic spectrum, providing 60 dB/dec attenuation, essentially preventing fault-induced problems from escalating. Moreover, its design allows for smaller reactive elements and effective power loss management, translating to superior fault ride-through capabilities and stable voltage/current flows during disturbances [20], [37].

The LCL filter's benefits extend to improved system impedance, reducing a fault's impact on the converter, and allowing for greater operational control. Crucially, by smoothing AC currents and DC voltage, the LCL configuration ensures precise power flow management. This control, particularly during faults, is vital for maintaining system stability. These capabilities solidify LCL converters as the superior choice for applications prioritizing reliability and fault resilience [37].

Although the LCL hybrid converter showed a good ability in improving the DC output voltage and in restraining the DC fault, it suffers from disadvantages. Since there are more semiconductor devices in the LCL hybrid converter than the three-level (NPC) converter, the LCL hybrid converter has higher switching losses and is more expensive. Moreover, to assure equal voltage sharing under dynamic conditions the series IGBT valve should be designed carefully. Furthermore, the wave shaping circuit, and the three-level converter should be synchronized to avoid high voltage spikes. Table 4 summaries the simulations results.

Table 4. Summary of simulation results with numbers

Converter type	Ripple factor	Reaches steady state at	Max. value at steady state	Suppress DC fault
Three-level	3%	1 s	105 kV	No
Hybrid	1.4%	0.6 s	100 kV	Yes
LCL hybrid	≈1.4%	0.6 s	100 kV	Yes
LCL 3 level	2%	0.7 s	104 kV	Yes

LCL hybrid converters have been researched by many. Ni *et al.* [38] examined the impact of harmonic distortions on the losses in converter transformers within LCL-HVDC systems, employing detailed simulations to optimize system design for efficiency. This research explores the broader implications of a novel LCL hybrid converter technology in improving fault suppression and DC output voltage quality, with a focus on practical performance evaluations under various operational scenarios. While both studies enhance understanding of HVDC systems, Ni *et al.* [38] concentrates on reducing harmonic-related losses, and the latter assesses enhancements in system stability and performance through innovative converter configurations.

Aboushady *et al.* [39] delves into the integration and challenges of using MMCs with an LCL circuit within high-power DC transmission systems. It addresses issues like high operating frequencies and DC fault management, proposing a scalable control structure for enhancing multi-port DC hub capabilities. In contrast, this research explores the application of LCL hybrid converters to improve efficiency and fault management in HVDC and HVAC systems, focusing on detailed simulations to evaluate different converter topologies. While study [39] is aimed at modular scalability and the technical refinement of DC grids, this research concentrates on specific design improvements for operational stability and fault handling in combined HVDC and HVAC setups.

The H-bridge cells in each phase act as an active filter improving the output waveform. This result is also supported by [17], [40]. DC fault suppression and stability improvements were also reported by [17], [40]. The LCL hybrid three-level bridge ability automatically regulate power conforms with the findings in [21], [41].

6. CONCLUSIONS AND FUTURE WORK

The development of the current power system has become a necessity to make the system more efficient and to reduce its losses, especially in transmission and distribution. High voltage DC (HVDC) has drawn great attention since it presents a solution to the most difficult problems in power transmission, such as the exchange of power between asynchronous grids and long-distance transmission. To improve the stability of HVDC transmission system, both line commutated converters and voltage source converters are used. VSC based HVDC (VSC-HVDC) is a new power transmission technology preferable in power transmission. Although VSCs have many attractive features they suffer from drawbacks. One of the main disadvantages is that it cannot suppress DC faults. A new type of voltage source converters is emerging which combines the advantages of modular multilevel converters and the two-terminal voltage source converters called hybrid converters that have the ability to suppress DC faults.

A model of this new type of VSC which is the series hybrid converter, was modeled in a two terminal system using simulation. Using MATLAB/Simulink, the system with its control was implemented.

The three-level neutral point clamped converter (NPC), the hybrid converter with AC side cascaded H-bridge cells and the LCL hybrid converter were simulated and compared. The three-level neutral clamped converter performance was studied, and then the H-bridge cells were added to converter to investigate the effect of these cells on the converter performance. After this, the LCL circuit was connected to the hybrid converter to notice its effect. To complete the study the LCL circuit was added to the three-level (NPC) converter to investigate the effect of this passive circuit alone on the converter performance. Investigation of the converters' operation under normal and abnormal operation conditions was carried out. The dynamic performance of these converters under DC and AC faults in the supplying grid AC system was investigated.

Based on the DC output voltage, the ripple factor for the DC output voltage of the converters and the operation of the converters during a DC fault, the topologies are presented and compared. In addition, the three-level neutral point clamped converter (NPC) and the LCL hybrid converter were studied in a three terminal HVDC during a three-phase fault. It was figured out that the LCL hybrid converter enhanced the DC output voltage of the three-level neutral clamped converter (NPC), and the DC and AC faults suppression capability is inherent. Both the LCL circuit and the H-bridge cells have good properties in order to develop the three-level neutral clamped converter (NPC) performance. However, the LCL circuit impact is not as good as the H-bridge cells. The H-bridge cells suffer from high switching losses and are more expensive. Moreover, the added value of connecting the LCL circuit to the hybrid converter is limited.

While the proposed LCL hybrid converter demonstrates enhanced fault suppression capabilities and improved DC output voltage quality, this study has several limitations. First, the analysis is conducted within an idealized simulation environment, not accounting for real-world factors such as component aging, temperature variations, and manufacturing tolerances, which could significantly influence the converter's performance in practical applications. Furthermore, the study does not include an economic analysis of implementing the LCL hybrid converter in large-scale power systems, a crucial aspect for understanding the feasibility and scalability of the proposed solution. Additionally, protection schemes and fault management strategies for multi-terminal hybrid HVAC/HVDC systems, including the use of AC and DC circuit breakers, were not explored. A comprehensive economic analysis, including both converter stations and protection schemes, would be particularly beneficial. Finally, this research does not provide a detailed investigation of the LCL hybrid converter's EMI characteristics, which is essential for ensuring reliable operation in real-world environments.

There are certain characteristics of VSC and their topologies which need to be further investigated. Future research will focus on methods for control systems and strategies using fuzzy logic since that would be able to improve the system performance and its dynamic response to various disturbances. Third harmonic injection for controlling converters will also be considered. Protection schemes and fault management of multi-terminal hybrid HVAC/HVDC system using AC and DC circuit breakers will be considered as well. Another logical extension of this research would be a thorough evaluation of the LCL hybrid converter's EMI characteristics. This would include an investigation of differential and common-mode EMI at higher frequencies and the design of tailored EMI filters to optimize system performance and ensure compliance with relevant EMI standards.

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