الجمهورية الجزائرية الديموقراطية الشعبية

République Algérienne Démocratique et Populaire

وزارة التعليم العالي و البحث العلمي

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

Ecole Nationale Polytechnique

Department of Electrical Engineering

Electrical Engineering Research Laboratory

Project of Graduation

Presented by:

Aissa Aymene Rachid DAFRI

In order to obtain the title of:

State Engineer in Electrical Engineering from ENP

Modelling and Analysis of MMC-HVDC Transmission Systems

Publicly defended, July 11, 2021 in front of the jury:

President	Madjid	TEGUAR	Prof.	ENP, Algiers, Algeria
Directors	Abdelouahab	MEKHALDI	Prof.	ENP, Algiers, Algeria
	Omar	KHERIF	Dr.	ENP, Algiers, Algeria
Examiner	Tahar	ZEBBADJI	MCA.	ENP, Algiers, Algeria

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ENP 2021

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Ecole Nationale Polytechnique

Département d'Electrotechnique

Laboratoire de Recherche en Electrotchnique

Projet de Fin d'Etudes

Présenté par :

Aissa Aymene Rachid DAFRI

En vue de l'obtention du titre de :

Ingénieur d'Etat en Électrotechnique de l'ENP

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ENP 2021

ملخص—هذا العمل مكرس لدراسة تقنية مقارنة لأنظمة الإرسال متعددة المستويات القائمة على تقنية نقل التيار المباشر. تم النظر في شبكتين مع ظروف تشغيل مختلفة (مثل التردد ، والجهد ، وما إلى ذلك). استنادًا إلى استمرارية العمل في العام الماضي على أنظمة نقل التيار المباشر ، تم اعتبار الارتباط بين شبكتين غير متزامنتين بقوة 400 كيلو فولت - 60 هرتز و 230 كيلو فولت - 50 هرتز بقوة 300 ميجاوات (نفس النموذج الذي تمت دراسته). في ظل بيئة ماتلاب/محاكاة، يتم إجراء عمليات محاكاة لتقنيات تحويل مصدر الجهد المتتالي متعدد المستويات. يتم عرض النتائج التي تم الحصول عليها ، بما في ذلك التيار والجهد على جانب التيار المباشر ، والتحقق من صحتها بنجاح مع تلك المحسوبة باستخدام النموذج النظري. يتضمن هذا المشروع أيضًا تحليلًا تقنيًا للمحولات متعددة المستويات ذات مصادر الجهد ، تليها دراسة مقارنة بين مختلف المحولات المتتالية متعددة المستويات (3 و 5 و 7 و 9 مستويات). تأخذ المقارنة في الاعتبار أداء واستقرار كل محول عند دمجه في نظام نقل تيار مستمر. بشكل عام ، فقد وجد أن المحولات المتتالية ذات المستويات الأعلى لها تفوق في الكفاءة والموثوقية والتوليد التوافقي مقارنة بالمحولات الأخرى ذات مستويات التشغيل المنخفضة. تقدم محولات الجهد ذات الجسر الكامل المتتالية العديد من الميزات المستقبلية لتقنية النقل المباشر الحالية وتطبيقاتها حول العالم.
الكلمات المفتاحية: رابط التيار المباشر عالي الجهد، محول مصدر الجهد، محولات تبديل الخط، الجسر الكامل المتتالي، شبكة الطاقة، متعدد المستويات، النمذجة والمحاكاة، الدراسة المقارنة، التحليل التوافقي.

Résumé—Ce travail est consacré à une étude comparative-technique de systèmes de transmission multiniveau basés sur la technologie VSC-HVDC. Deux réseaux ayant des conditions d'exploitation différentes (i.e., fréquence et tension) ont été considérés. Basé sur la continuité des travaux de l'année dernière sur les systèmes HVDC, un lien entre deux réseaux asynchrones 400 kV- 60 Hz et 230 kV- 50 Hz est considéré pour une puissance de 300 MW (i.e., le même modèle étudié). Sous environnement MATLAB/Simulink, des simulations de la technologie VSC multiniveau en cascade sont réalisées. Les résultats obtenus, comprenant le courant et la tension du côté DC, sont présentés et validés avec succès avec ceux calculés à l'aide du modèle théorique. Ce projet comprend également une analyse technique des VSCs multiniveaux, suivie d'une étude comparative entre différents convertisseurs multiniveaux en cascade (3, 5, 7 et 9 niveaux). La comparaison tient en compte la performance ainsi que la stabilité de chaque convertisseur lorsqu'il est intégré dans un système de transmission HVDC. En général, il s'est avéré que les convertisseurs en cascade des niveaux plus élevés ont une supériorité en termes d'efficacité, de fiabilité et de génération d'harmoniques par rapport aux autres convertisseurs avec des niveaux de fonctionnement inférieurs. En outre, le CHB VSC-HVDC offre de nombreuses fonctionnalités futuristes pour la technologie de transmission HVDC et ses applications dans le monde entier.

Mots-clés : Liaison HVDC, Voltage Source Converter (VSC), LCC, CHB-VSC, Réseau électrique, Multiniveaux, Modélisation et simulation, Etude Comparative, Analyse d’Harmonique.

Abstract—This work is devoted to a comparative-technical study of multilevel transmission systems based on VSC-HVDC technology. Two networks with different operating conditions (i.e., frequency and voltage) have been considered. Based on the continuity of last year's work on HVDC systems, a link between two asynchronous 400 kV- 60 Hz and 230 kV- 50 Hz networks is considered for a power of 300 MW (the same model studied). Under MATLAB/Simulink environment, simulations of multilevel cascaded VSC technologies are performed. The obtained results, including current and voltage on the DC side, are presented and successfully validated with those calculated using the theoretical model. This project also includes a technical analysis of multilevel VSCs, followed by a comparative study between different cascaded multilevel converters (3, 5, 7 and 9 levels). The comparison considers the performance as well as the stability of each converter when integrated into an HVDC transmission system. In general, the higher-level cascaded converters were found to have superior efficiency, reliability and harmonic generation compared to other converters with lower operating levels. In addition, the VSC-HVDC CHB offers many futuristic features for HVDC transmission technology and its applications worldwide.

Keywords: HVDC link, Voltage Source Converter (VSC), LCC, CHB-VSC, Power grid, Multilevel, Modeling and simulation, Comparative study, Harmonic analysis.

Acknowledgment

I would like to send my sincere thanks to Prof. Abdelouahab MEKHALDI and Dr. Omar KHERIF, ENP, for having proposed this subject to me and for their continuous follow-ups throughout the period of my end-of-studies project. Their invaluable advice, guidance and encouragement greatly contributed to the completion of this work.

I warmly thank Prof. Madjd TEGUAR , ENP, for the honor I have received by agreeing to be the president of the jury and to evaluate our memory.

My sincere thanks also go to Prof. Tahar ZEBBADJI, ENP, for honoring me by agreeing to examine and evaluate my graduation project.

I would like to thank Mr. Fateh ZEKKOUR for having devoted his precious time to me, in order to introduce me to the subject, and for sharing his knowledge in the field of Electrical Networks.

I would like to thank also Mr. Hakeem AGGOUNE and Akram SLIMANI for sharing their work and knowledge in HVDC Systems and for providing their valuable advice.

I express my gratitude to all the teachers of the National Polytechnic School, and in particular, those of the Department of Electrical Engineering for the knowledge they have transmitted to us, their availability and their efforts.

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Liste of abbreviations

AC	Alternative Current
CHB	Cascded H-Bridge
DC	Direct Current
FACTS	Flexible AC Transmission Systems
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolaire Transistor
LCC	Line-Commutated Converter
PWM	Pulse Width Modulation
MMC	Modular Multilevel Converter
MTDC	Multi Terminal Direct Current
RES	Renewable Energies
NPC	Neutral Point Clamped
SCL	Short Circuit Level
SCR	Short Circuit Ratio
STATCOM	STATic COMpensator
SVC	Static Var Compensator
VSC	Voltage Source Converter

List of Symbols

C_{dc}	DC side capacity	F
Ec	Energy Stored by a Capability	J
f	Frequency	Hz
φ	Phase shift	rad
i_1	Fundamental component of line current	AT
i	Instantaneous line current	AT
I_1	RMS value of the fundamental line current	AT
$I_{1\max}$	Maximum value of the fundamental line current	AT
Id	Current coming out of the converter, DC side	AT
P	Active power	W
Q	Reactive power	VAr
Rc	Switching resistance of the converter	Ω
S	Apparent power	GO
t	Time	s
τ, T	Time constants	s
u	Instant complex voltage	V
U	Complex voltage effective	V
v	Instantaneous phase-to-neutral	V
V	Simple effective voltage	V
Vd	Voltage at the output of the converter, DC side	V
V_{d0}	Average value maximum voltage Vd	V
V_{max}	Maximum phase-to-neutral voltage	V
Z	Impedance	Ω
θ	Angle	rad
ω	Pulsation	rad s − 1

General Introduction

General Introduction

Nowadays, the global demand for clean energy and electricity is rising fast. In fact, the International Energy Agency (IEA) predicts that, by 2030, global electricity consumption will be close to 30,000 TWh a year, which will be almost twice the amount of energy consumed in 2010 [1]. To meet these needs, the usage of new sources of energy and construction of new infrastructures for their transport, become crucial and essential. This point has led to the exploration of new research axes in the field of transport and production of electrical energy [2]. Concerning the latter, a new long-term ecological strategy is adopted by many worlds' economic powers. It consists in a progressive integration of clean energy sources in the electrical networks. The development and integration of these energy sources such as wind, solar and fuel cells have gained significant momentum during recent years, providing an estimated 19.1% of global power generation in 2013 [3]. The power systems are managed by generation capacities following demand patterns, but in the future, as more renewable and intermittent generation is integrated into the power system, intelligent demand control will play a major role in balancing the power system. This will require the active involvement of power electronics which is identified as a key enabling technology for the efficient integration of renewable energies (RES) into the grid. Power electronics and new converter technologies may support some of the sustainability goals by enabling the cost-efficient and reliable integration of RES into the power system [4].

Currently, electrical energy is mainly produced, transmitted and distributed in alternating current (AC) via high voltage alternating current (HVAC) transmission networks. However, this type of transmission is not the best way to interconnect renewable energy sources with the grids under some circumstances such as the long distance transmission [5]. Indeed, the resources of the electrical energies (e.g., wind farms, solar plant, …etc.) are often located in remote areas such as in the sea, in uninhabited areas or in desert regions [5]. Thus, the optimal routing of these energies over long distances is not feasible if the power transmission is in alternating current [6]. Other limitations are also related to the use of this type of transmission, including the need to install numerous reactive energy compensation stations along the overhead transmission lines [7]. Furthermore, the interconnection of the two networks is not possible via an HVAC link if their frequencies are different [8]. These imperfections of HVAC transmission have led the power electronics and power system community to further develop new technologies, resulting in improved transmission and power conversion techniques, especially high voltage direct current transmission (HVDC) technology.

HVDC has been a viable technology since 1954 and has played a vital role in both long-distance transmission and in interconnection of ac systems [9]. In particular, cumulative HVDC capacity has grown rapidly due to the steady stream of new voltage sourced converter (VSC) used in the HVDC transmission systems with capacities of several hundred MW up to about 1GW that have entered service since around 2014 when multilevel converter technology became widely applied to HVDC projects [10]. This trend is set to continue beyond 2020, with an anticipated 35 GW or more of new capacity to come on line between 2020 and 2028. This is roughly double the new capacity added in the decade from 2010 to 2019 [11]. These VSC based HVDC systems provide some functional advantages over Line Commutated Converter (LCC) based HVDC schemes and conventional high voltage alternating current (HVAC) [12]. These facts show how HVDC can solve a variety of challenges in grids, and also in the growing number of cases where HVDC has a competitive edge over AC options. In other words; rather than only being used for a limited range of applications where special conditions apply, as in the past, HVDC has become a widely used option for a more diverse range of situations in which VSC is seen as the backbone of future HVDC grids and super grids [7].

VSC HVDC has seen such a dramatic expansion in use over recent years mainly because it offers benefits for the stabilization of existing AC grids. There are potential risks of a variety of instabilities in AC grids, such as voltage or frequency instabilities, power swings, and transients. A variety of measures are adopted to prevent these from happening or to suppress them quickly when they do, including placing operational limits on transmission capacity or installing phase-modifying equipment. Furthermore, many places, especially sites suitable for large renewable energy projects, are prone to instability due to vulnerabilities in existing local grids and a lack of short circuit capacity, meaning that greater penetration of renewables often requires additional measures to be taken to address these instabilities. References [13], [14], [15] focused on the development and scenario of modeling and simulation for VSC-HVDC transmission system integration with AC strong and weak grids such as renewable energy networks. In which, we can see that VSC HVDC doesn't just provide a connection for the transmission of electric power, it can also help maintain or improve stability in existing AC grids, with an increasing number of instances where active use is made of this capability. While, [16], [17], [18] conducted a comparative analysis between multilevel converters with different level stages in order to have lesser switching losses and lower total harmonic distortion. In which they showed that they can achieve a higher number of output levels with greater efficiency and lesser harmonic content that results in quality power and elimination of the need of filtering. Moreover, some studies provided analysis about the impact of VSC topology on fault characteristics (AC and DC faults) in HVDC transmission systems by assessing the response of the system to each kind of fault. This allowed better understanding of the signatures provided by the AC and DC faults that enabled ways of protection for the transmission system, which are discussed in [19], [20]. Therefore, more and more extensive technical studies of HVDC transmissions are necessary for such a project for a better comprehension of their functioning and to be able to operate them in an optimal way.

Entitled "Modelling and analysis of MMC-HVDC Transmission Systems", this graduation project tends to expose a performance comparative study of the different multilevel VSC-HVDC transmission systems between two networks with different operating conditions. Based on the model studied in a previous project of last year's students and in continuous to their work [21], [22] a link between two asynchronous networks 400 kV- 60 Hz and 230 kV- 50 Hz is considered for a transferred power of 300 MW. The modelling and simulation of the line in question is performed under MATLAB/Simulink environment using VSC-HVDC technologies at 3,5,7 and 9 levels VSC-HVDC technology. Where a comparison in terms of performance and stability of the different multilevel technologies of the VSC-HVDC transmissions is done in order to draw the strong and weak points of each technology. The results obtained have shown that low level VSC-HVDC transmission systems have some technical disadvantages (high harmonic emission, lower fault handling capabilities, higher signal ripples) compared to higher level VSC-HVDC. In fact, when stepping up to higher levels multilevel VSC-HVDC systems become more reliable and redundant in power transferring performance point of view.

Indeed, this manuscript is structured in three distinct parts that contain four chapters. In the first chapter, we present general notions related to HVDC transmission systems. First, the general scheme of an HVDC link is illustrated with a brief description of the main components. Then, the existing types and different configurations of an HVDC link are presented with a brief description of each one. This was followed by a comparison between HVAC and HVDC systems in terms of cost, reliability, technical performances and applications. Finally, we end the chapter with a presentation of the most important features and technical challenges in order to highlight the promising new technology of MMC-HVDC. The second chapter deals with the modeling and simulation of the multilevel VSC-HVDC transmission line. First, the various basic elements which are used in the HVDC transmission technology are presented in detail. In addition, the sizing and operation of the two level and three level voltage sourced converter technologies are performed. Then, the principle of active and reactive power transfer in a VSC-HVDC transmission link is explained by presenting the limits of this transfer. In the next and third chapter, multiple simulations environment of the three level VSC-HVDC transmission system are performed under MATLAB/Simulink to study and analyses the performance and reliability of this technology in question in the connection of two asynchronous networks and under different operating conditions (AC and DC short-circuit faults, DC filters capacitance size variation, … etc.).

The fourth chapter represents the second part of the performed simulation studies. It dealt with the evaluation and comparison of the multilevel voltage sourced converters that are integrated in DC transmission link in performance and stability point of view. This chapter help drawing out the advantages and disadvantages of each studied technology. The analysis is based on simulations through MATLAB/Simulink which concerned the harmonic generation in AC and DC sides caused by each converter. Then, a fault analysis was performed to point out the response and behavior of the transmission systems in face of different AC and DC fault occurrences. It was followed by a simulation study, in which the interactions of the HVDC transmission systems with weak AC grids are in question. This comparative study may give a better understanding of the capabilities presented by the new technology of the multilevel VSC implemented in the HVDC transmission systems.

We conclude our project with a presentation of the essential points representing a global synthesis of this study. In addition, we offer some perspectives that will be very useful in the future work of the Electrotechnical Research Laboratory of the National Polytechnic School.

Part I

Review of HVDC Transmission Systems and their Applications

Chapter 1

Review of HVDC Transmission Systems

1.1. Introduction

High voltage direct current transmission systems can be considered as an appropriate solution for power system stability and interconnection for AC grids. In this chapter, the mentioned DC transmission technology and its relevant features for electric power transfer are discussed. Furthermore, basic structure of HVDC transmission systems along with their existing types and technologies are described, followed by a comparison between HVAC and HVDC systems. This comparison is established in terms of cost, reliability, technical performances and applications. Finally, the most important features and technical challenges are presented in order to highlight the promising new technology of MMCs-HVDC.

1.2. Basic Structure of HVDC Systems

An HVDC transmission usually refers to that the AC power generated at a power plant is transformed into DC power before its transmission. At the inverter level (i.e., receiving side), the electric power is then transformed back into AC power. Fig. 1.1 presents a basic structure of an HVDC transmission system.

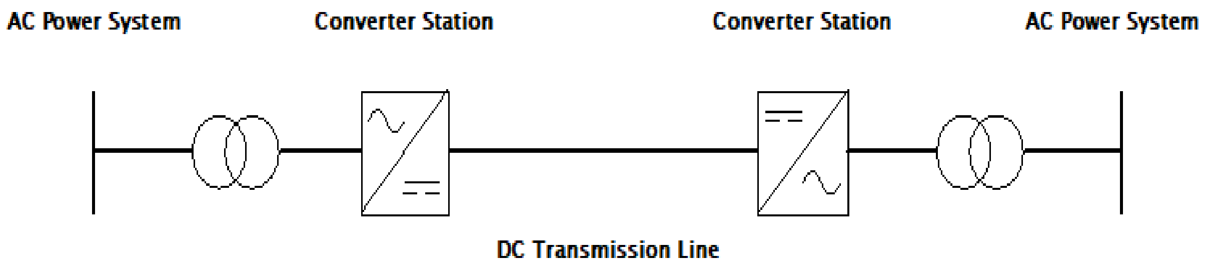


Fig. 1.1: Basic Structure of an HVDC system

As can be seen in this figure, the transmission system contains two isolation transformers; two converter stations (rectifier and inverter) and a DC transmission line that separate the stations. Such a transmission system permits to economically transmit electric power through up conversion of voltage from the AC side to the converter along with the DC side [23]. Fig. 1.2 shows the overall structure of an HVDC transmission with its different components.

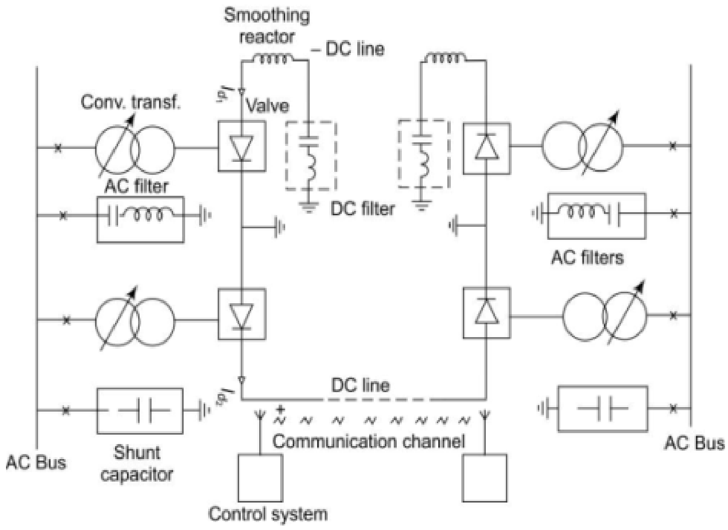


Fig. 1.2: Structure and components of an HVDC transmission system [23]

Obviously, the illustrated structure of the HVDC system is composed of many components and elements which are essential to the power transfer operation. Therefore, these different components and their main utilities concerning harmonic elimination, system protection and power conversion are described in the following paragraphs.

1.2.1. AC Circuit Breaker

Each AC side is connected to an HVDC converter station via a “converter bus”. The breaker is usually used to isolate the HVDC system, in a malfunctioning case, from the AC system, allowing for fast disconnection and reconnection in the event of a loss of a busbar (around 300 ms) [24]. In addition, an AC breaker carries full load current, interrupts fault current, and energizes the usually large converter transformers. The purposes of this breaker are for the interface between AC switch yards or between AC busbar and HVDC system [25].

1.2.2. AC Harmonic Filters

An AC filter is used to attenuate and eliminate the harmonics created by the converters on both sides of the HVDC link. Which might cause overheating of the equipment and interference with communication systems. In case of an outage, several capacitor banks and AC filters are installed, so the link can operate in a derated state [26].

1.2.3. Converter Transformer

Converter transformers are used to provide the required entry voltage of the converter from the AC busbar. They are special types of transformers that are specifically designed to withstand high harmonics currents and voltage stress presented by converters of the HVDC link.

1.2.4. Converter

A converter, which is an essential component of HVDC power transmission, is developed using power electronics. It performs the conversion from AC to DC (rectifier) or from DC to AC (inverter). It consists mainly of a combination of connected thyristor valves or IGBTs. Indeed, the IGBTs-based converters are considered as the new technology in power electronics [27]. These converters, series connected IGBTs together with their auxiliary electronics, are used to perform fast and efficient switching operation that can handle high voltages [28].

1.2.5. DC Smoothing Reactor and Filters

The smoothing reactor reduces the DC ripple current to prevent it from becoming discontinuous at low power levels. Moreover, it forms an integral component, together with the DC filter, to protect the converter valve during a commutation failure by limiting the fast rise time of the current flowing into the converter [25].

1.2.6. DC Switchgears

As in AC substations, switching devices are also needed on the DC side of the HVDC link. Such devices can be characterized as switches with direct current commutation capabilities, commonly called “DC Switchgears". they are usually modified AC equipment used to interrupt DC fault currents (employed as disconnecting switches) [24].

1.3. Types of HVDC Transmission Systems

HVDC systems can be connected in various arrangements and configurations [29]. Each of these configurations is used for a specific operation, depending on the location and purpose of use. These configurations and types of HVDC transmission systems are described in the following paragraphs.

1.3.1. Monopolar HVDC Systems

Monopolar configuration HVDC transmission system consists of two converter stations, the DC transmission line that connects them and a return path [25]. In this configuration, the return line is earthed or provided with metallic return. Fig. 1.3 presents an example of a monopolar HVDC System with earth Return.

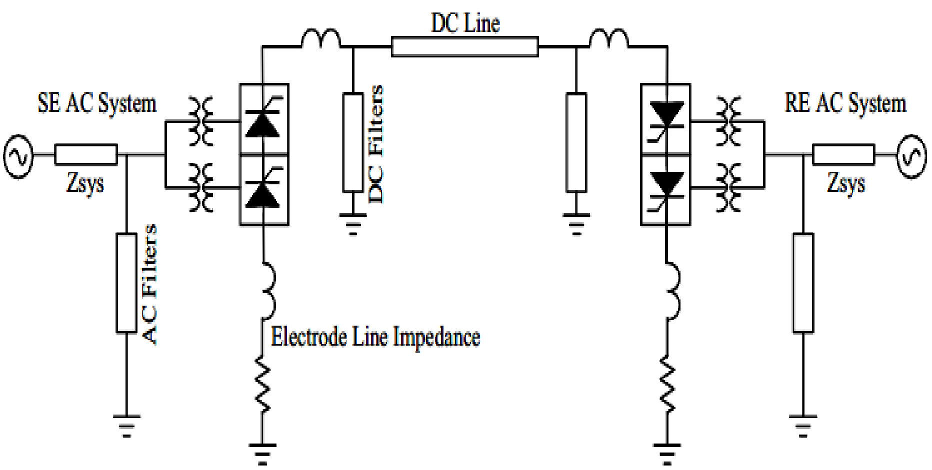


Fig. 1.3: Structure of Monopolar HVDC transmission system [25]

The transmission system, in Fig. 1.3, consists of converter units at each end, a single conductor and return through the earth. It may be a cost-effective solution for a HVDC cable transmission or the first stage of a bipolar scheme. Monopolar HVDC system, with metallic return, usually consists of one high-voltage and one medium voltage conductor. It is worth noting that a metallic return path is preferred instead of an earth return, when the underground/undersea metallic components may cause some interference [29].

1.3.2. Bipolar HVDC Systems

Bipolar HVDC transmission system configuration represents a parallel connection of two monopolar HVDC systems for the transmission of electricity. It presents a configuration that is commonly used in practical applications in the high-voltage DC transmission [30]. Fig. 1.4 shows a bipolar HVDC System that consists of two poles, each of which includes converter units, in series or parallel.

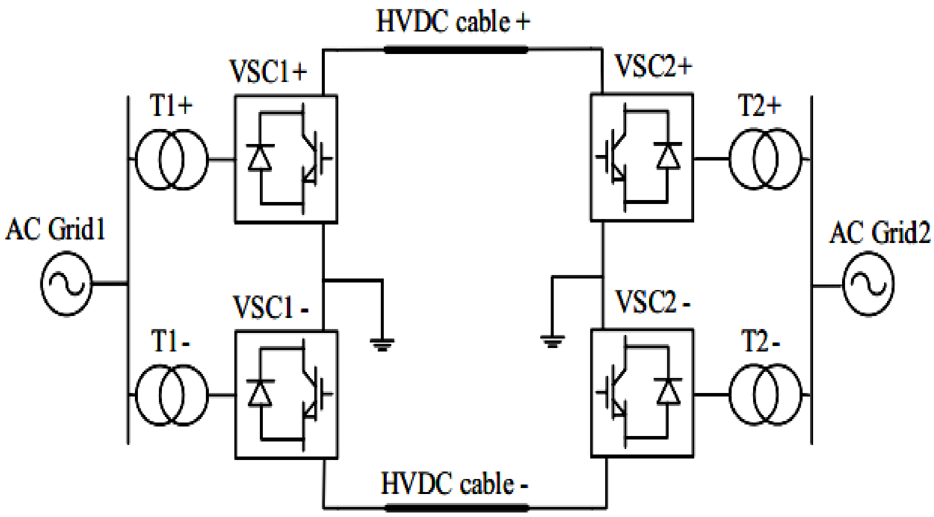


Fig. 1.4: Structure of Bipolar HVDC transmission system [30]

Compared to the first configuration, it is clear that there are two conductors in this configuration; one with positive and the other with negative polarity for power flow in one direction. For power flow in the other direction, both conductors reverse their polarities [10]. During an outage or maintenance of one pole, the other one could be operated continuously with the earth return. It is worth noting that a third conductor can be added end-to-end to carry unbalanced currents during bipolar operation and serves as the return path when a pole is out of service [24].

1.3.3. Back-to-Back HVDC Systems

A back-to-back HVDC station is used to create an asynchronous interconnection between two AC networks, which could have the same or different frequencies. Both converters (rectifier and inverter) are located in the same station with no DC transmission line [31]. Fig. 1.5 shows a back-to-back HVDC link, where there is no DC transmission line and both converters are located at the same site.

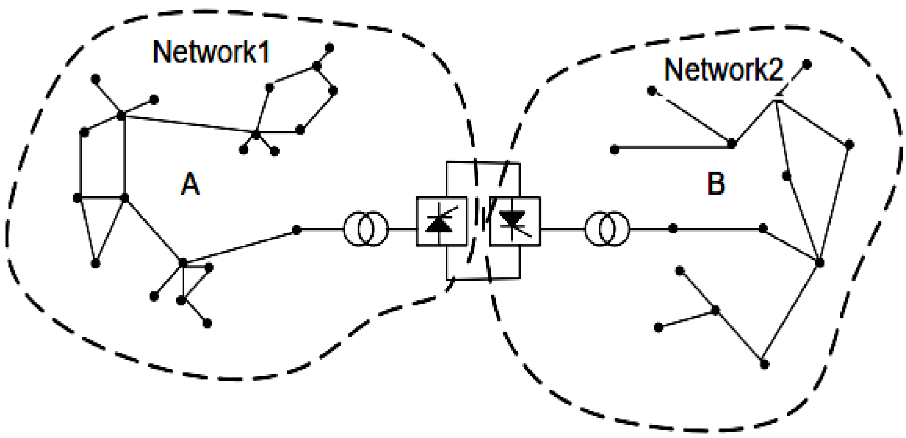


Fig. 1.5: HVDC Back-to-Back transmission system [31]

Control system, cooling equipment and auxiliary system may be integrated into configurations common to the two converters. In addition, DC filters are not required, nor are electrodes or electrode lines [2]. Generally, for a back-to-back HVDC link, the DC voltage rating is low in comparison with HVDC long distance interconnections via overhead lines or cables [32].

1.3.4. Multi-Terminal HVDC Systems

Multiterminal HVDC transmission system refers to an HVDC system that consists of three or more transforming stations. Its architecture is more complex compared to that of a two-terminal system shown previously. It requires a significant complexity to facilitate communication and control between each transforming station. However, it is considered to be a relatively new technology and has potential for a wide range of applications in the future such as interconnecting wind farms, island grids and asynchronous networks [25]. Fig. 1.6 shows an example of a four-terminal HVDC transmission system.

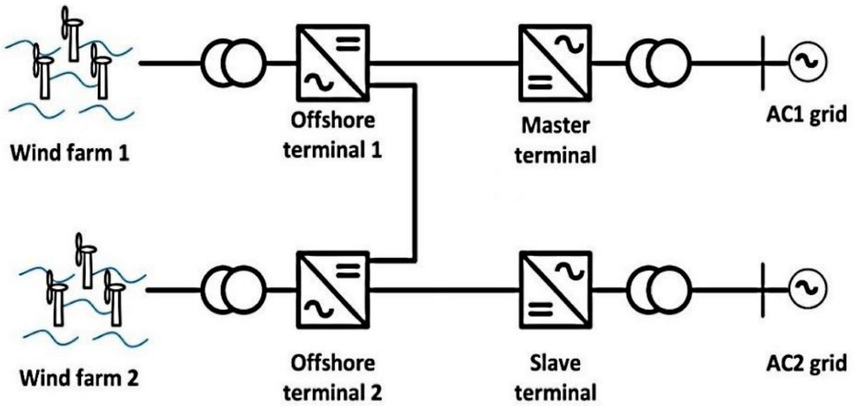


Fig. 1.6: Multi Terminal HVDC [33]

The presented structure of the multi-terminal HVDC transmission system couples two onshore AC grids from different areas and two offshore wind farms, this is also called a hybrid multi-terminal HVDC transmission system [33].

1.4. Comparison Between HVDC and HVAC Transmission

An evaluation of transmission costs, technical considerations, and the reliability/availability offered by the transmission alternatives is necessary to make a planning selection between either HVAC or HVDC transmission.

1.4.1 Transmission Economics

The cost of a transmission line comprises the capital investment required for the actual infrastructure, towers, conductors, insulators and terminal equipment and also costs incurred for operational requirements. For the same transmission capacity, HVDC transmission lines cost less than HVAC transmission lines in the same length. Fig. 1.7 shows the investment costs and total costs of transmission with distance for overhead line transmission with HVAC and HVDC [34].

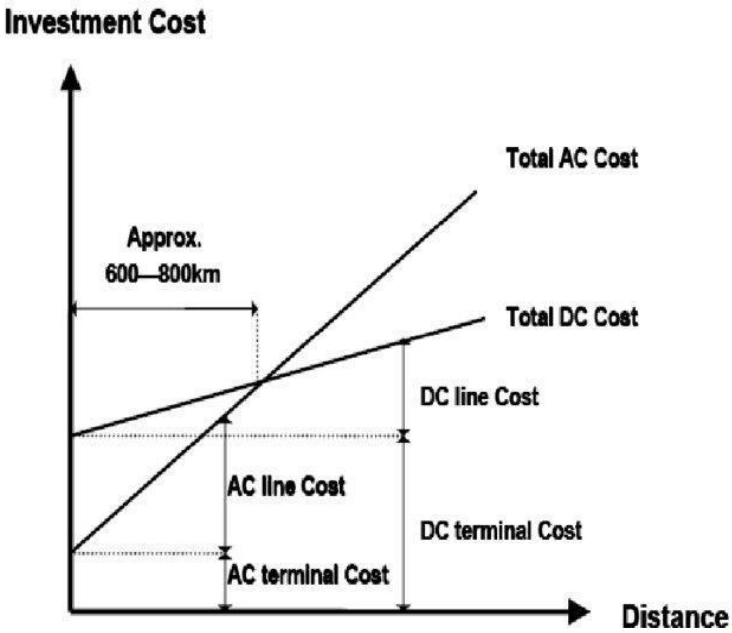


Fig. 1.7: HVAC versus HVDC break-even costs [29]

DC transmission of bulk power over long distances has certain distinct advantages over conventional AC power transmission. In DC transmissions, inductive and capacitive parameters do not limit the transmission distance and capacity, so the DC conductor is fully employed [35]. For long distance power transmission over 500 km, the saving in cost is substantial as shown in Fig. 1.7. A DC line requires only 2 conductors whereas an AC line requires 3 conductors in AC systems. The cost of the terminal equipment is higher in the DC line than that in AC line. It is understood from Fig. 1.7 that a DC line is economical for long distances which are greater than the break-even distance. The break-even distance also varies with the power transmitted over the line [23].

On the other hand, corona and skin effects tend to be less significant on the DC conductors than for AC. This leads to the choice of economic size of conductors with DC transmission. The other factors that influence the line costs are the costs of compensation and terminal equipment.

DC lines do not require compensation but the terminal equipment costs are increased due to the presence of converters and filters [36]. Table 1.1 gives a comparison of the power transfer capability of HVDC and HVAC systems over various distances.

Table 1.1: Power transfer capability of HVDC and HVAC [36]

Distance in km	Capability of HVDC Transmission MW		Capability of HVAC Transmission MW			
	400kV	800kV	400kV	750kV	1000kV	1200kV
50	2250	9000	405	1660	3680	5790
700	1690	7000	313	1250	2770	4340
900	1460	6000	261	1080	2400	3770
1100	1360	5000	219	900	1987	3125

As observed from the table, HVDC transmission systems have better handling capabilities of bulk power transferring over long distances compared to that of HVAC transmission. It is shown that for the same operating voltage (ex: 400 kV), HVDC transmissions have 5 times the transfer capacity of a conventional HVAC system. This is due to some HVAC transmission limitations which are presented in detail in the next section.

1.4.2. Technical Performance

The HVDC transmission system has a lot of positive features which are lacking in the AC transmission, but are mainly due to the fast controllability of power in DC lines through converter control [14]. Following are some technical advantages:

- Full fast control over power transmitted.
- High ability to enhance both the transient and dynamic stability of an AC system when embedded with a DC link.
- DC power does not have an alternating Reactive Part like AC power. So, it has a higher power transmission efficiency.

In addition, The HVDC transmission system overcomes some limitations of the AC transmission and we can describe them in the following points.

1.4.2.1. Stability Limits

Power transfer in HVAC systems is limited by the load angle, which increases when the transmission distance is increased. Hence, it is required to maintain relatively low values of this angle under normal operating conditions, since any disturbance in the power flow can cause large oscillations that affect the system's stability. However, the carrying capability of DC lines is unaffected by the distance of transmission, the thermal conditions and current carrying capacity of the conductor[37].

1.4.2.3. Line Compensation

AC lines require shunt and series compensation in long distance AC transmission, to overcome the problems of line charging and stability limitation. Series capacitors and shunt inductors are used for this purpose. The other method of improving the stability and voltage regulation is by means of FACTS technology (SVC) [23].

1.4.2.5. Corona and Radio Interference and Skin Effects

Corona loss and radio interference are lower in DC systems. Further, there is no skin effect in the conductors of a DC system, whereas it increases the effective resistance of the AC system [37].

1.4.2.6. AC Interconnection Problem

AC interconnections control have to be coordinated using tie-line power and frequency signals. Even with this coordinated control, the operation of AC interconnections can always pose a problem due to the presence of large power oscillations which can lead to frequent tripping, transmission of disturbances from one system to another and the increase in fault level [38].

1.4.2.7. Cable for Underground or Undersea Transmission

In DC lines, there is no charging current or reactive power taken, unlike in AC systems. Also, electric fields are unidirectional and ionic motion is absent. Therefore, a working stress of 400 kV/cm is provided against 100 kV/cm in AC cables. Furthermore, DC cables are subjected to less overcurrent stresses and can transmit power for about 2.5 times that with AC [23].

Limitations of the HVDC transmission lines can be summarized in the need for huge filters on both AC and DC sides to suppress the harmonics adding to the cost of the conversion stations. Reactive power compensation is essential since a DC system cannot generate reactive power when the converters operate with gate control [39]. Hence, a reactive power is to be supplied from the AC side at both ends which adds more installation costs [40]. Over the years, however, there have been significant advances in DC transmission, which have tried to overcome the listed disadvantages like:

- The development of Modular construction of converters that no longer needs huge harmonic filters and can reduce voltage ripples.
- Application of fiber optics and digital electronics in the control of converters. So, the complexity of control does not pose a problem and can actually be used to provide reliable and fast control of power transmission under all conditions.
- Advances of the power electronics allowed to reduce the converter equipment costs

1.4.3. Reliability and Availability of HVDC Systems

Reliability and availability deal with the degree to which system performance is limited by system failures. Generally, this means the probability of the scheme to transmit its rated load at any point in time under normal operational conditions. Specifically, for the purposes of an HVDC project, and it is expressed in terms of the number of forced outages of the scheme per year, normally termed “Forced Outage Rate”, after which emergency repair work would be necessary in order to restore the equipment to normal operation. And availability is a measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown point in time [25].

Authors in [39] provided a study of existing HVDC links in the world and it presents that the HVDC lines show considerably better performance than HVAC transmission with respect to permanent faults. Therefore, the reliability of the DC transmission system is quite good and comparable to that of AC systems [24].

Furthermore, developments like IGBTs and new techniques of control and protection have improved reliability to reach very high levels compared to HVAC transmission systems. In [23], it is indicated that, when comparing the reliability of various alternatives, it must be remembered that the bipolar DC line can be as reliable as a double circuit AC line with the same power capability. This is because in the event of failure of one pole of a DC system, the other pole can supply at least 50% energy with ground return. Table 1.2 points out some characteristics of comparison between the HVDC and HVAC interconnections which shows that HVDC links technically are superior to HVAC links and are preferred for interconnection between two individually controlled AC systems.

Table 1.2: Comparison Between HVDC and HVAC Interconnection [23]

Characteristics	HVDC Link	HVAC Link
Power Transfer ability	High, limited by temperature rise	Lower, limited by power angle and the reactance
Control of Power Flow	Fast and bi-directional	Slow and Difficult
Frequency disturbance	Reduced	Communicated between the system
System support	Excellent	poor
Transient performance	Excellent	poor
Fault levels	Remain unchanged after connection	Get added after the connection
Power swings	Damped quickly	Continue for long period of time
interconnection	Asynchronous	synchronous
Frequency conversion	Possible	Not possible
Transient Stability Limit	Very High	Low

From Table 1.2, we can see that the HVDC transmission systems have a lot of advantages and wide applications which can be utilized in various fields all around the globe. Fig. 1.8 presents some of these important applications.

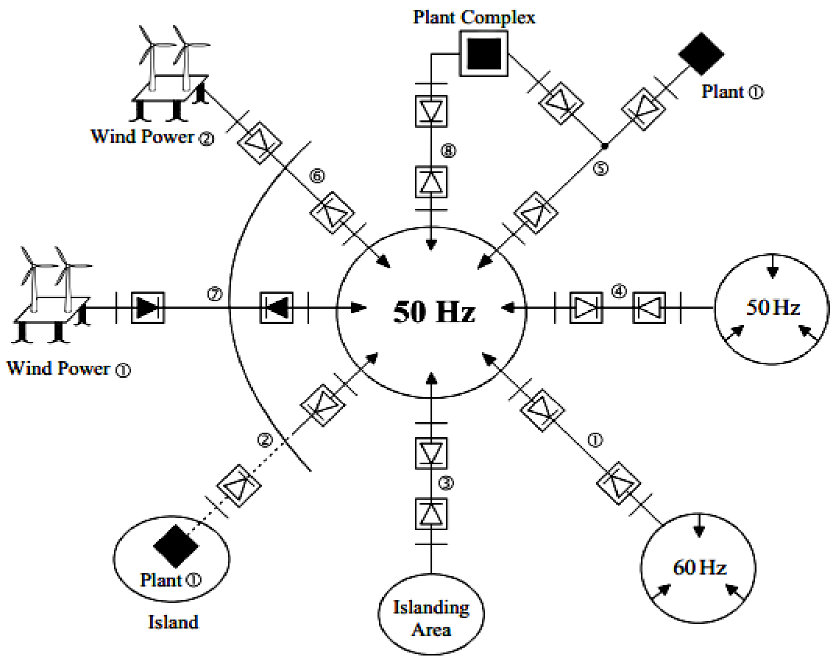


Fig. 1.8: Application of the HVDC Transmission Technology [23]

Some of the possible utilities for the HVDC transmission technology in power grids are presented in the figure. These utilities and applications are labeled and briefly described in the following.

1. Power transmission of bulk energy through long distance overhead line.
2. Power transmission of bulk energy through sea cable.
3. Fast and precise control of the flow of energy over an HVDC link to create a positive damping of electromechanical oscillations and enhance the stability of the network by modulation of the transmission power by using a Back-to-Back.
4. Since an HVDC link has no constraints with respect to frequency or to phase angle between the two AC systems, it can be used to link systems with different frequencies using an Asynchronous Back-to-Back.
5. When power is to be transmitted from a remote generation location across different countries or different areas within one country, it may be strategically and politically necessary to offer a connection to potential partners in the areas traversed by using a multiterminal DC link.
6. An HVDC transmission system can also be used to link renewable energy sources, such as wind power, when it is located far away from the consumer.
7. VSC (Voltage-Source Converter) based HVDC technology is gaining more and more attention. This new technology has become possible as a result of important advances in the development of Insulated Gate Bipolar Transistors (IGBT). In this system, Pulse-Width Modulation (PWM) can be used for the VSC as opposed to the thyristor based conventional HVDC. This technology is well suited for wind power connection to the grid.
8. Since reactive power does not get transmitted over a DC link, two AC systems can be connected through an HVDC link without increasing the short circuit power; this technique can be useful in generator connections.

1.5. HVDC Transmission Technologies

Although HVDC Transmission is now considered as a mature technology, a lot of research and development work is going on to provide a better understanding of HVDC link performance to achieve higher efficiency and more economical design of relevant equipment, and to justify alternative uses of HVDC system configurations. Some of the HVDC transmission systems are presented in the following paragraph.

1.5.1. LCC-HVDC Systems

Generally, the HVDC system based on the thyristor converter is named as the traditional HVDC system, which is also known as the line commutated converter HVDC system (LCC-HVDC). Fig. 1.9 gives a basic structure of the LCC-HVDC transmission system.

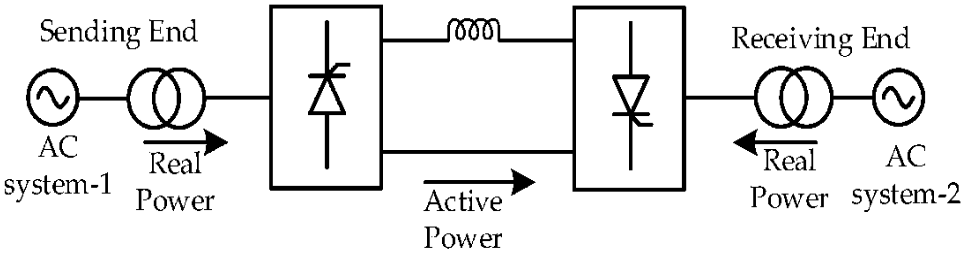


Fig. 1.9: Basic Structure of an LCC-HVDC transmission system [37]

LCC-HVDC transmission system has the advantages of transmitting power over long distances, large transmission capacity, low transmission power loss, and so on [41]. However, the LCC-HVDC system also has some technical disadvantages such as the need for the AC grid to provide commutation voltage for the normal operation of thyristors. Thus, commutation failure could occur when it is connected with a weak AC power grid. In addition, the thyristor-based converter requires large reactive power, which means a large number of filters and capacitors should be installed.

1.5.2. VSC-HVDC Systems

VSC HVDC power transmission uses IGBT-based voltage source converters with advanced control strategies. It presents an efficient power transmission and provides dynamic reactive power support for the linked AC systems. As Fig. 1.10 shows the main difference between the VSC-HVDC and the LCC-HVDC is the converter stations (Voltage sourced converters instead of thyristors-based converters).

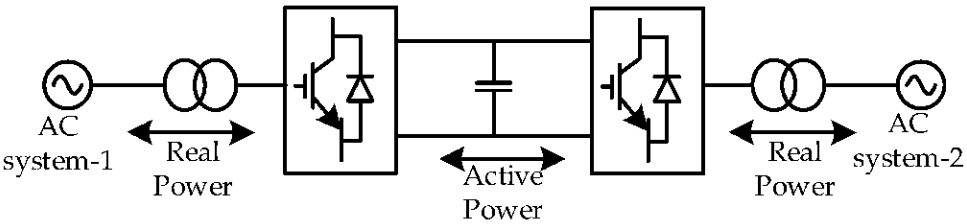


Fig. 1.10: Basic Structure of an VSC-HVDC transmission system [37]

These stations mainly include the multilevel VSC or the MMC. The VSC uses the full-controlled IGBT switch, which avoids the commutation failure problem of the LCC-HVDC system. In addition, the VSC can control the active power and reactive power respectively. During the reverse power flow, the VSC-based DC system only needs to change the current direction, without changing the voltage polarity.
Moreover, because of the waveform quality of the VSC which is much better than the LCC, the filters and reactive compensation equipment can also be reduced significantly. However, the operation power loss of the VSC is larger than the LCC and the fault damage in the VSC-HVDC system is much more serious [41]. It is particularly suitable for the following applications:

- Connecting renewable energy sources.
- Delivering energy to an independent system such as an island or an oil platform.
- Providing energy to an urban area with high-rise buildings that are experiencing rapid load growth.

- Providing power through transmission lines installed over a long distance.

1.5.3. Hybrid-HVDC Systems

Hybrid HVDC system is a new transmission concept developed in recent years. It combines the LCC-HVDC's characteristics of bulk power transmission and low cost with VSC's characteristics of non-commutation failure and dynamic reactive power support, which enable the Hybrid HVDC system to be a fundamental technology to avoid the risk of multi commutation failure in the multi HVDC infeed at receiving end, thus bringing broad application potential [42]. As shown in Fig. 1.11 Hybrid HVDC refers to a system that combines the LCC and VSC simultaneously in one HVDC system.

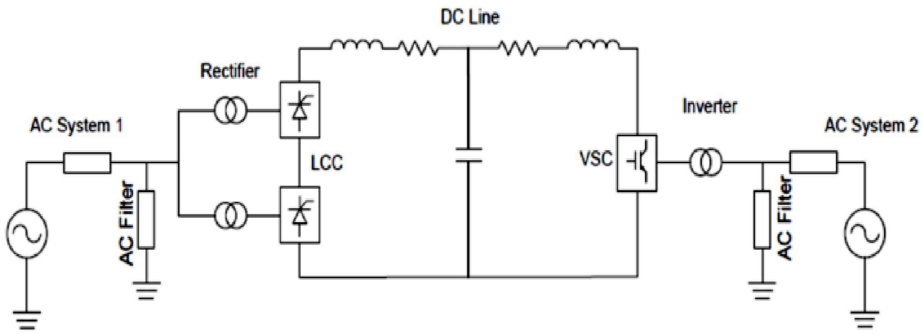


Fig. 1.11: Basic Structure of a Hybrid-HVDC transmission system [42]

Hence, either a rectifier or inverter terminal can adopt the LCC topology while another one adopts VSC topology. Besides, the concept of hybrid LCC-VSC HVDC can be applied to upgrade the existing LCC-HVDC connection by replacing one of the terminals with VSC. Also, the LCC-HVDC and VSC-HVDC system can be interconnected to build a new hybrid network with the possibility to conduct various topologies in function of the presented application and needed characteristics [43]. Some of these technical characteristics are presented in Table 1.3.

Table 1.3: Technical characteristics of the LCC-HVDC and VSC-HVDC systems [26]

Technical characters	Basic element	Harmonic component	Reactive/active power	Power loss	Capacity and voltage rating	Power flow reverse	DC fault handling	DC fault current
LCC-HVDC	thyristors	Large-low frequency component	Consume large reactive power	0.7%	6400MW (11000 kV)	DC voltage polarity reverses	Adjust trigger angle	small
VSC-HVDC	IGBT	Small high frequency harmonic component	Controlled	1.6%	400-800MW (300 kV)	Current direction changes	Uncontrolled	Large

As shown, VSC-HVDC transmission systems have multiple technical advantages concerning harmonic components, reactive power consumption and DC fault handling capabilities over the LCC-HVDC systems. However, conventional LCC-HVDC systems provide lesser power losses and higher voltage ratings which are preferred in bulk power transferring.

1.6. MMC-HVDC Systems

MMC is considered as the newest VSC topologies that was developed in recent years. It scales the voltage wave to approach the sine wave during voltage modulation. When the voltage level number is large enough, the converter output AC voltage can be very close to the sine wave, thus reducing the harmonic component effectively. Compared with the multi-level VSC, the switching loss of the IGBT can be significantly reduced when the step wave modulation is used. The modular design of the MMC avoids the IGBT series-connection problems, thus can be used in the higher voltage system. But the MMC requires more IGBTs, resulting in higher investment. The topology and control are also more complex, which leads to new problems, such as the sub-module capacitor voltages balance control and the circulation control [44]. Fig. 1.12 presents a description of the Modular multilevel converter configuration and its submodule.

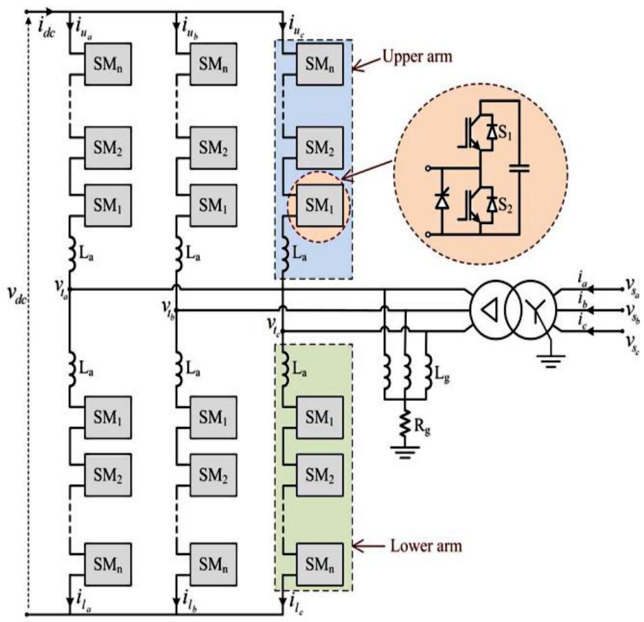


Fig. 1.12: Modular multilevel converter and configuration scheme of HB submodule in the upper arm [44]

It shows the configuration complexity of the MMC topology that has a big number of submodules connected in series (around 200 SMs). It requires a complex control technique for the submodules to ensure the efficiency of conversion operation.

1.6.2. Configuration of MMCs

As presented in Fig. 1.12, the DC system of the MMC is often referred to as a DC-bus or DC-link, connected to the positive and negative bars of the converter legs. The three-phase AC system is connected to the midpoint of each leg. Each leg of the MMC is divided into two arms. The arms connected to the positive bar are referred to as the upper arms (u), and the arms connected to the negative bar are referred to as the lower arms (l). Each arm has a group of submodules and an inductor (L). Arm inductor is connected in series with each submodule to limit the current due to instantaneous voltage difference between the arms [45].

The main features of MMC are:

- Modular construction with an ability to scale the voltage and power rating.
- Can generate an output voltage and current waveforms with reduced ripple. So, an output voltage with a very low total harmonic distortion can be obtained.
- MMC can produce the output voltage waveform with a very large number of voltage levels. Hence, it is possible to operate the submodules with a very low switching frequency.
- Can employ redundant submodules in each arm to achieve a fault-tolerant operation.

A submodule is a simple power conversion circuit. Usually, low voltage IGBT devices and DC capacitors are used to configure a submodule [46]. The commonly used submodule configurations in a modular multilevel converter are:

- Half-bridge (HB) submodule
- Full-bridge (FB) submodule
- Flying capacitor (FC) submodule
- Cascaded half-bridge (CH) submodule
- Double clamp (CD) submodule

1.7. Technical Challenges of MMC-HVDC Systems

It is clear that MMC is the most developed technology used for HVDC transmission. However, these systems require special concern on the number of the existing challenges in this new configuration. The design of the arm inductance and submodule capacitors represents the main constraint. Arm inductance tunes the switching frequency harmonics in the arm current and limits the DC short-circuit current. Therefore, sizing of the arm inductor depends on the arm current ripple and short circuit current [47]. The suppression of undesirable low-frequency currents needs to be considered during the design of an arm inductor. The submodule capacitor is sized based on the tradeoff between size, cost and capacitor voltage ripple [46]. Moreover, additional technical challenges associated with the operation and control of MMCs are presented in the following paragraphs.

1.7.1. Submodule Capacitor Pre-Charging Process

MMC submodules have floating capacitors with zero initial voltage. These submodule capacitors must be charged to its nominal voltage level before starting the normal operation. However, the charging process of submodule capacitors during startup and after a fault can lead to a large inrush current because of the small equivalent impedance of the converter. The pre-charging of submodule capacitors without inrush current is one of the major challenges in MMC technologies [34].

1.7.2. Submodule Capacitor Voltage Control and Ripple

Having series-connected submodules with unequal capacitor voltages cannot be accepted in an MMC configuration. This will increase the differential current and thus, increase the ripple content in the submodule capacitor voltages. Which means that the harmonics inside the DC-link voltage will be increased. Thus, capacitor voltages should follow a predefined reference signal. Moreover, these voltages should be balanced to lower the differential current and converter losses. The MMC has several submodules in each arm and controlling these submodules is one of the challenging tasks [47]. The interaction between the arm currents and voltage causes a voltage ripple in submodule capacitors. The ripple in submodule capacitors is dominated by the fundamental and second-order harmonic components only. The magnitude of voltage ripple is inversely proportional to the fundamental frequency. Hence, the suppression of voltage ripple is a trade-off between the performance, efficiency, reliability and the cost/size of the MMC [48].

1.7.3. Circulating Currents and Fault Tolerance

The voltage difference between the upper and lower arms of the MMC legs results in a circulating current. it has little influence on the output voltages and currents at the AC side. However, it distorts the arm current, leading to extra power losses, a higher rating of devices, and submodule voltage ripples. Therefore, the circulating currents must be suppressed for a reliable and efficient operation of MMC [34].

The MMC is always designed with a redundant submodule to continue their operation during faults. Typically, the submodules are designed with a bypass switch connected across the AC output terminals. During the fault condition, the bypass switch is used to disconnect the faulty submodule and insert one of the redundant ones in the arm. Thus, the effect of faults on the MMC operation can be significantly minimized [49]. However, detecting faults and inserting redundant submodules without inrush current is a great challenge. The DC short-circuit fault is another major issue in the MMC-HVDC systems. The DC circuit breaker is commonly employed to protect the system during the DC faults. On the other hand, the submodules with DC fault-blocking capability can be employed in the MMC-HVDC system. During the fault condition, the submodules are controlled to generate the negative voltage level at the AC output terminal, which blocks the fault current owing through the devices [48].

1.8. Conclusion

An overview of HVDC transmission systems was presented in this chapter. It is found that the HVDC systems produced many advantages compared to the HVAC transmission. These advantages mainly include the interconnection of asynchronous networks, long-distance bulk power delivery, economic and environmental benefits. Besides, this study showed that the development of power electronic devices will also promote the integration of HVDC technology significantly and will have great prospects. Especially when it comes to the MMC-HVDC technology that has attractive aspects of high voltage operation in terms of power quality, efficiency, redundancy and modularity. This modular structure will allow the application for a wide power range and will offer exclusive technical characteristics for HVDC transmission technology.

Part II

Modelling and Simulation of Multilevel VSC-HVDC Transmission Technology

Chapter 2

Modelling Procedures of Multilevel VSC-HVDC Systems

2.1. Introduction

This chapter deals with the modelling and simulation of the VSC-HVDC link. The different basic elements of the technology are presented in detail in the first part. Then, the dimensioning and the operation of three level VSC converter technology are performed. In addition, the principle of active and reactive power transfer in a VSC-HVDC link is explained and the limitations of this transfer are presented.

2.2. Structure of VSC-HVDC Technology

In order to ensure its proper operation, a VSC-HVDC transmission line has several important elements, namely transformer, AC filter, phase inductor, converter and so on. Among these elements, three are major (AC power network, converter and DC line). Fig. 2.1 shows a typical representation of a VSC-HVDC transmission line.

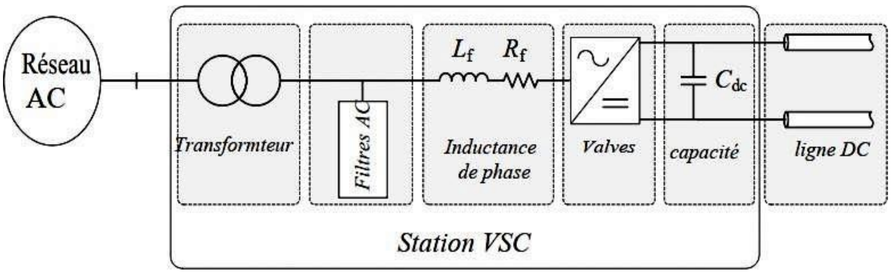


Fig. 2.1: Structure of a VSC-HVDC transmission line

It is clear that transformers and filters have an important role in ensuring the proper functioning of the line. In the following, we explain each element in the 3-level VSC-HVDC structure.

2.2.1. Converter Structure

Related to LCC technology, VSC consists in using other components instead of thyristors. These are components that can be switched on and off, such as insulated gate bipolar transistors (IGBTs). Fig. 2.2(a) shows the basic structure of a VSC (phase structure). This element, called a half-bridge converter, is the simplest switching device capable of producing an AC signal from a DC source by delivering an output voltage as a simple square wave. Fig. 2.2(b) shows the output signal of the converter [50].

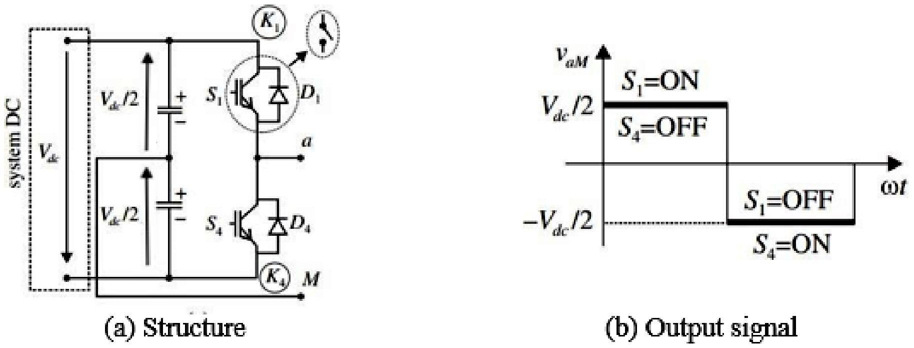


Fig. 2.2: Structure of a half-bridge converter and the output voltage [50]

The half-bridge VSC consists of an upper S1 and a lower S2 switching cells. Each cell consists of a fully voltage-controllable unidirectional element and an antiparallel diode to allow current flow in both directions (positive and negative). When the switch S1 enters the conduction mode and S2 is blocked, the output voltage of the converter is equal to $\frac{V_{dc}}{2}$. Otherwise, the output voltage changes polarity when both S1 and S2 change state. The switching states of a converter represent a set of signals used to control each device in the electrical circuit. Based on these switching states, four possible current paths have been obtained in a half-bridge VSC converter. These paths are shown in Fig. 2.3.

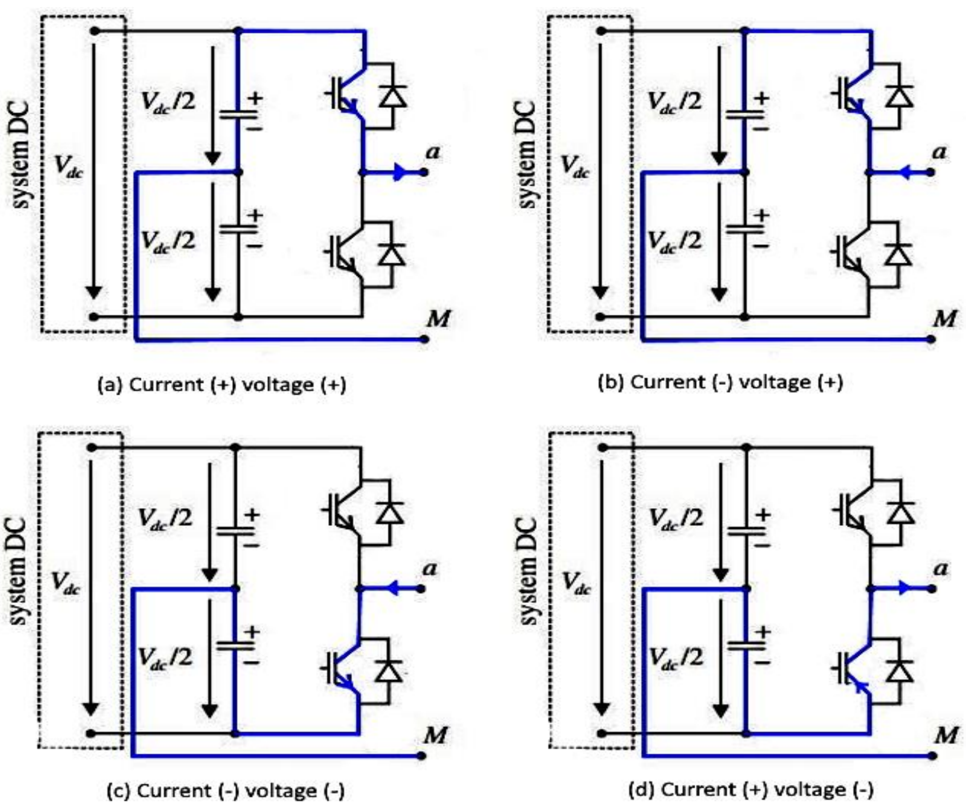


Fig. 2.3: Possible current direction ("+" and "-" indicate the sign) in a half-bridge VSC converter

It should be noted that the direction of the positive current in the VSC is from the DC side to the AC side. As a result, the output current can be either negative or positive. The output voltage is positive when the upper valve of the VSC is activated (Figs. 2.3(a) and 2.3(b)).

Under these conditions, if the current is negative (Fig. 2.3(b)), the current flows through the antiparallel diode (D1), because the controllable switch cannot conduct the current in the reverse direction. On the other hand, the current flows through the upper controllable switch (S1) if the current is positive (Fig. 2.3(a)). In rectifier operation, if the two switches (S1 and S2) are blocked, the diodes D1 and D2 form a rectifier which supplies the DC capacitors. The peak value of the AC voltage at the upper and lower terminals of the capacitors is

$$\sqrt{2}v_{aM} = \frac{V_{dc}}{2}$$

Where, v_{aM} is the voltage between phase 'a' and the neutral point and V_{dc} is the DC line voltage.

2.1.1. Two-level converter

The three-phase two-level VSC is an extension of the half-bridge converter. It has three basic elements (as shown in Fig. 2.2(a)). A representation of this type of converter is given in Fig. 2.4.

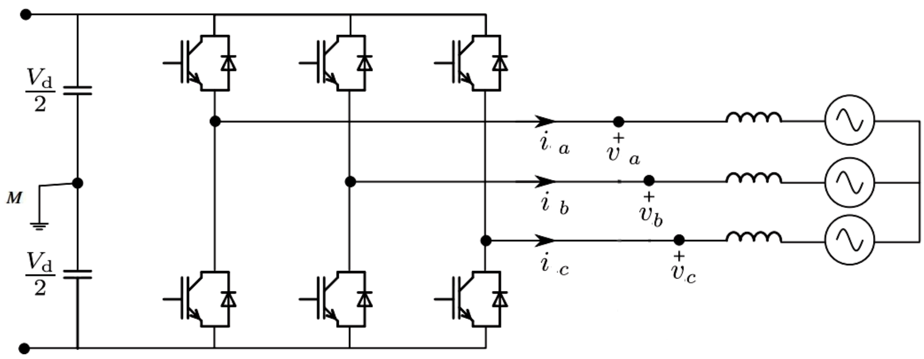


Fig. 2.4: Schematic of a three-phase two-level VSC

The simplest mode of operation for a two-level VSC is full-wave operation. In full-wave operation, each valve turns on and off with each cycle of the AC voltage, resulting in six pulses per fundamental frequency period. Regardless of the current value (positive or negative), the switches impose the voltages between the output terminals a, b and c and the midpoint M of the DC voltage source (v_a, v_b, v_c). On the other hand, we can write the compound voltages (v_{ab}, v_{bc}, v_{ca}) in terms of the simple voltages as follows:

$$v_{ab} = v_a - v_b \tag{1.1a}$$

$$v_{bc} = v_b - v_c \tag{1.1b}$$

$$v_{ca} = v_c - v_a \tag{1.1c}$$

Since the system is three-phase and balanced, the sum of the three currents i_a, i_b, i_c is zero. This results in the following expressions:

$$v_a + v_b + v_c = 0 \rightarrow v_a = -(v_b + v_c) \tag{1.2}$$

By subtracting the compound voltages term by term, we will have:

$$\begin{aligned} v_{ab} - v_{bc} &= (v_a - v_b) - (v_b - v_c) \\ v_{ab} - v_{bc} &= 2v_a - (v_b + v_c) \end{aligned} \tag{1.3}$$

So

$$v_{ab} - v_{bc} = 3v_a \tag{1.4}$$

We can also write

$$v_a = \frac{1}{3}(v_a - v_b) - \frac{1}{3}(v_c - v_a) = \frac{2v_a}{3} - \frac{v_b}{3} - \frac{v_c}{3} \tag{1.5}$$

For v_b and v_c, we find in the same way the following expressions:

$$v_b = \frac{1}{3}(v_b - v_c) - \frac{1}{3}(v_a - v_b) \tag{1.6}$$

$$v_c = \frac{1}{3}(v_c - v_a) - \frac{1}{3}(v_b - v_c) \tag{1.7}$$

By replacing the composite voltages $(v_a - v_b)$, $(v_b - v_c)$ and $(v_c - v_a)$ by their expressions in function of v_M we find:

$$v_a = \frac{2}{3}(v_a - v_M) - \frac{1}{3}(v_b - v_M) - (v_c - v_M) \tag{1.8}$$

$$v_b = \frac{2}{3}(v_b - v_M) - \frac{1}{3}(v_a - v_M) - (v_c - v_M) \tag{1.9}$$

$$v_c = \frac{2}{3}(v_c - v_M) - \frac{1}{3}(v_a - v_M) - (v_b - v_M) \tag{1.10}$$

One can summarize the simple and compound output voltages of the two level VSC in the following Table 2.1.

Table 2.1: Single and compound voltage as a function of switching state

S1	S2	S3	S4	$(v_a - v_M)$	$(v_b - v_M)$	$v_{ab} = v_a - v_b$
1	0	1	0	$\frac{Vdc}{2}$	$\frac{Vdc}{2}$	v_{dc}
1	0	0	1	$\frac{Vdc}{2}$	$\frac{-Vdc}{2}$	0
0	1	1	0	$\frac{-Vdc}{2}$	$\frac{Vdc}{2}$	$-v_{dc}$
0	1	0	1	$\frac{-Vdc}{2}$	$\frac{-Vdc}{2}$	0

From results shown in Table 1 we can notice that the voltage v_{aM} of the converter has two levels $\left\{\pm \frac{v_{dc}}{2}\right\}$ while the compound voltage v_{ab} has three levels $\left\{\pm \frac{v_{dc}}{2}, 0\right\}$ and this is fully achievable by controlling the PWM connected to gates of the IGBT switches of the two level VSC.

2.1.2. Three-level converter

HVDC applications have so far been limited to three main types: two-level converter, three-level converter and modular multi-level converter [81]. However, the most commonly used types are the first two. Therefore, we present the 3-level VSC based on "Neutral-Point-Clamped". Fig. 2.5 shows a structure of a 3-level NPC converter.

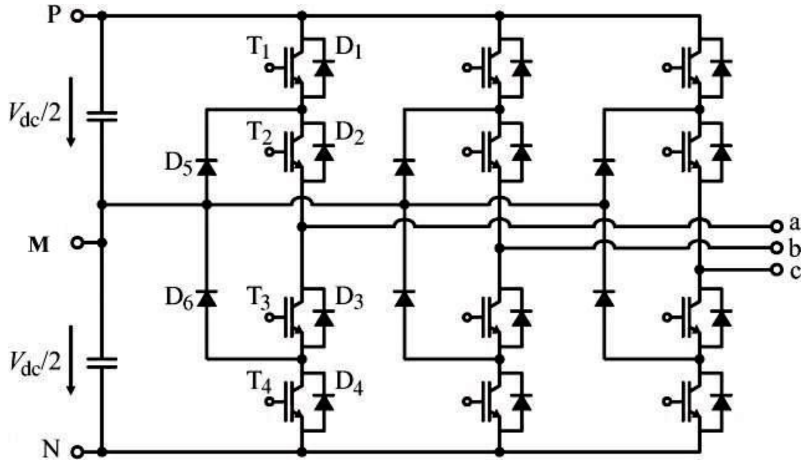


Fig. 2.5: Three Phase 3-level VSC Converter

According to this figure, the structure is composed of three symmetrical arms each consisting of four switches in series and two others in parallel, plus two diodes allowing to obtain the zero of the voltage v_{aM}. Each switch is composed of a controlled switch (T1, T2, T3 and T4) and a diode connected in a head-to-tail fashion.

The operating state of the switches of an NPC converter arm can be represented by the switching states as shown in the following Table 2.2.

Table 2.2: Operating status of a three-level converter arm

Switching status	T1	T2	T3	T4	v_{aM}
P	1	1	0	0	$\frac{Vdc}{2}$
O	0	1	1	0	0
N	0	0	1	1	$\frac{Vdc}{2}$

For the operation of the converter, we distinguish two cases.

- Current $i_a > 0$: In the [O] switching state, switches T1 and T4 are deactivated while T2 and T3 are conducting. The blocking diode D1 is activated by the positive load current ($i_a > 0$), so the output voltage is 0. Subsequently in the switching state [P], the upper switch T1 is turned on, the voltage at the terminal of diode D5 is inverted and thus turned off, the load current is switched from D5 to T1, as T3 and T4 are already stopped, the output voltage is equal to $\frac{V_{dc}}{2}$.

- Current $i_a < 0$: in the [O] switching state, T2 and T3 are conductive and the diode D6 is activated by the negative load current, then in the [N] switching state the upper switch T4 is activated, the blocking diode D6 is inverted and thus deactivated. The load current is switched from D6 to T4. Since T1 and T2 are already at standstill, the output voltage is equal to $-\frac{V_{dc}}{2}$.

2.2.2. Transformer

A VSC station is usually connected to the electrical grid via a power transformer. This facilitates the connection of the converter to an AC system with a nominal voltage. In addition, this transformer blocks the propagation of zero sequence harmonics to the AC grid by providing galvanic isolation between the AC grid and the VSC station [51]. On the other hand, the transformer provides a coupling reactance between the VSC and the AC system, which also reduces the fault currents and thus can reduce the size of the AC filter [52].

The transformer parameters are based on those of the AC network and the HVDC line. The transformer power rating Sn is equal to that of the DC transmission line, i.e.,

$$S_n = U_{dc}.I_d$$

The voltage at the primary U_{In} is equal to the AC grid voltage. we write:

$$U_{In} = U_{AC}$$

In addition, the secondary voltage $U_{2n}$of the transformer is determined from the voltage produced by the converter using the following relationship:

$$U_{2n} \cong \frac{v_{dc}}{2\sqrt{6}}$$

Where V_{dc} represents the voltage in the DC link side.

2.2.3. Phase Inductor

Phase inductor is one of the most important components of a VSC station because it facilitates the transfer of active and reactive power between the VSC station and the rest of the AC system. With one side of the reactor connected to the AC system, the VSC is able to apply a controllable voltage to the other side of the reactor. The phase difference of this voltage compared to the AC system voltage will induce a defined amount of active and reactive power [53].

A secondary function of the phase inductor is to filter the harmonics of the converter output current, and thus limit the short-circuit currents of the valves [51]. The choice of the size of the phase inductor depends on the switching frequency, the saturation of the converter and the control algorithm. The value of the inductance is generally between 0.1 pu and 0.2 pu (compared to the basic inductance) [54].

2.2.4. DC Filter Capacity

DC capacitor is the energy storage element in the VSC. It is able to provide a sufficiently stable DC voltage from which an AC voltage will be generated on the AC side of the converter. It also reduces the voltage ripple on the DC side. In addition to reducing ripple, the DC capacitance reduces the propagation of harmonics between different VSC substations connected to the same DC bus [51].
The design requirements for the DC capacitor are as follows [55]:

- The operating DC voltage;
- The limits of DC voltage ripple under transient conditions, such as AC system failures;
- The harmonic currents transmitted to the DC side.

Requirement of a small voltage ripple implies a large capacitance; on the other hand, a small capacitor has advantages considering the control and dynamics of the converter [56]. The choice of the size of the DC capacitor is a compromise between the voltage ripple ΔU_{dc} (DC cable manufacturers usually specify the DC voltage ripple of about 3 - 10%), the lifetime of the capacitor, the cost, and the speed of DC voltage control [57].

Based on the ripple specification, a lower limit can be set for the DC capacitance value [52]:

$$C_{dc} > \frac{S_{VSC}}{2.\omega.\Delta U_{dc}.U_{dc}} \tag{1.11}$$

where, C_{dc} is the DC capacity, S_{VSC} is the apparent power rating of a VSC inverter in MVA. In terms of control speed, the upper limit can be set as follows.

$$C_{dc} < \frac{2.\tau.S_{VSC}}{U_{dc}^2} \tag{1.12}$$

where, τ is the time constant of the DC capacitance load from zero to the nominal DC voltage, this time constant is generally chosen to be less than 10 ms to achieve the required transient response speed performance. However, the size of the DC capacity is usually determined by the total stored energy, the energy to power ratio E_s is defined using the capacity energy E_c and S_{VSC}.

$$E_s = \frac{E_c}{S_{VSC}} \tag{1.13}$$

Knowing that

$$E_c = \frac{1}{2} C_{dc} U_{dc}^2$$

it is possible to obtain a convenient formula for the DC capacity size as the following shows.

$$C_{dc} = \frac{2.E_s.S_{VSC}}{U_{dc}^2}$$

where, E_s practically is between 10 and 50 kJ/MVA [52].

2.2.5. AC Filters

The output voltage of VSC converters is not purely sinusoidal. In case of PWM control, the output voltage contains harmonics that are multiples of the switching frequency ($Kf_m + N.f$,where f_m is the carrier frequency, f is the output voltage frequency and K and N are integers and their sum is an odd integer) [54]. This causes harmonics at the same frequencies in the current of the phase inductors outside the sinusoidal component. These currents should not flow in the rest of the AC network, as they could cause additional losses in other components and distortion of the voltage waveforms [56].

Considering an PWM control and the high order of the harmonics, a passive high-pass filter is used which offers a low impedance over a wide frequency band. Thus, these filters are designed to damp more than one harmonic, for example: a filter tuned to the 24th harmonic will give a low impedance for the 23rd and 25th harmonic and for most higher order harmonics [58]. A second-order high-pass filter is used whose electrical diagram is given in Fig. 2.6(a).

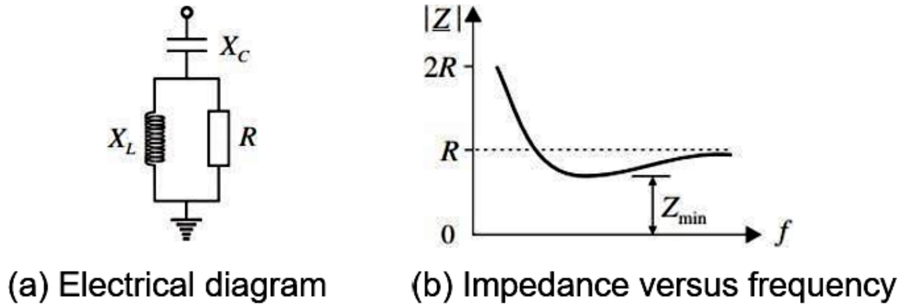


Fig. 2.6: Second order passive high-pass filter [52]

Using the impedance equation, the variation of impedance as a function of frequency could be plotted (Fig. 2.6(b)). The impedance of such a filter is given by:

$$Z = \frac{1}{j\omega C} + \left(\frac{1}{\frac{1}{R} + \frac{1}{j\omega C}}\right)$$

Where, C, R and ω are the capacitance, resistance and the period of the concerned AC filter.

2.2.6. DC Transmission Cables

Today, there are two types of power transmission means in use. These are overhead lines with bare conductors, which are generally used for long-distance power transmissions, and cables that are used for underground and submarine power transmissions [59]. Since the DC cable is not exposed to lightning, storms, falling trees, etc., short circuits of the DC lines are greatly reduced. This is an important consideration for VSC transmission, as such faults require isolation of the link by circuit breakers at both ends to allow the release of reactive energy [60]. On the other hand, VSC transmission allows only one polarity and therefore the cable does not need to be designed for polarity reversals, which greatly simplifies cable design [61]. Fig. 2.7 shows an example of the XPLE (cross-linked polyethylene) cable.

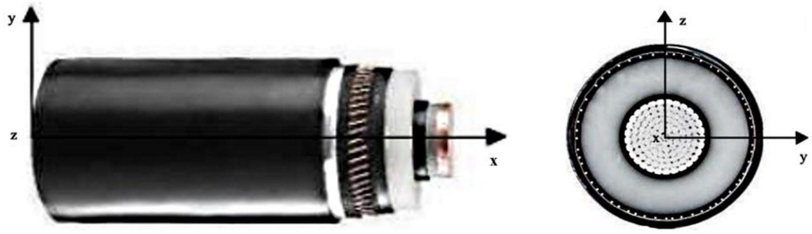


Fig. 2.7: XPLE HVDC cable for VSC application from ABB [61]

These cables are used in VSC transmission systems which are based on polymeric insulation technology and present lower design cost than ones used with AC transmission.

2.3. Principal of power control

A VSC has the ability to control active and reactive power separately. This is because the exchange of active and reactive power between a VSC converter and the AC grid is controlled by the phase angle and magnitude of the VSC output voltage with respect to the AC grid voltage, respectively [62]. To understand how active and reactive powers are exchanged between the VSC and the AC grid, the simplified connection circuit of a VSC with an AC grid in Fig. 2.8 is analysed.

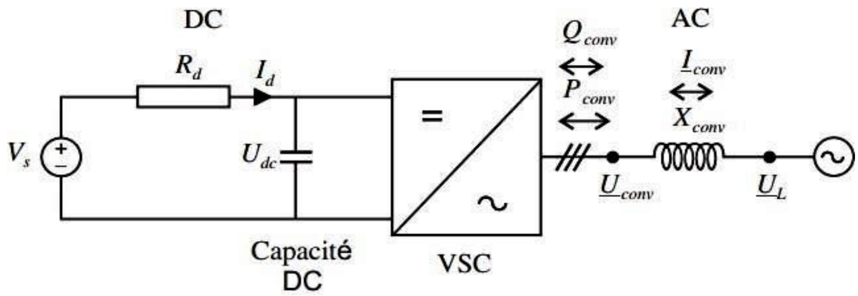


Fig. 2.8: Simplified diagram of a VSC converter connected to an AC network [52]

Note that the AC filters are neglected to simplify the study. Therefore, the line current I_L is equal to the one at the output of the converter I_{conv}. The inter-phase voltage on the AC side is taken as the phase reference, i.e., $\underline{U_L} = U_L \angle 0^{\circ}$. Therefore, the fundamental interphase voltage value at the converter level is equal to $\underline{U_{conv}} = U_{conv} \angle \Phi^{\circ}$ where Φ is the angle between the grid voltage and the AC converter voltage VSC. The single converter AC voltage is equal to:

$$V_{conv} = \frac{U_{conv}}{\sqrt{3}}$$

this can also be written as a function of the DC voltage in the DC line as follows [63]:

$$\underline{V_{conv}} = \frac{\sqrt{2}}{\pi}.m.U_{dc}.e^{-j\Phi} \quad (1.15)$$

where, m is the modulation index.

For full-wave operation, the modulation index is equal to unity, while in the case where PWM is used, this index is between 0 and 1. Thus, the voltage between phases of the converter on the AC side is written as follows:

$$\underline{U}_{conv} = \frac{\sqrt{6}}{\pi}.m.U_{dc}.e^{-j\Phi} \tag{1.16}$$

Neglecting the transformer resistance, the expression of the current at the output of the converter on the AC side can be written as follows:

$$\underline{I}_{conv} = \frac{\underline{V}_{conv}-\underline{V}_L}{\underline{Z}_{conv}} = \frac{\frac{\sqrt{2}}{\pi}.m.U_{dc}.e^{-j\Phi} - V_L.e^{-j0}}{jX_{conv}} \tag{1.17}$$

knowing that

$$X_{conv} = X_{tr} + X_f$$

Where, X_{tr} the transformer reactance and X_f the phase reactance equal to L_f . The active and reactive powers, P_{conv} and Q_{conv}, exchanged between the VSC and the AC system are as follows:

$$P_{conv} = \frac{U_{conv}U_L}{X_{conv}} \ sin\ sin\ \Phi \tag{1.18}$$

$$Q_{conv} = \frac{U_L^2}{X_{conv}} - \frac{U_{conv}U_L}{X_{conv}} \ cos\ cos\ \Phi \tag{1.19}$$

From these two equations, we find that:

- if the U_L voltage is lower than U_{conv}, the VSC converter supplies reactive power to the AC system. Therefore, the converter operates in capacitance mode.
- if the U_L voltage is higher than U_{conv}, the VSC converter absorbs reactive power from the AC system. Therefore, the converter operates in the inductive mode.

Thus, the reactive power can be varied independently by controlling the two voltages U_L and U_{conv} while the active power control can be done separately by varying the phase angle Φ between the voltages U_L and U_{conv}. With respect to the phase angle Φ, the converter can operate in rectifier or inverter mode as follows:

- If the $U_L$voltage lags behind the U_{conv} voltage, i.e., the VSC absorbs the active power from the AC network and works as a rectifier, an equivalent current will be injected into the DC line and the U_{dc} voltage will increase.
- If the voltage U_{conv} is ahead of the voltage, i.e., the VSC injects active power into the network, on the DC side, an equivalent current will be drawn and the voltage U_{dc} will decrease.

The current in the DC line can be derived from the power expression by neglecting the converter losses:

$$U_{dc}I_d = P_{dc} = P_{conv} = \frac{U_{conv}U_L}{X_{conv}} \ sin\ \Phi \tag{1.20}$$

By replacing U_{conv} by the expression given in (1.16), we find the following current expression:

$$I_d = \frac{\sqrt{6}}{\pi}\frac{U_L}{X_{conv}} \sin \Phi \tag{1.21}$$

On the DC side of a VSC-HVDC link, the magnitude and direction of the power can be changed by proportionally changing the magnitude and direction of the I_d current. Furthermore, under normal operating conditions, the DC voltage is kept approximately constant. In order to understand the power transfer on a VSC link, consider the diagram shown in Fig. 2.9.

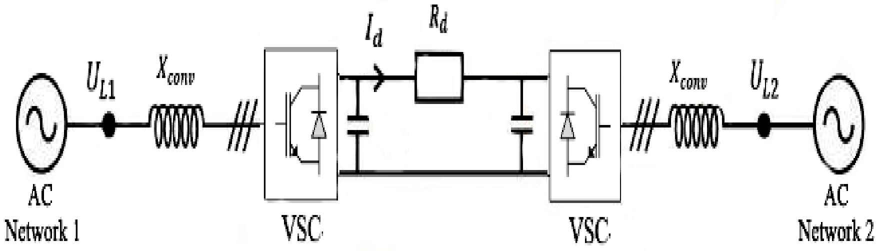


Fig. 2.9: Diagram of a VSC transmission [52]

In a VSC-HVDC link, the polarity of the DC voltage is always the same, and therefore the direction of the energy flow on the DC line is determined by the direction of the DC current I_d, according to Ohm's law, the current flowing from converter (1) to converter (2) is determined by

$$I_d = \frac{U_{dc1} - U_{dc2}}{R_d} \tag{4.22}$$

Thus, the direction of the DC current I_d will always be from the larger DC voltage converter to the smaller DC voltage converter, so the DC voltage at the rectifier must be greater than the DC voltage at the inverter [57]. The operation of a VSC converter can be summarized in the four quadrants of the (P, Q) plane as shown in Fig. 2.10. It can be considered as the equivalent of a synchronous generator without mechanical inertia, which has the ability to control active and reactive power separately.

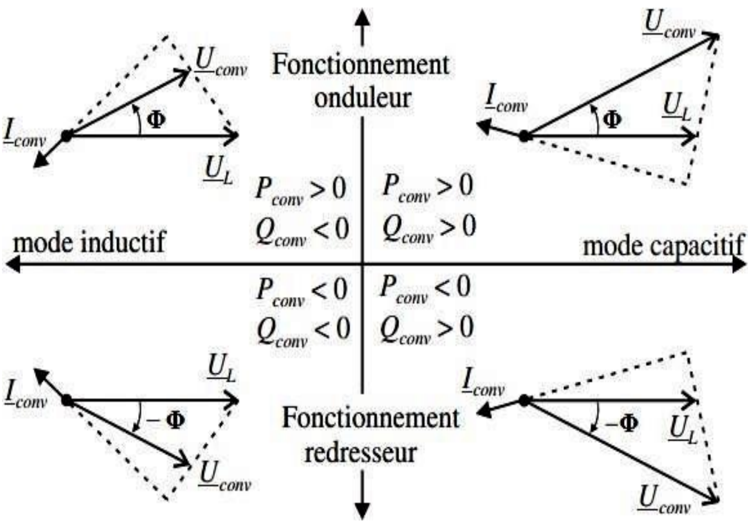


Fig. 2.10: Different operating modes of a VSC-HVDC converter [52]

Fig. 2.11 illustrates the P-Q capabilities for a VSC system from a stability perspective. As also shown in Fig. 2.10, a VSC can operate in all four quadrants of the P-Q plane. An inverter injects active power into the AC system and therefore $P_{conv} > 0$, while a rectifier absorbs active power from the AC system and $P_{conv} < 0$, both converters can operate either in capacitive mode, with $Q_{conv} > 0$, or in inductive mode, with $Q_{conv} < 0$.

There are mainly three factors that limit the active and reactive powers produced/absorbed by a VSC converter [64]:

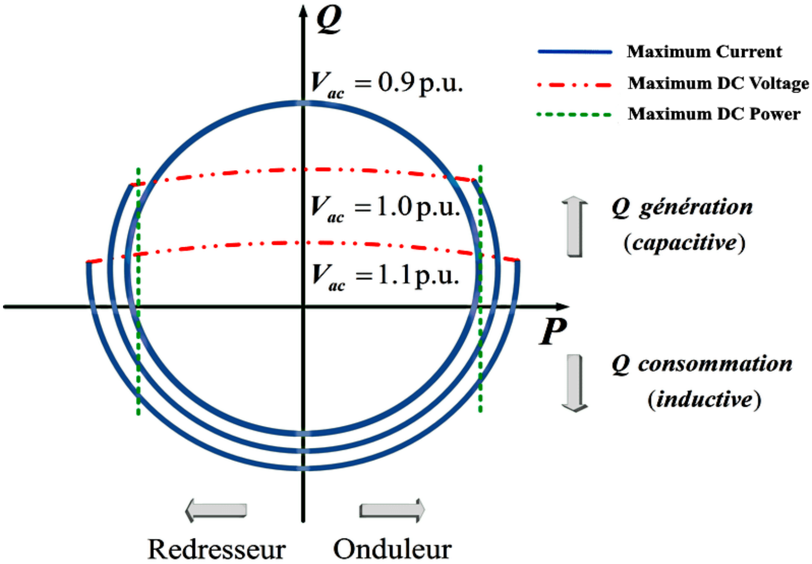


Fig. 2.11: Simplified P-Q diagram [63]

Maximum current in IGBTs [65]**:** If we fix the current, the P-Q capacitances depend on the AC voltage, the higher the AC voltage, the higher the P-Q capacitance. The reactive power is limited by the minimum (U_{min}) and maximum (U_{max}) safety limits of the AC voltage (U_L). At a high voltage value (U_{max}), the reactive power is limited by the maximum AC voltage of the converter U_{conv}, which in turn is limited due to the limitation of the DC voltage U_{dc}.

Maximum DC voltage level: The reactive power mainly depends on the difference between the grid voltage U_L and the AC voltage across the VSC (U_{conv}), which is a function of the DC voltage U_{dc} and the grid AC voltage. In capacitive mode, if the AC voltage of the grid is high, the AC voltage of the VSC must be higher, which in turn is limited by the DC voltage. The difference between the maximum AC voltage and the DC voltage will be small. Thus, in capacitive mode, the reactive power capacity increases as the AC voltage decreases. This makes sense from a stability point of view.

Maximum active power limit: This limit is determined by the current rating of the VSC and the P_{dc}rating of the transmission cable.

2.4. Conclusion

This second chapter deals with the modelling of the multilevel VSC-HVDC transmission line. In the first part, the various elements that constitute the HVDC transmission technology were presented in detail. In addition, the sizing and operation of the two level and three level voltage sourced converter technologies were performed. Then, for further understanding of VSC-HVDC technology, the principle of active and reactive power transfer in the transmission link was explained by presenting the limits of this transfer.

Chapter 3

Performance Analysis of Three Level VSC-HVDC Transmission System

3.1. Introduction

A simulation and performance analysis of the 3-level VSC-HVDC transmission system were performed in this chapter. First, simulation studies of the effect of DC and AC filters on eliminating and reducing the generation of harmonics in the transmission system were analysed and discussed. Followed by a short-circuit faults and converter losses analysis, in order to test the transmission system reliability in face of different faults occurrences. Finally, a comparison between the results of the three level VSC technology used in transmission systems has been conducted for the purpose of drawing out the strong and weak features of the technology.

3.2. Description of The Studied Three Level Model

The line used in this simulation is an interconnection between two high-power networks, one of which (named Network 1) is characterized by an interline voltage of 400 kV and a frequency of 60 Hz, while the other (named Network 2) has an interphase voltage of 230 kV with a frequency of 50 Hz. Both transformers are of the Dy1 type on the rectifier bridge and inverter bridge sides, and their parameters are shown in Table 3.1.

Table 3.1: VSC-HVDC transmission parameters

Parameters	Transformer 1	Transformer 2
Apparent power (MVA)	300	300
Frequency (Hz)	60	50
Primary voltage (kV)	400	230
Secondary voltage (kV)	211	211
Primary resistance R_p (pu)	0,0025	0,0025
Secondary resistance R_s (pu)	0,0025	0,0025
Primary inductance L_p (pu)	0,075	0,075
Secondary inductance L_s (pu)	0,075	0,075
Iron resistance R_F (pu)	500	500
Magnetization inductanceL_μ (pu)	500	500

The line is a bipolar configuration with two identical overhead lines whose characteristics are summarized in Table 3.2.

Table 3.2: Parameters of the Simulated HVDC Cable

Cable Length (km)	75
Resistance (W/km)	0,014
Inductance (mH/km)	0,159
Capacity (mF/km)	0,231

We performed a simulation of the 3-level VSC topology. The DC capacity has been set to the value of 120µF to obtain an acceptable DC voltage ripple rate. The smoothing inductance for each station is 0.3 H to decrease the DC current ripple. In addition, the cable and transformer parameters are summarized in Tables 3 and 4, respectively. Fig. 3.1 shows the Simulink scheme used to simulate the 3-level VSC- HVDC transmission.

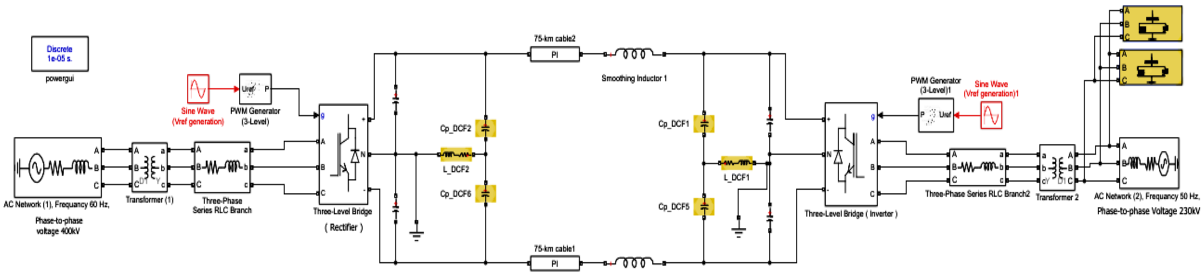


Fig. 3.1: Schematic of the VSC-HVDC transmission based on the 3-level converter

In the simulation, we have grouped the control into a pulse generator block. This Block consists of a reference signal generator and 3-Level PWM generator used for generating pulses for carrier-based pulse-width modulation (PWM) converters using three-level topology. In the following, the operating principle is explained.

3.3. Pulse Width Modelling

In general, the larger the control signal, the larger the pulse. The output voltage of the comparator controls the semiconductor converter devices. This voltage is positive if $V_{ref} \leq V_m$, zero if not. The control signal for the valves is a square wave signal, having pulses of unequal width. Two parameters are generally used to characterize the PWM:

- The modulation index: which is the ratio between the amplitude of the reference V_{ref} and the peak value of the modulation wave V_p : $m = \frac{V_{ref}}{V_p}$
- The voltage adjustment coefficient r (or the duty cycle) with f_m the carrier frequency and f the reference frequency (equal to the desired frequency of the fundamental output voltage wave).

The choice of r depends on the balance between switching losses and harmonic losses, a higher value of r increases the switching losses but reduces the harmonic losses [56]. Fig. 3.2 shows the operating principle of the generation of control signals that drive the interceptors of a VSC converter arm. The same operation is done for the twelve existing switches of the three phase 3-level VSC-HVDC transmission station.

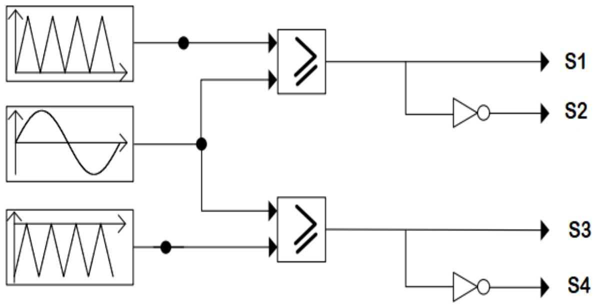


Fig. 3.2: PWM signal generator for 3-level VSC

In practice, full-wave control is not used for 3-level converters due to the performance restrictions associated with this control method. Instead, other methods are used such as PWM [80]. The VSC converter contains switches that can be controlled on opening and closing. A simple comparator with a sawtooth support can transform a sinusoidal command into a pulse-width modulated output. The sinusoidal reference signal is compared with two carriers (positive and negative). The positive (respectively, negative) one gives the two firing signals for the switches S1 and S2 (respectively, S3 and S4). Fig. 3.3 shows the reference signal, the triangular carriers and the control signals for switches S1-S3 (Switching frequency of 1000Hz just for an example sample).

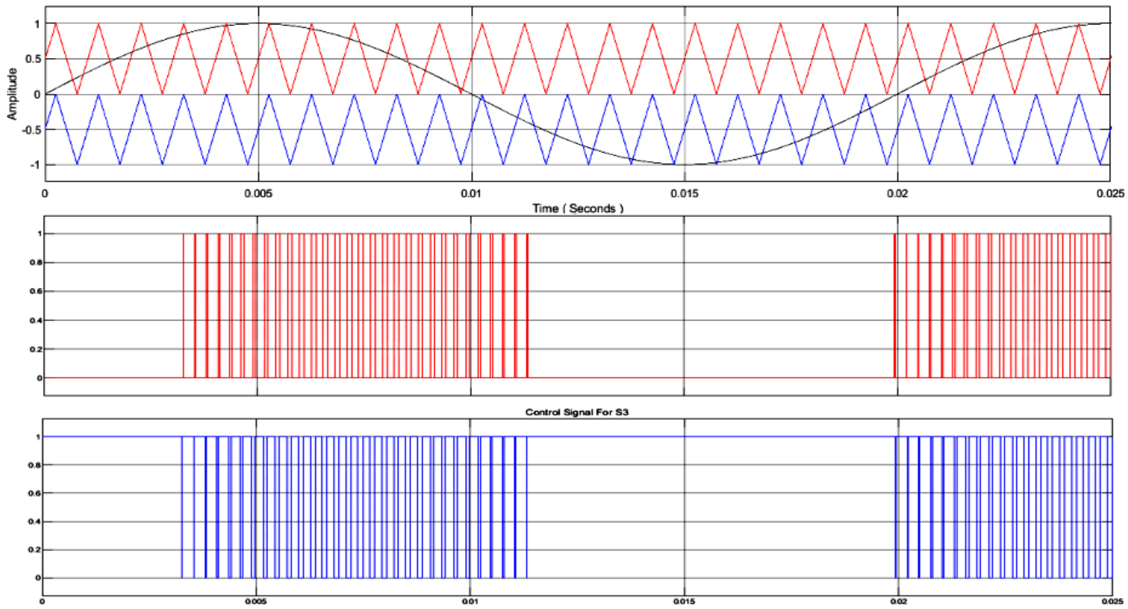


Fig. 3.3: Control Signals for Switches S1-S3

We have presented only two signals from switches S1 and S3 because the other two from S2 and S4 are the complements of S1 and S3 respectively. To obtain the nominal operating point of (i.e., Pn = 300 MW, Ud = 317 kV and Id = 966 A), we apply the following commands:

- For the rectifier station, the control is with a modulation index m=0.437, as well as the phase shift between the reference voltage and the grid voltage Φ = -70◦.
- For the inverter station, the control is with a modulation index m=0.433, as well as the phase shift between the reference voltage and the grid voltage Φ = +81◦.

The simulation results, obtained from the Simulink environment that consist of voltage $U_d(t)$, DC transferred power $P_d(t)$ and current $I_d(t)$ curves are presented in following Fig. 3.4. It shows the evolution of DC power, voltage and current with respect to chosen simulation time (3 seconds).

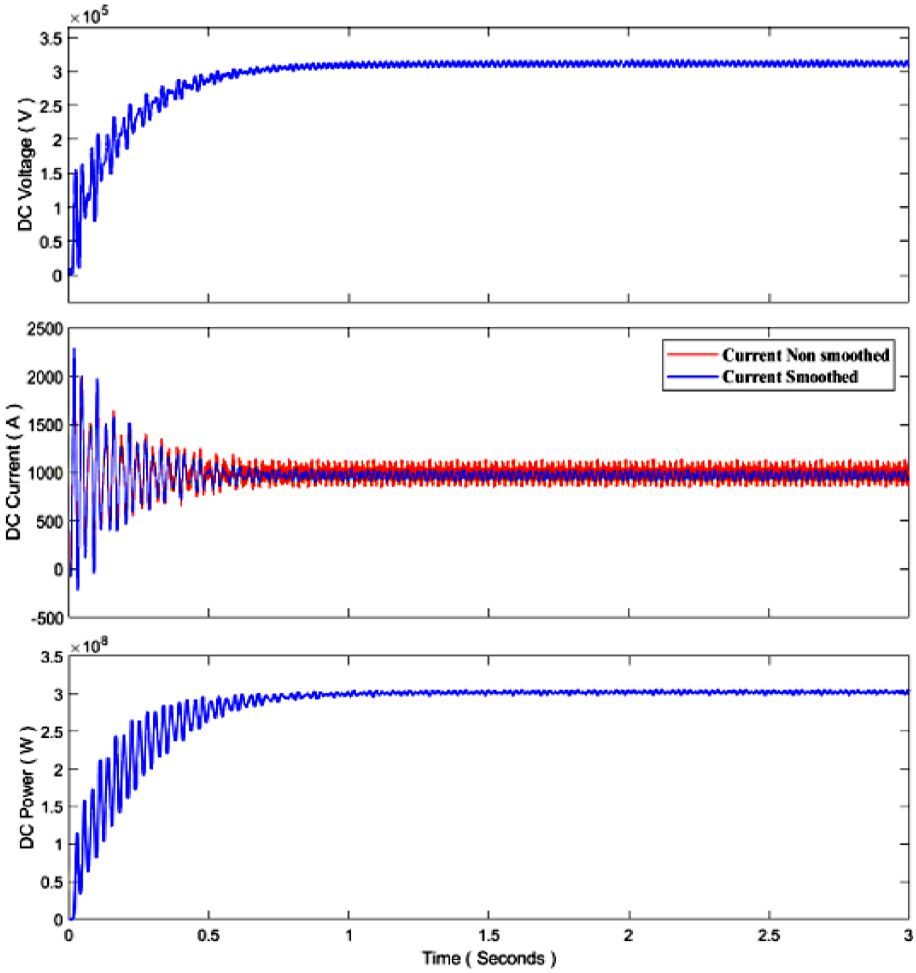


Fig. 3.4: Simulation results of the 3-level converter based VSC-HVDC transmission: (a) DC Voltage, (b) DC Current, (c) DC Power

From Fig. 3.4(a) we see that the voltage stabilizes at the point of 0.9s with a value of 310kV and also presents some ripples which will be discussed in the following paragraph. Current of Fig. 3.4(b) reaches its steady state first after only 0.5s. The blue curve of current shows the effect of the smoothing inductor placed in the transmission lines when compared to the red curve that contains fluctuations and high THD (Total Harmonic Distortion). Which is presented in following Fig. 3.5 along with harmonic analysis after being smoothed with the inductor.

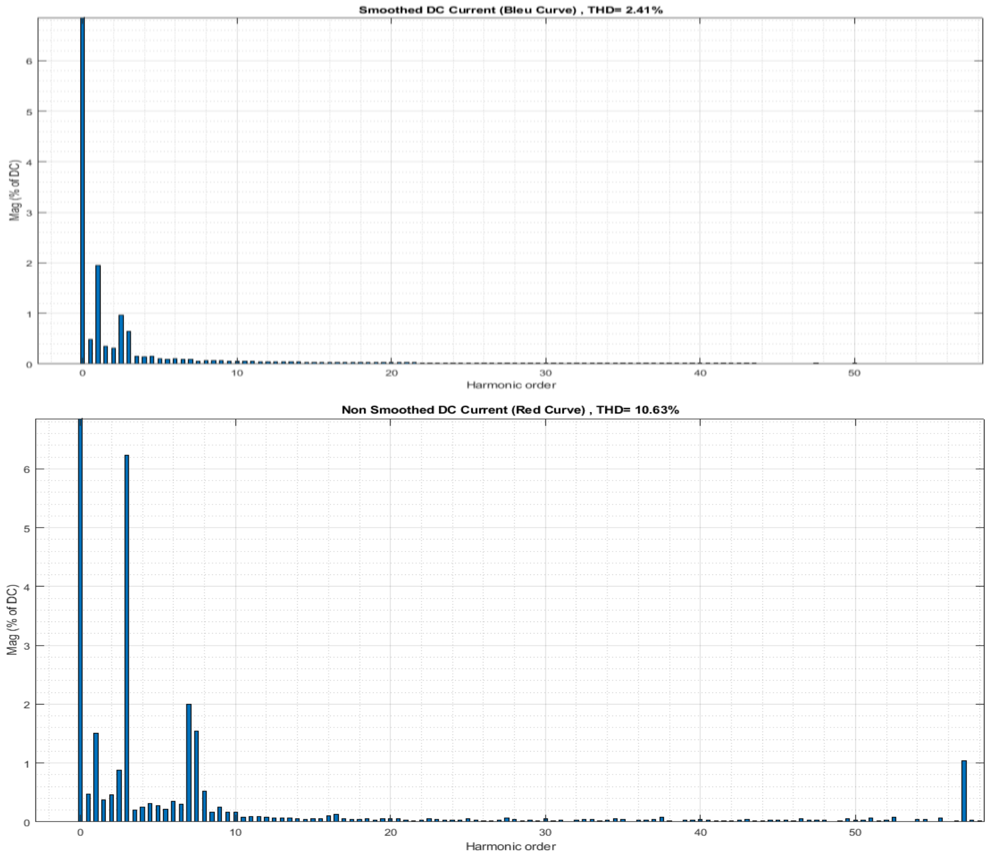


Fig. 3.5: FFT Analysis of Harmonic Order of the DC Current before and after smoothing

From Fig. 3.5 we can see clearly that before the current passes in the inductor placed in transmission lines it has a relatively high THD (10.63%). However, after the passage by the 0.3H inductor the THD rapidly decreases to a value of (2.41%). Which shows the importance of the smoothing inductor in transmission lines for eliminating and attenuating harmonics and fluctuations.

3.4. Generation of Harmonics

VSCs generate harmonics on both the AC and DC sides. Therefore, measures must be taken to limit the amplitude of harmonics entering the AC side. Among these methods, PWM pulse width control is used. However, this method is not sufficient to eliminate all harmonics that transfer from one converter to another. DC capacitors are used in the DC side to attenuate fluctuations affecting the DC voltage U_d and current I_d, they are used also to minimize the voltage ripple presented earlier in Fig. 3.4(a). AC filters are also used in the AC side to decrease the harmonics in the phase current to obtain a form close to the sinusoidal form. A Matlab simulation study of the generation of harmonics was done and the results are presented in the following paragraphs.

3.4.1. DC Side Harmonics

The correct choice of the size (volume) of the DC capacitor is important for the operation of the converters as well as their cost [66]. To compare the effect of the DC capacitance size on the line voltage as well as the current, we performed a simulation study by varying the values of the DC capacitance from 70 µF to 150 µF and we observed Fig. 3.6 that shows the results obtained from the Matlab simulation.

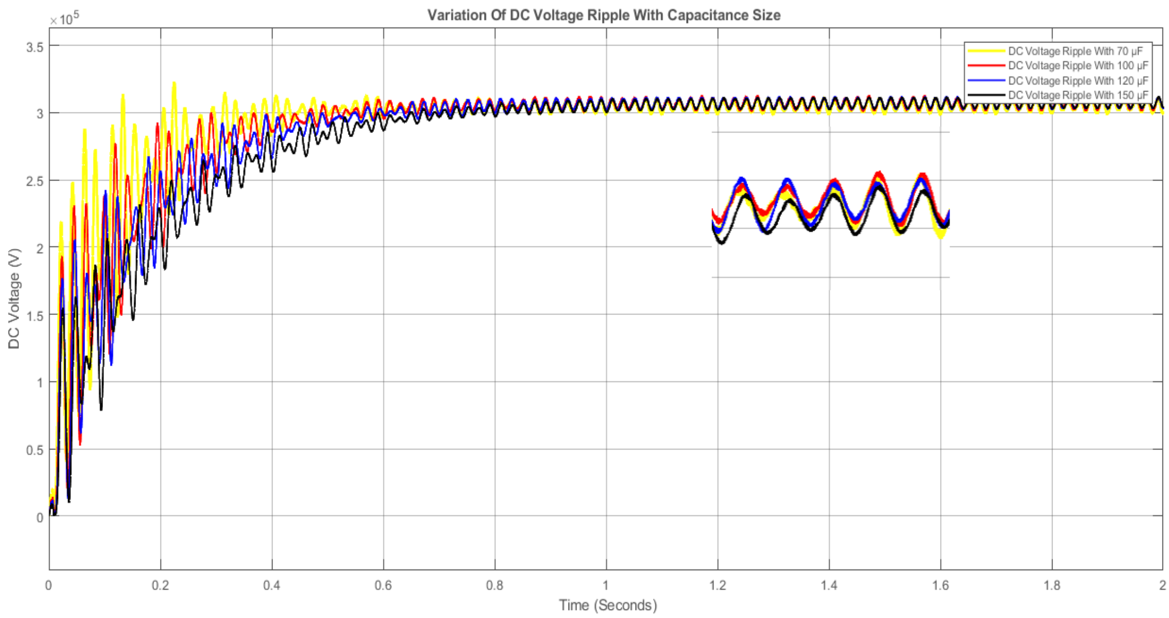


Fig. 3.6: Variation of DC Voltage ripple with various capacitance size

The filter in the DC stage permits the passage of the DC component, but eliminates the high frequency components. To filter out the harmonics produced by switching frequencies close to 1800 Hz and higher, a capacitor C is installed at each pole of the DC output. In this simulation study we varied the capacitance size and observed its effect on the DC voltage ripple and the current fluctuations. Fig. 3.6 represents the change in DC voltage ripple percentage after varying the DC side capacitance size from 70 µF to 150 µF for a 300MW of power transferred. In which we noticed that the fluctuations that happen before the voltage reaches the steady state decrease significantly when the capacity is increased to higher values. From Matlab/Simulink environment variation of voltage ripple was calculated and results are presented in following Table 5.

Table 3.3: Voltage Ripple versus capacitance size

Capacitance Size (µF)	Voltage Ripple (%)
70	10
100	6.3
120	4.4
150	3

Which shows that in order to minimize the DC voltage ripple to an acceptable percentage on the DC side, we have to increase the size of the capacity connecting the two poles. The choice of the size of the DC capacitor is a compromise between the voltage ripple ΔU_{dc} (DC cable manufacturers usually specify the DC voltage ripple of about 3 - 10%), the lifetime of the capacitor, the cost, and the speed of DC voltage control. Fig. 3.7 shows the results of the simulation study of the effect on the DC current when varying the size of the capacity. We varied the capacity from 70 µF to 150 µF and kept the value of the smoothing inductor constant at 0.2 H at each transmission line.

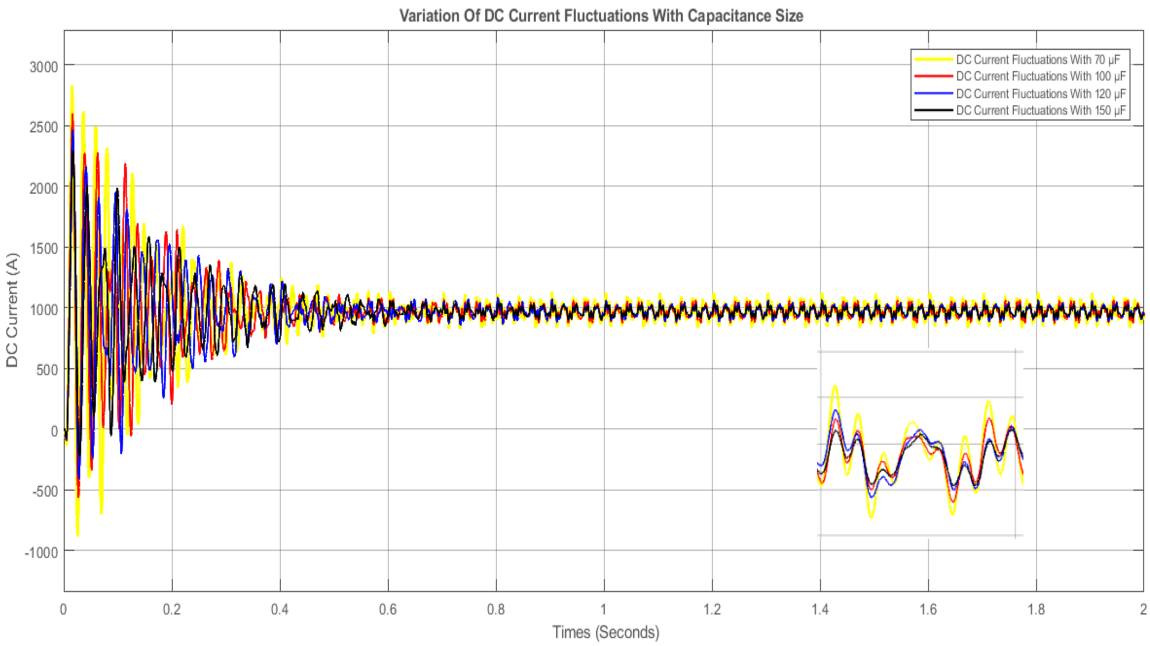


Fig. 3.7: Effect of varying the capacitance size on the DC current

The curves from Fig. 3.7 present DC currents at different installed capacity sizes. The black curve shows less harmonic distortion and less fluctuations than the other curves which is a result of the high value capacity installed between the poles (150 µF). While the current with 70 µF installed capacity (yellow curve) contains more fluctuations and presents a higher THD value. It can be seen that the filters (DC capacitors) have eliminated high frequency harmonics in both of the current and voltage signals.

3.4.2. AC Side Harmonics

To cancel the harmonics in the AC side, which are present in the signal after the commutation inductance, AC filters must be placed in parallel with the output of VSC. Tuned to harmonics of order 48^{th} and 52^{nd} which are the existing high order harmonics as presented in Fig. 3.8(a). These filters in addition to neutralizing the harmonics for which are tuned, should compensate for the reactive power consumed by commutation inductances. Fig. 3.8 presents the FFT Analysis from the Matlab environment of the VSC output voltage before and after implementation of the AC filters.

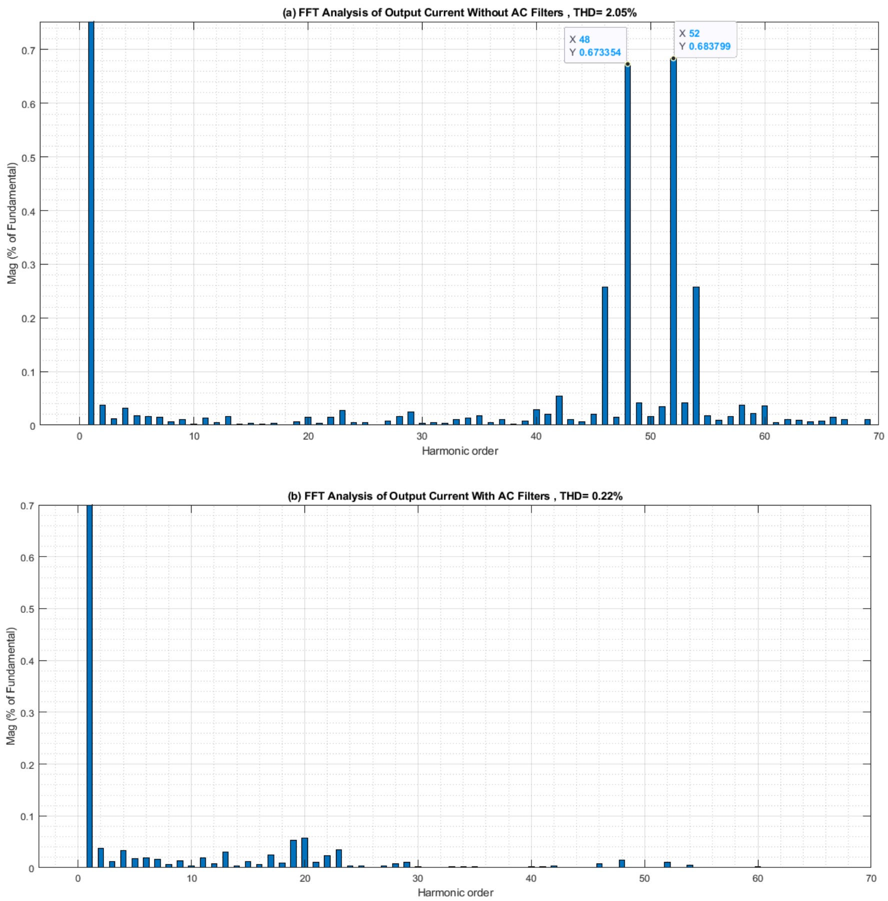


Fig. 3.8: FFT Analysis of VSC Current: (a) Without AC Filter, (b) With AC Filter

We used an LC series filter to eliminate the harmonics centered around the 50^{Th} order. The values of the capacitor and inductor needed are calculated as follows. The capacitor C of the filter must have a reactance, at the fundamental frequency (50Hz), of value:

$$X_{cw1} = \frac{V^2}{Q}$$

And a reactance for the frequency that we want to cancel:

$$X_{cw2} = X_{cw1}\,\frac{w_1}{w_2}$$

To nullify the harmonic component, we have to produce a resonance by fulfilling the following condition:

$$X_{cw2} = X_{Lw2}$$

By substituting and expanding, the expressions for the calculation of the capacitance and inductance in the tuned filters are:

$$L = \frac{V^2}{Q}.\frac{w_1}{w_2^2} \; and \;\; L = \frac{Q}{w_1.V^2}$$

Where Q is the reactive power to compensate, w_1 is the angular frequency at 50 Hz and w_2 is the frequency of the harmonic which is to be removed. Fig. 3.8(b) shows the results obtained after the implementation of the AC filter. In Fig. 3.8(b) the harmonics of order 48^{th} and 52^{th} that needed to be removed are attenuated significantly with the AC filter along with the adjacent harmonics centered around the 50^{th} order . This led the THD to decrease from 2.05% to an acceptable value of 0.22%. Fig. 3.9 shows the current and voltage signals before and after the inclusion of the AC filter in the output of the VSC transmission system.

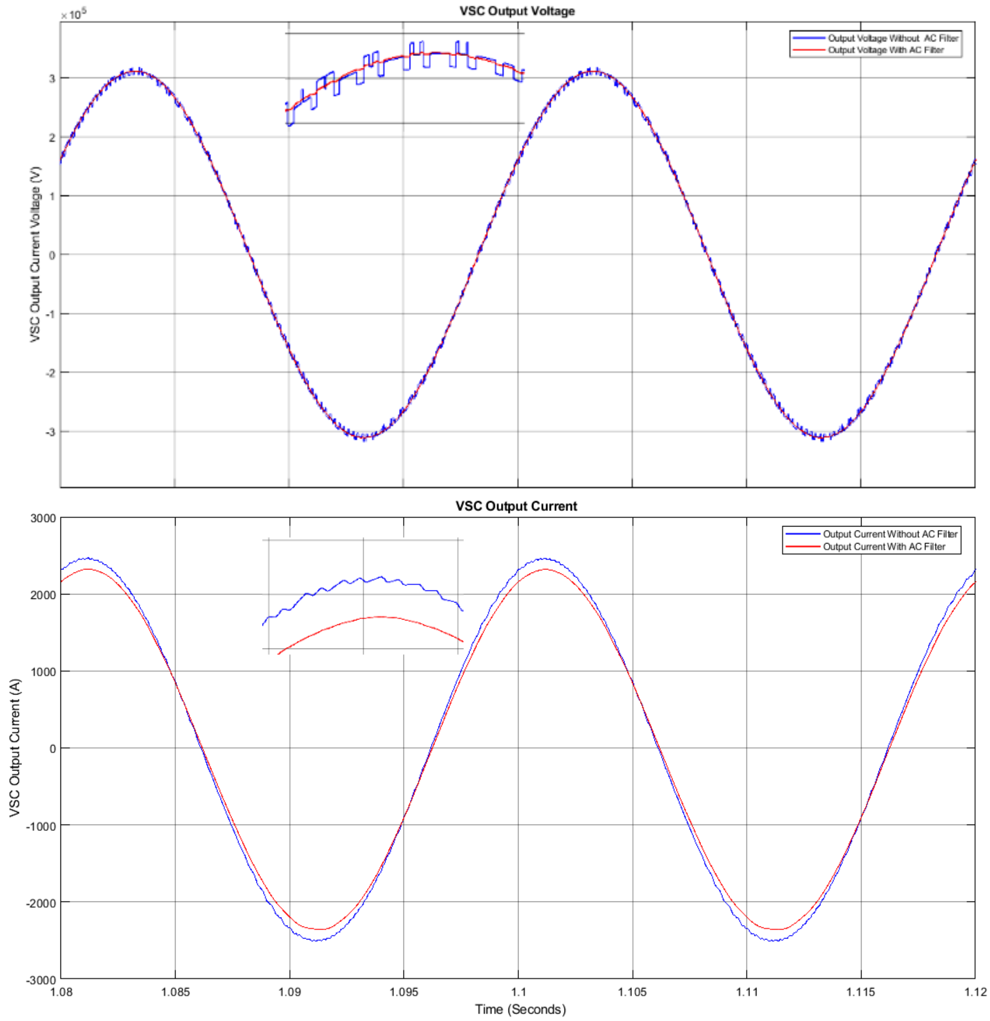


Fig. 3.9: Output Voltage and Current Before and After the Implementation of AC Filter

We notice that the output current and voltage before the AC filter (red curve) are more fluctuating than the resulting output current and voltage after the inclusion of the AC filter (bleu curve). This shows the importance of implementing filters to reduce and eliminate harmonic fluctuations contained in the output signals of the VSC inverter station. Which will present a better performance and lesser losses due to the presence of high frequency harmonics.

3.5. Three Level VSC Fault Analysis

The purpose of this part is to observe and analyse the reaction of the VSC-HVDC transmission system to DC and AC short circuit faults based on the results obtained from the Matlab/Simulink environment.

3.5.1. DC Short Circuit Faults

Following a DC short circuit fault, the VSC becomes practically an uncontrollable diode bridge which feeds the short-circuit fault from the AC side [52]. This fault is transferred to the networks, creating strong disturbances of the AC voltages. As a result, a high-voltage DC circuit breaker is required in the link in question for the elimination of DC short circuits. However, the design of such a device is difficult to design in practice due to the extremely high intensity arc. Therefore, DC faults are eliminated in VSC-HVDC connections by means of AC circuit breakers on both sides, with opening times of 50 to 100 ms [52].

In order to study the behaviour of a VSC-HVDC link in the face of a DC short circuit fault, simulation of two types of DC faults (line-earth fault, line-line fault) has been carried out on the 230 kV-50Hz network side. Faults are simulated with different fault line impedances (Breaker resistance Ron = 0.1, 1, 10, 100) at different times with a duration of 50 ms. We have simulated each DC fault individually in the transmission system after reaching its steady state. Same results are obtained when gathering all four of DC faults in one sequence to avoid additional figures. Fig. 3.10 shows the reaction to line-earth DC fault on the DC voltage and current as well as the VSC output current.

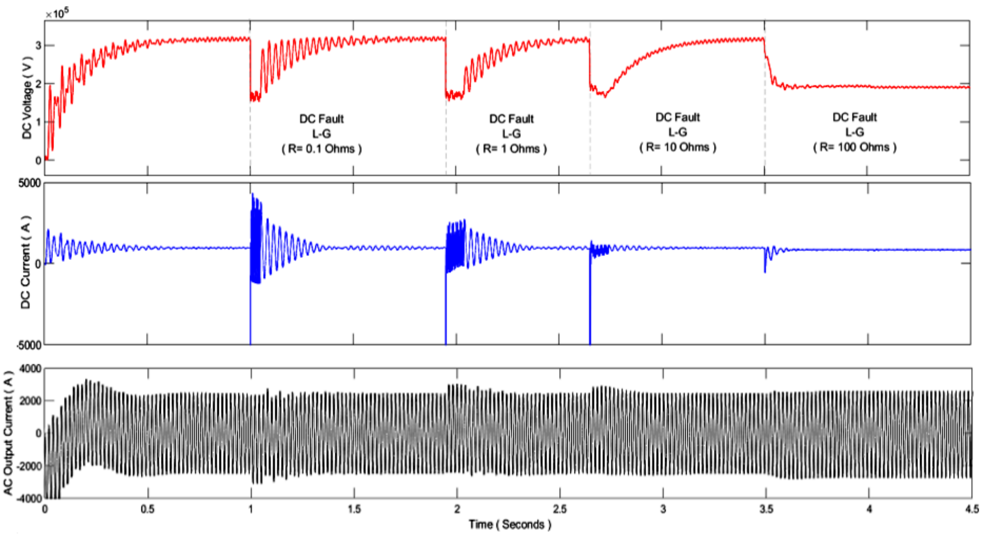


Fig. 3.10: Signals of VSC Transmission System in Response to the Line-Earth DC Fault

As shown in Fig. 3.10, before the occurrence of the DC fault, the DC voltage and current reach their steady state after only 0.5 seconds. When the first simulated fault occurs at exactly 1s with a resistance value of 0.1 Ohms, the DC current decreases rapidly to 10 times its value, accompanied by a DC voltage drop of approximately 110kV with some disturbances affecting the output AC current. After 50 ms the fault is eliminated and the VSC-DC voltage and current take 0.5s to restore the normal function at the nominal values.

Also, the same behaviour happened for DC faults associated with line resistance of R = 1, 10 presenting lesser line disturbances and a decreased current peak value. However, For the last simulated fault (R= 100 Ohms), the DC voltage does not restore its normal function at the nominal value (317kV). Therefore, the VSC-HVDC link must be disconnected by opening the

AC circuit breakers at both ends, to bring it back into service. Fig. 3.11 represents VSC system reaction to the line-line DC fault on the DC voltage and current as well as the VSC output current.

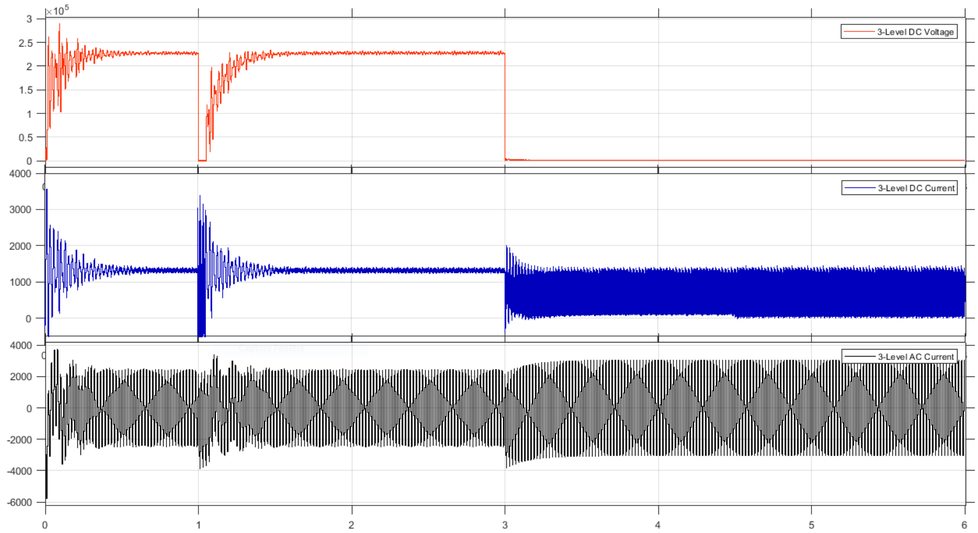


Fig. 3.11: VSC Transmission System behaviour to the Line-Line DC Fault

In this simulation study concerning occurrences of Line-Line DC faults, we observed the same behaviour presented earlier with Line-Earth DC faults. But, with higher voltage drop which reached 315kV leaving a DC voltage of approximately 2kV. However, in this case the loss of the VSC transmission link restorability acted from the Line-Line fault associated with resistance value of R=1 Ohms, unlike the previous case which happened after with the fault of 100 Ohms resistance. Also, we noticed an increase in the output voltage after this fault occurrence and the DC current was unable to restore its nominal value. DC current presented a significantly high number of fluctuations that needed to be eliminated by disconnecting AC circuit breakers to prevent further system damage.

This behaviour of the VSC-HVDC transmission system in the face of DC short circuit faults presents a big disadvantage concerning power transfer. It shows that the occurrence of a DC fault will lead to a loss of power transfer and will present the obligation to restore the transmission system by disconnecting the AC breakers whenever a DC fault occurs.

3.5.2. AC Short Circuit Faults

In this section, we have simulated a short circuit fault on both of the AC sides of the VSC-HVDC link. This is to analyse the behaviour of this technology following single-phase or three-phase short circuit faults. A three-phase short circuit faults with different fault resistances (R= 0.001, 0.01, 0.1,1,10, 100) were considered in both sides of the AC network, which occurred at different times and lasted 50 ms. The results found have been presented in Fig. 3.12 and Fig. 3.13. As Fig. 3.12 shows the curves of the DC current and voltage, as well as the line current and voltage in the inverter AC side.

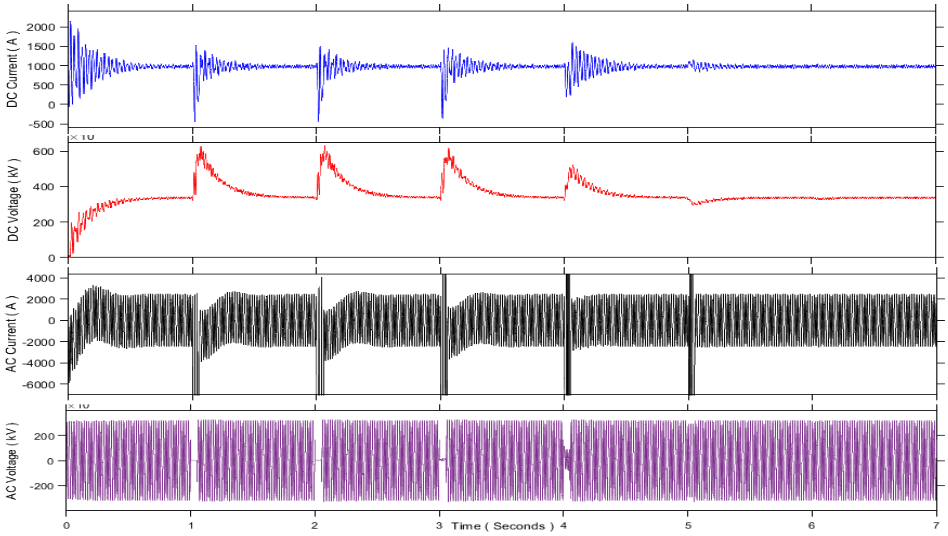


Fig. 3.12: VSC Transmission System response to the AC Three Phase Fault on the Inverter Side

From the presented results, we can see that when the three-phase short circuit fault occurs, the AC voltage on the inverter side experiences a sudden voltage drop which results in rapid increase in the output AC current as shown in Fig. 3.12. The currents undergo strong fluctuations during the fault but resume nominal operation after its elimination. Similarly, a sharp voltage spike (600 kV) is observed, but the nominal value is resumed after a duration of 0.5 s. Thus, the IGBTs must be sized to withstand these stresses during the fault. Fig. 3.13 presents the results obtained from simulating a three-phase short circuit fault on the rectifier AC side.

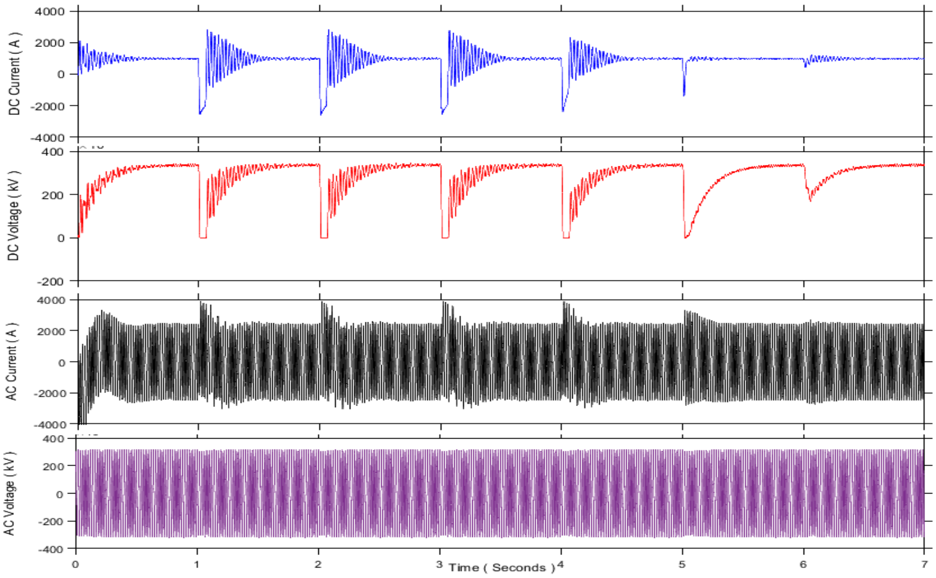


Fig. 3.13: VSC Transmission System behaviour to the AC the 3-Phase Fault on Rectifier Side

Obviously, The VSC output voltage isn’t affected by the fault occurring on the AC rectifier side, unlike the DC voltage which experiences a voltage drop to zero when occurrence of the fault and restores its nominal value after the fault is eliminated. The currents from the DC and

AC side undergo strong fluctuations but resume their nominal operation after the elimination of the fault. Same results are obtained from performing a mono phase short circuit fault as shown in Fig. 3.14.

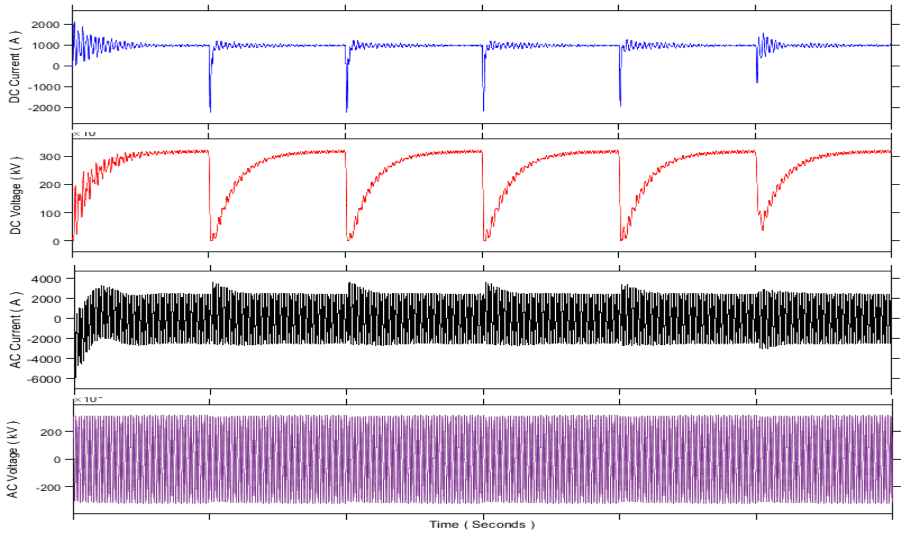


Fig. 3.14: VSC Transmission System response to the AC Mono Phase short circuit Fault

Finally, from the observed results and the simulation study which is performed to analyse the behaviour of the VSC-HVDC transmission system in face of AC and DC short circuit faults. It is found that the VSC-HVDC transmission systems are more robust to the occurrence of AC faults, and will resume the normal function at the nominal point after the elimination of the three phase or the mono phase AC fault. Unlike DC faults which will present a disadvantage in the VSC-HVDC transmission system when occurring at the DC side.

3.6. Converter Losses

The efficiency of an HVDC link is essentially a function of the losses generated in the transmission lines and by the converters. Fig. 3.15 shows the evolution of losses in converters as a function of the DC transferred power.

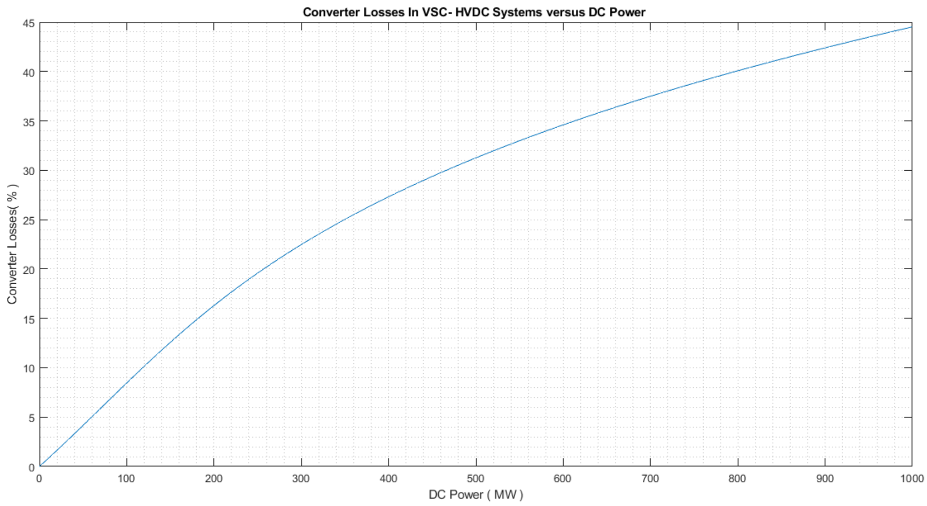


Fig. 3.15: Converter Losses in VSC-HVDC Systems versus DC power

From this figure, the losses of the VSC-HVDC interconnection increase almost linearly with the transmission power. The switching and conducting losses of IGBT semiconductor is about half of the overall losses of the converter valve and then the switching losses of FWD (Free Wheeling Diode) is about one third of the whole energy dissipation. The simultaneous opening and closing of IGBTs at high switching frequencies and at very high voltages and currents create more switching losses. Although increasing the switching frequency minimizes the harmonic content on the AC side, it nevertheless leads to higher switching losses.

3.7. Conclusion

In this chapter, the Three level VSC-HVDC based transmission link has been simulated using MATLAB/Simulink software. Its performance was evaluated based on multiple simulation studies concerning the effects of DC and AC filters on eliminating and reducing the generation of harmonics in the transmission system. Also, short-circuit fault and converter losses analysis was performed in order to test the transmission system reliability in face of different faults occurrences. The comparison between the results of each simulation showed that the three level VSC technology used in transmission presents efficiency in performance and high reliability concerning fault handling capabilities which proves that it is the future of HVDC transmission.

Part III

Comparative Studies on the HVDC Transmission Technologies

Chapter 4

Comparative Study on CHB-Based HVDC Transmission Systems

4.1. Introduction

In this chapter, a comparative study of the HVDC transmission systems is performed with integrating various multilevel converters. Cascaded H-bridge multilevel configurations are considered where 3, 5, 7 and 9 levels converters are simulated under MATLAB/Simulink environment. The effect of the number of levels and its impact within the grid, in terms of performance, are discussed and compared to the conventional configuration of VSC-HVDC transmission (3 levels). Parametric analysis is also carried out to evaluate the performance of the proposed systems under various conditions, generalizing the obtained results. Several types of frequently appeared faults are studied such as short-circuit at AC and DC sides and AC phase loss. Finally, the interaction of the proposed systems with weak AC networks is investigated for different values of SCR.

4.2. Description of the studied model

AC/DC and DC/AC converters in the stations of the HVDC transmission system described in Chapter 3 are replaced by 5, 7 and 9-level CHBMI. It is important to remember that two H-bridge modules are cascaded to form a three phase 5-level converter. This converter was integrated into the transmission system and controlled by SPWM technique with four triangular carriers and a sine wave reference signal. Fig. 4.1 presents the Matlab/Simulink model for the multilevel VSC connected to the transmission system.

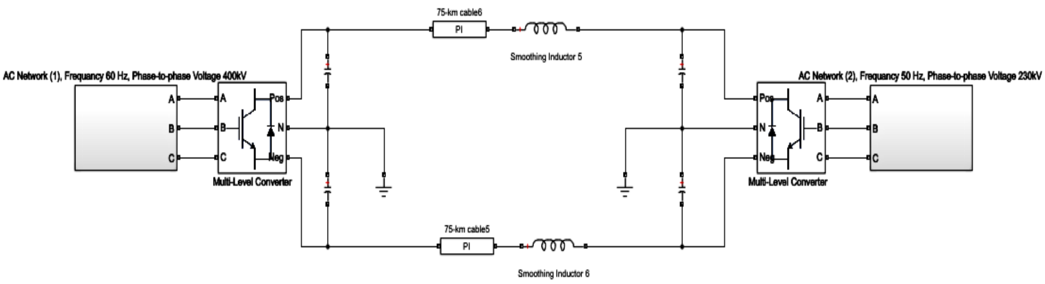


Fig. 4.1: Matlab/Simulink Model for Multi-Level VSCs

Several modules are cascaded then to study the impact of converters with higher levels. The number of the H-bridge in the previous converter was increased to three and then to four to form 7 and 9-level voltage sourced converters, respectively. In which, they were implemented in the same power transmission system. Fig. 4.2a, 4.2b and 4.2c show cascaded H-bridges converters with levels 5, 7 and 9, respectively.

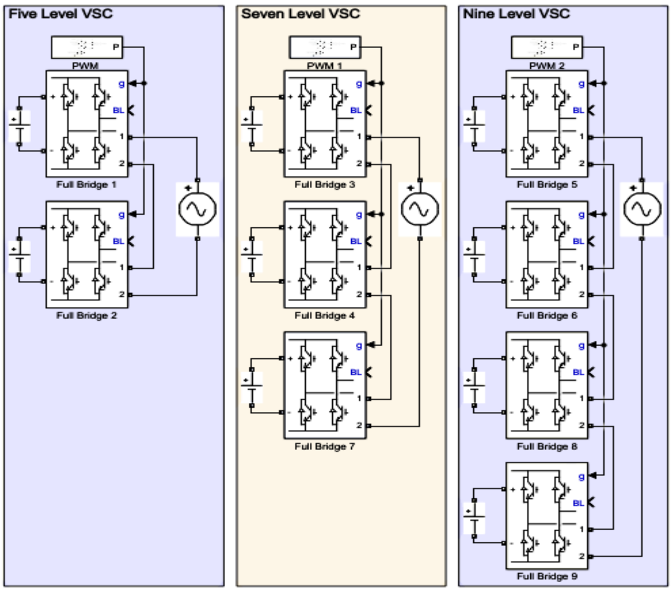


Fig. 4.2: Cascaded Multi-Level VS Converters

SPWM signals that were used to control each of the previously mentioned multilevel voltage sourced converters ($f_s = 2500$ Hz) are presented in the following Fig. 4.3 (Switching frequency of 1000Hz just for an example sample).

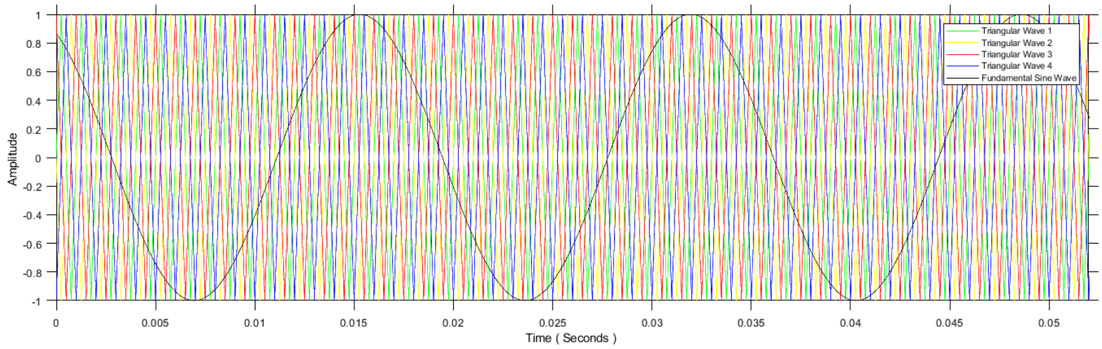


Fig. 4.3: Carrier arrangement for PS-SPWM technique

This figure shows the most common modulation technique used for CHB VSC, the PS-SPWM which can maintain a good controllability over gating signals for IGBTs. For an *N*-level CHB-VSC, the sinusoidal modulation signal is compared with *N-1* triangular carrier signals that are phase shifted by 360/(*N-1*) degrees. The generated SPWM signals control the corresponding IGBT switches [67]. The six triangular carrier waveforms, each with 60° phase shift accompanied by sinusoidal modulation waveform, control the IGBTs gate signals of the 7-level converter. For 5-level and 9-level converters the triangular carrier waveforms are phase shifted with 90° and 45°, respectively.

4.3. Comparatives of Harmonics and Ripple Generation

Multilevel converters used in HVDC transmission systems are known by their low harmonic generation on both of the AC and DC sides [68]. Therefore, simulation studies were performed, in order to evaluate and test the efficiency and performance of these multilevel converters in comparison with results obtained earlier (3-level converters). Under the Matlab/Simulink environment, we simulated 5, 7 and 9-level converters with different sizes of HVDC link DC filters. The obtained results are discussed in the following paragraphs.

4.3.1. DC Side Ripple Generation

The simulation results, obtained from the Simulink environment that consist of voltage $U_d(t)$, current $I_d(t)$ curves are presented in following Fig. 4.4. It shows the evolution of the DC voltage and current of all the multi-level converters with respect to chosen simulation time (1 seconds). It is important to note that a 70uF between the line's capacitance size has been used with each converter.

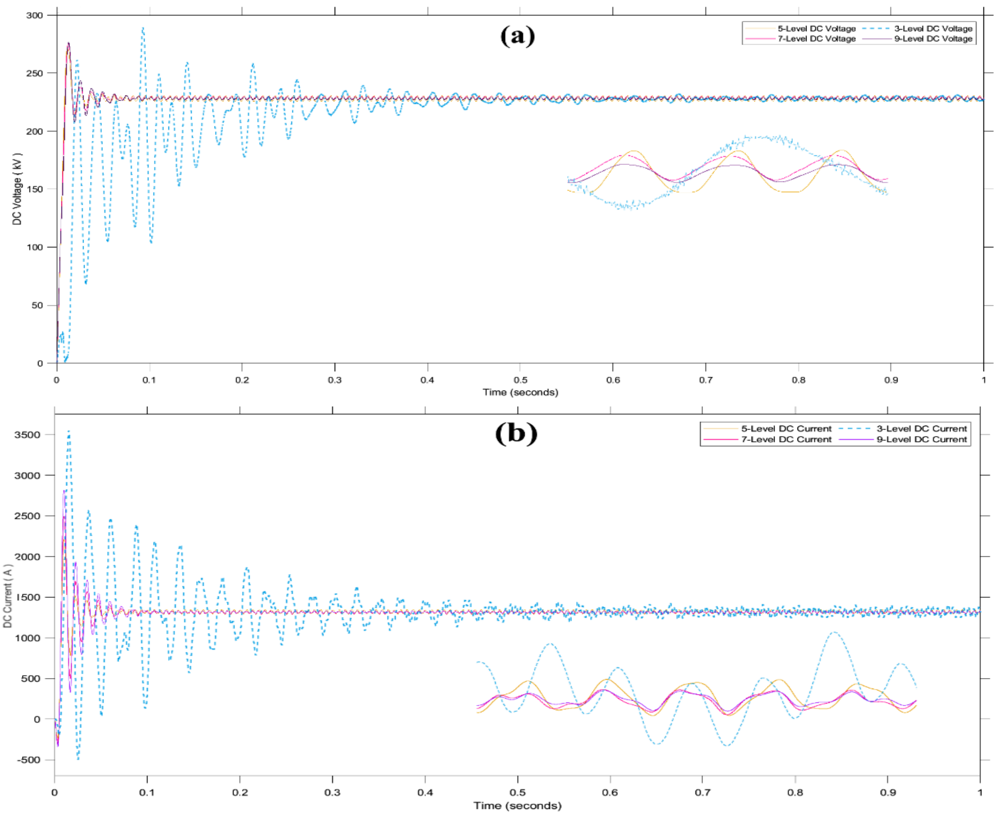


Fig. 4.4: Simulation results of the Multilevel VSC Based HVDC transmission: (a) DC Voltage, (b) DC Current

From this figure, it is shown that the DC voltage is affected by the number of levels in the multilevel converters. Overall, the ripples decrease with the increase of the number of the level. Compared to the conventional 3-level converter, the 5-level converter showed significant reduction in the fluctuations and peak values in the transient state of the DC voltage signal. Also, the voltage reaches its steady state in only 0.1 seconds which means 6 times faster than the conventional three level converters. Moreover, the voltage ripple was decreased by a 2.02 % after introducing the 5-level CHB converter and by a 3%, 3.5% for the 7- and 9- level converters respectively. Regarding the DC current, the same constatation of the DC voltage can be noticed. Current ripple was reduced to 4.4%, 3.28% and 2.6% in the 5, 7 and 9 level converters respectively. This results in the improvement of power transferring performance and reduces converter losses that are due to existing high harmonic fluctuations after each increase in the level number of the converters. In general, stepping up the conversion levels of the converter may provide an alternative to avoid using high capacitance size capacitors, which help reduce the installation cost of HVDC transmission systems with a reduced THD. However, one can observe that there is no effect being noticed after stepping up the converter level from 7. In order to justify this observation, Table 4.1 presents signal ripple with various multi-level converters.

Table 4.1: Development of Signals Ripple with Multi-Level VSC

	DC Current Ripple	DC Voltage Ripple	Evolution of Voltage Ripple
3-Level VSC	9.18%	4.08%	4.08%
5-Level VSC	4.4%	2.06%	2.02%
7-Level VSC	3.28%	1.2%	0.86%
9-Level VSC	2.6%	0.87%	0.33%

Obviously, increasing the converter level's number will affect the signal's ripple by reducing it as possible to a permissible value. But it is noticed that the percentage of the evolution of the signal's ripples from one level to another is decreasing which proves that implementing levels higher than 7-levels will not be a good choice regarding the cost and complexity of the converter station. In the purpose of comparing the effect of DC filters on the line voltage as well as the current of the CHB multilevel converters. Additional two simulation studies were performed. In the first simulation, the DC filters were completely removed from each HVDC transmission system that contained different VSCs. In the second simulation, DC filters with maximum capacitance size of 150uF were used for each system (150uF capacitors presented best filtered signals in previous study of three level VSCs). Figs. 4.5 and 4.6 show the results relative to the first and second simulation, respectively.

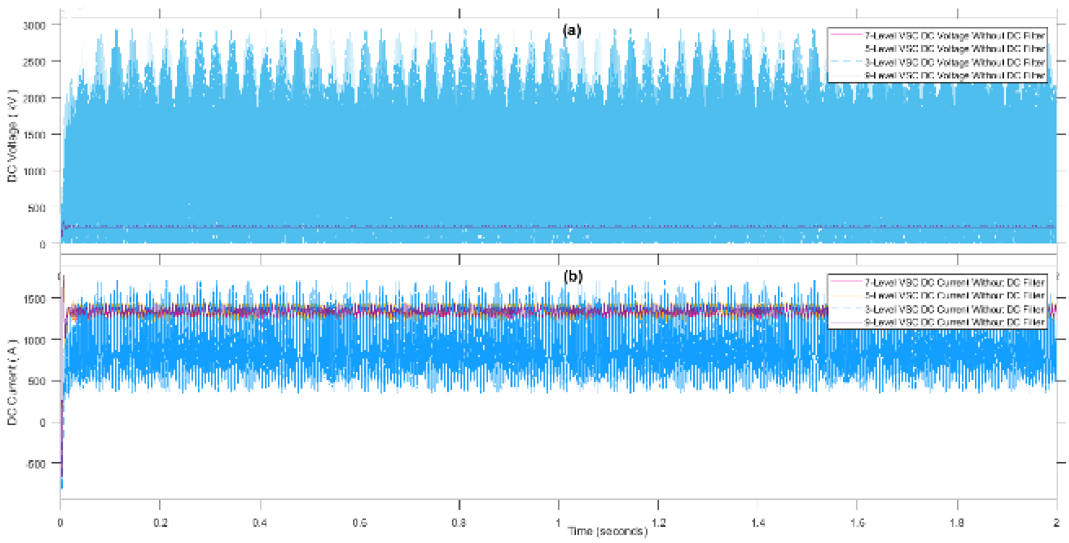


Fig. 4.5: Simulation results of the Multilevel converters based VSC-HVDC transmission systems without DC filters: (a) DC Voltages, (b) DC Currents

Results in Fig. 4.5 show DC signals obtained from multilevel VSCs-HVDC transmission systems in which the DC filters have been removed. it is noticed that for the three level converters it is impossible to operate without integrating filters in the DC side of the transmission system with such a polluted signal (DC voltage and current). However, concerning multilevel converters with levels higher than three, the system can function normally having a considerable harmonic rate. For example, the voltage ripple of the 9-level converter with the DC filter removed is of 3.99%, which is better than a 3-level converter using a 70uF DC link filter (voltage ripple of 4.08%). This can help avoid the implementation and use of DC filters in HVDC transmission systems, reducing the total system installation costs.

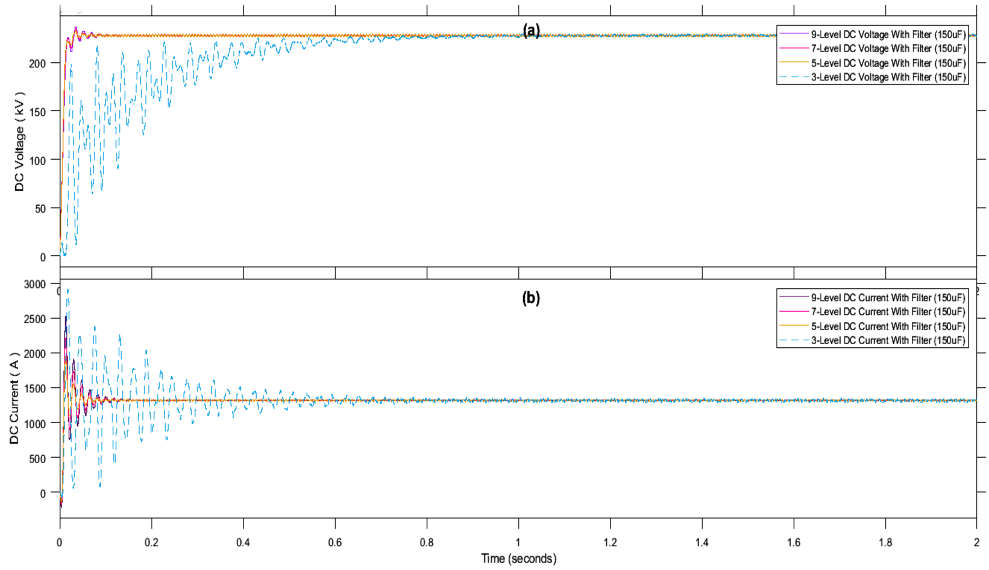


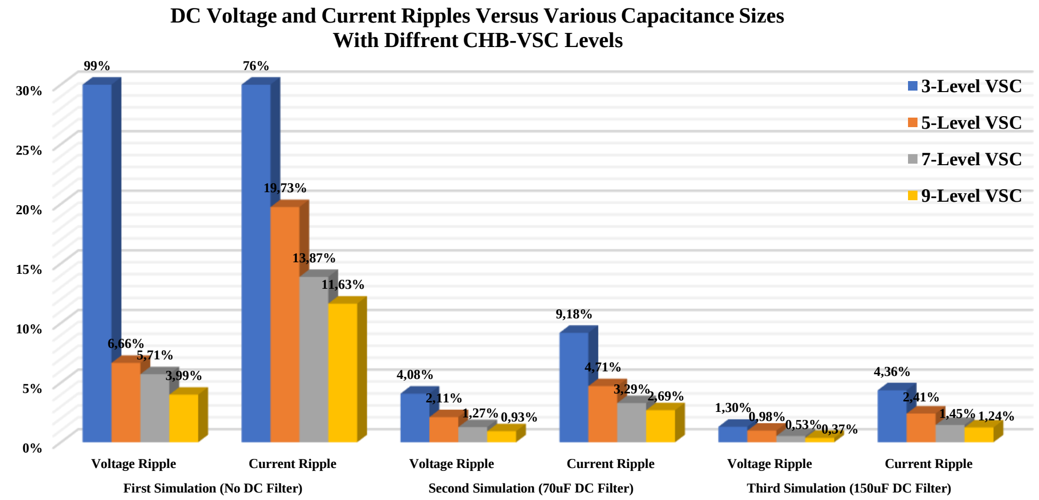
Fig. 4.6: Simulation results of the Multilevel converters based VSC-HVDC transmission systems with 150uF DC filters: (a) DC Voltages, (b) DC Currents

The results, shown in Fig. 4.6, represent the less polluted signals that can be obtained from applying a big capacitance size DC filter (a capacitance size of 150uF in the DC side filters of the multilevel VSCs transmission systems). As one can see that transient state signals peak values are at a minimum value compared to results of the simulation studies given previously. It shows very smooth signals (small THD) with significantly reduced voltage and current ripples. Obviously, as presented earlier, stepping up from 7-level to 9-level VSCs still with a minimum effect even with a big DC filter implemented which indicates that the loss will be at a double concerning costs and complexity of the studied transmission system. A comparison of DC signals' ripples obtained from the performed three simulations is presented in Table 4.2.

Table 4.2: Comparison of Multilevel VSC DC Signals' Ripples

	First Simulation (No DC Filter)		Second Simulation (70uF DC Filter)		Third Simulation (150uF DC Filter)	
	Voltage Ripple	Current Ripple	Voltage Ripple	Current Ripple	Voltage Ripple	Current Ripple
3-Level VSC	99%	79.00 %	4.08 %	9.18 %	1.30 %	4.36 %
5-Level VSC	6.66 %	19.73 %	2.11 %	4.71 %	0.98 %	2.41 %
7-Level VSC	5.71 %	13.87 %	1.27 %	3.29 %	0.53 %	1.45 %
9-Level VSC	3.99 %	11.63 %	0.93 %	2.69 %	0.37%	1.24 %

This table shows different percentages of signal ripples for different combinations of multilevel VSCs and implemented DC filters in the power transmission systems. Fig. 4.7 gives a chart representation of the values of Table 4.2 for signal ripples in case of various capacitance sizes and with different VSC levels.



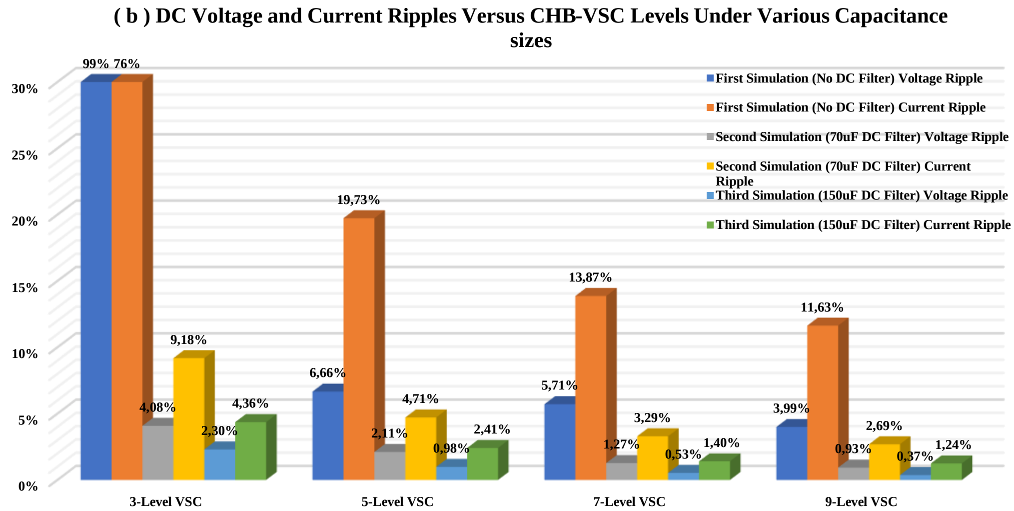


Fig. 4.7: Charts of Signals Ripples of CHB based VSC-HVDC transmission systems: (a) Versus operating Levels for Various Capacitance sizes (b) Versus Capacitance Size for Different Levels

Charts of Fig. 4.7(a) and (b) give a brief view of possible choices that can provide acceptable power transfer performance for the best available installation cost. Different combinations are possible for practical use which will improve the utilization of power systems. For example, for a voltage ripple smaller or equal to 4%, we can use a 9-level or 7-level VSC-HVDC transmission system with DC filters removed or we can choose to add a 70uF DC filter with a 5-level VSC-HVDC transmission system. It all depends on the permissible total installation cost and the desired power transfer system performance.

4.3.2. Output Signals Harmonics

In the previous paragraphs in chapter 3, it was found that high order harmonics needed to be cancelled by integrating AC filters on the AC grids. However, by increasing the operating levels of conversion for the multilevel VSCs, good results can be obtained as the following Fig. 4.8 shows.

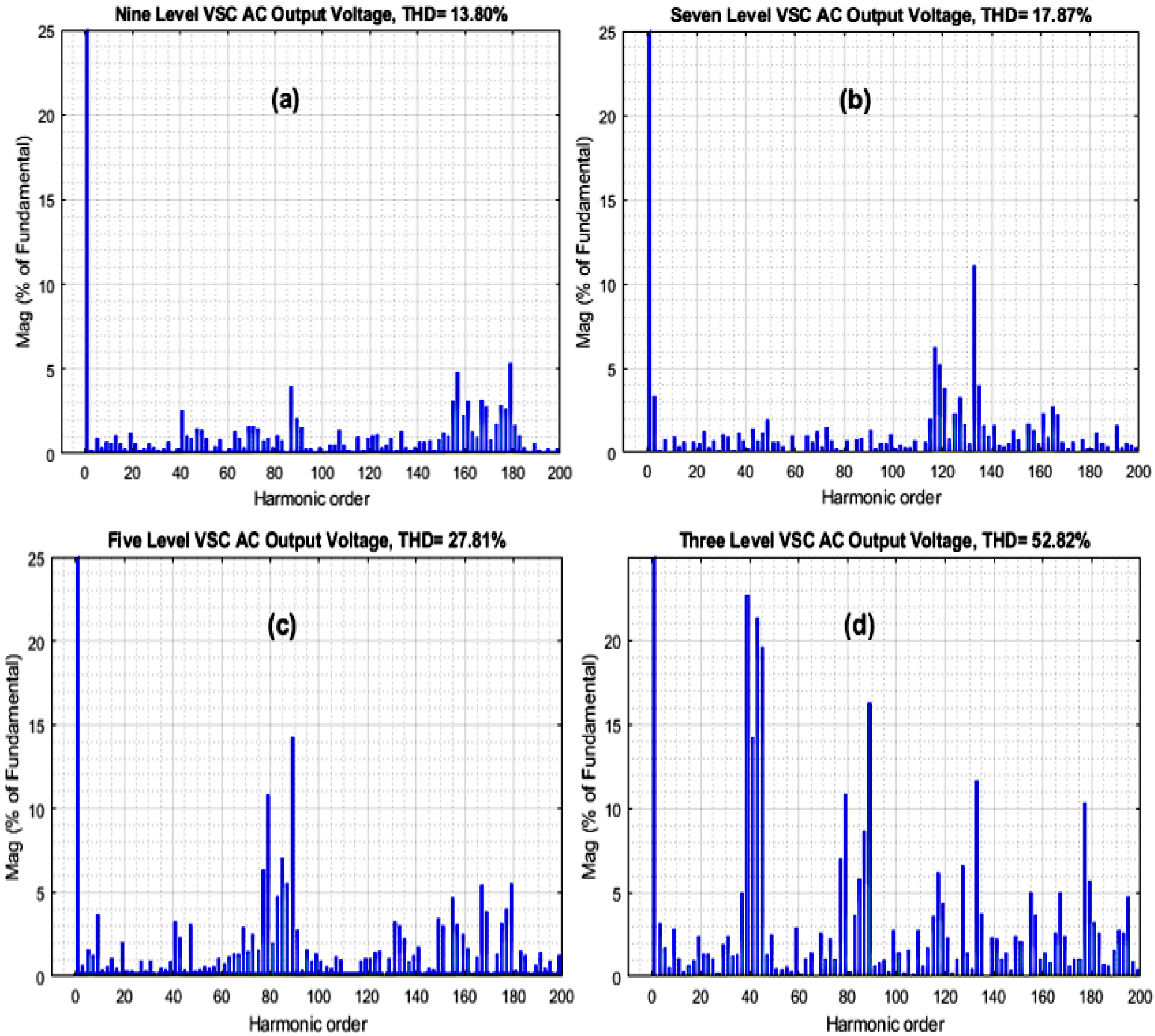


Fig. 4.8: FFT Analysis of Multilevel VSCs Output Voltage:(a) 9-Level VSC, (b) 7-LevelVSC, (c) 5-Level VSC, (d) 3-Level VSC

Matlab FFT Analysis shown in Fig. 4.8 illustrates the different harmonic distortions of the AC output voltage for each of the multilevel converters which are connected to the transmission system (5, 7 and 9-Levels). The AC output signal of the 3-level VSC-HVDC transmission system presented a big amount of high order harmonics, which grouped around the 40th, 80th orders. On the other hand, the 5, 7 and 9-levels VSCs transmission systems had given great results concerning the elimination and tuning of these harmonics.

It is observed that with each step up in conversion levels of the VSC-HVDC transmission systems, the grouping of the harmonics attenuates and moves to higher order frequencies. For example, Fig. 4.8(c) shows that in the case of 5-level VSCs systems, the harmonics that were grouped around the 40th order which were found in 3-level VSCs systems don't exist anymore, but harmonics of higher orders (around 80th) are present. Same behavior was noticed concerning 7 and 9-level VSCs systems, that presented harmonics of order 120th and 160th which will offer high frequency harmonics that are easy to eliminate with reduced AC filters. This improvement of total harmonic generation led to the significant decrease in the THD from 52% for 3-level VSCs to 13% for 9-level VSCs which may result in the enhancement of the power utilization. Fig. 4.9 shows the signals of 3-level ,7-level and 9-level output voltages respectively.

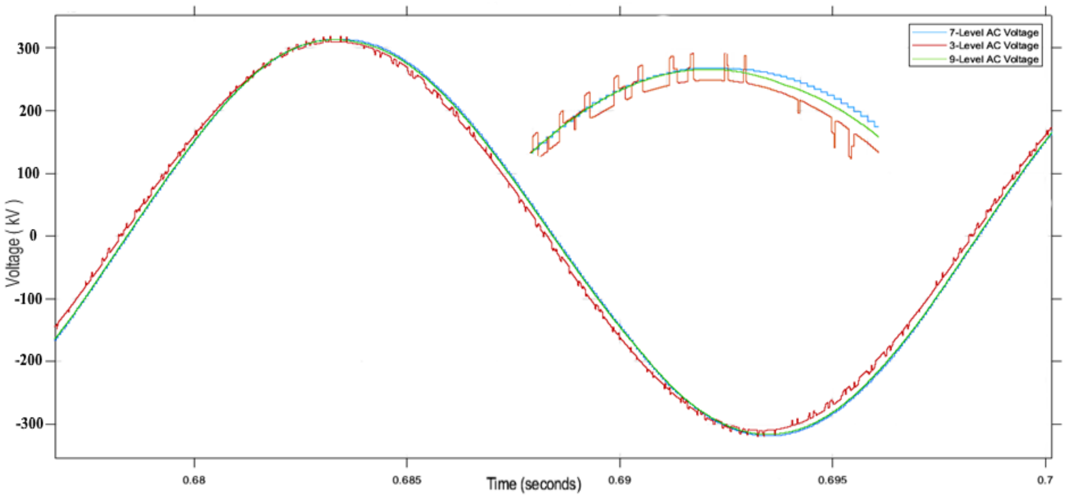


Fig. 4.9: Multilevel Converters Output Voltages

It is clear that the 9-level output voltage (green curve) presents less harmonic distortion and smoother form than the other two signals (3-level and 7-level signals) due to its high efficiency. The output voltage signal gets closer to the sinusoidal form.

4.4. Multi-Level VSC Faults Analysis

This section is performed to analyse the reaction of each Multi-level VSC in the HVDC transmission system during the occurrences of DC and AC short-circuit faults. Simulation using Matlab/Simulink environment is carried out where four faults are applied to transmission systems that contain different level VSCs (3,5,7 and 9 levels). Results and comparison of the transmission systems behaviour are presented in following paragraphs.

4.4.1. DC Short Circuited Faults

This part provides a study case of the CHB multilevel HVDC links response in face of DC short circuit fault. A simulation of Line-to-earth fault has been carried out on the DC link side. This fault is simulated using a fault line impedance (Breaker resistance) of 100 Ohms that applied at the time instant t= 1s, with a duration of 100 ms and different multilevel VSC-HVDC transmission systems. The obtained results are presented in Fig. 4.10, which shows the response to the line-earth DC fault on the DC voltage and current of the CHB multi-level converters.

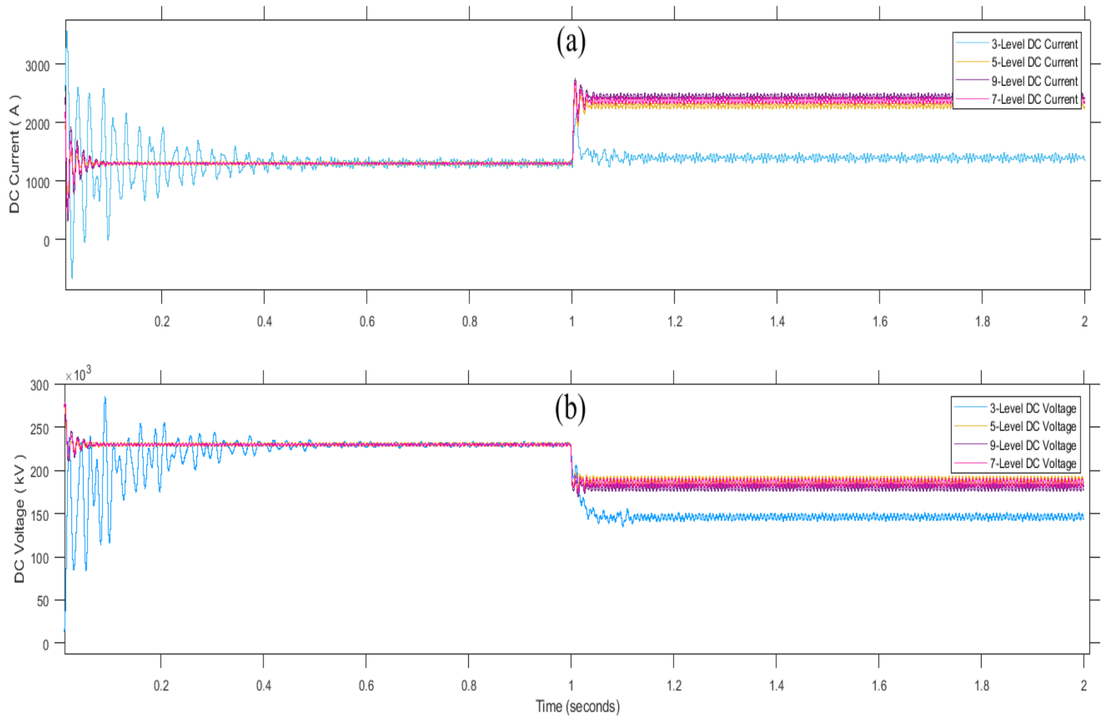


Fig. 4.10: Multi-Level VSC Transmission Systems behaviour to the Line-Earth DC Fault

As illustrated in this figure, it is observed that in the post-fault stage, there was a considerable voltage drop in each of the transmission systems, due to the immediate discharge of the DC link capacitor banks as a result of the fault occurrence. This may lead the HVDC transmission system to lose its functioning at the nominal power point, thus, disconnecting the AC grids by opening the circuit breakers at both ends is necessary to restore the system into service.

Inrush current peaks of the DC current shown in Fig. 4.10, might cause overheating and blocking of the switching components of the converters. Thus, increasing the operating levels of the VSCs may lead to a reduction in the robustness of the transmission system in face of DC faults and protection techniques will be indispensable for the safety of the system (DC switchgears, advanced control techniques, ..., etc.).

4.4.2. AC Short-Circuit Faults

An AC three phase short circuit fault is applied on the inverter AC side in each of the multi-level VSCs-HVDC links in order to analyse the response of HVDC technology following this type of fault. Four three-phase short circuit faults with different fault impedances (breaker resistance R= 0.01, 0.1,1 and 10) were considered at different times for a duration of 50 ms. Fig. 4.11 shows the effect of AC short-circuit faults on the AC voltage and current signals.

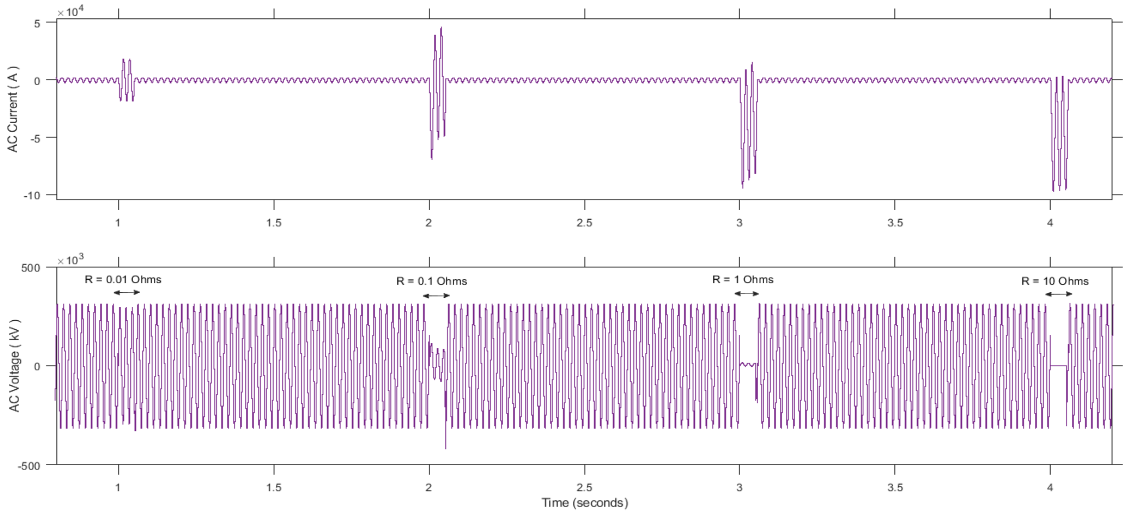


Fig. 4.11: AC Short Circuit Faults in both the AC Voltage and Current

From this figure, it can be seen that the AC short circuit faults are characterized by a voltage sag (decrease of voltage value to zero) and a high increase in the line current up to 3 and 4 times the nominal value. Results of the response of the CHB-HVDC transmission systems to the AC short circuit faults have been presented in Fig. 4.12, which shows the curves of the current and voltage of the DC link with the different discussed faults.

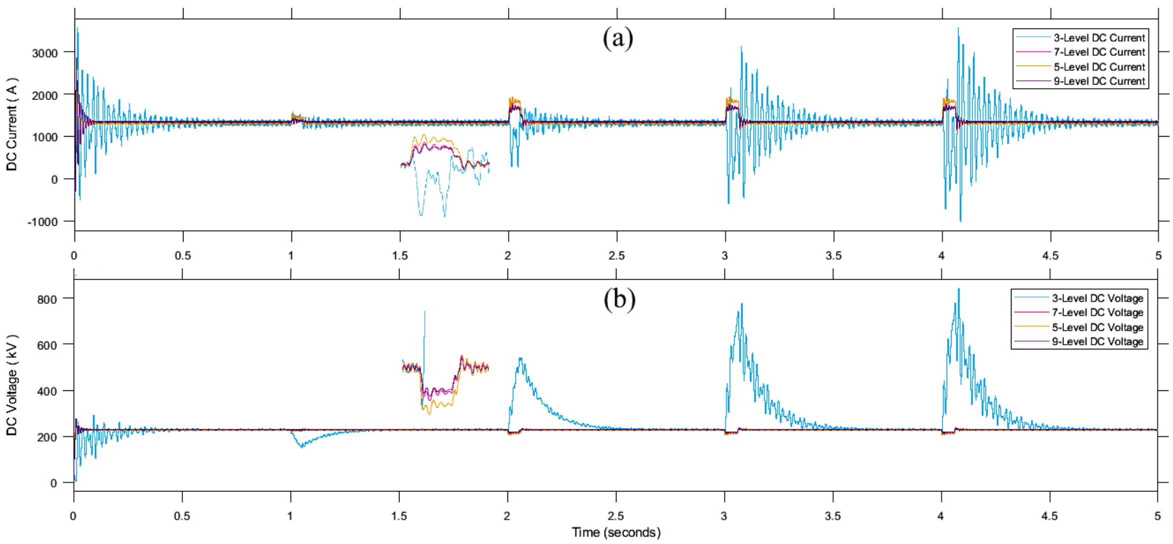


Fig. 4.12: Multi-Level VSC Transmission Systems behaviour to Three Phase AC Faults

As shown in Fig. 4.12, the occurrence of AC short circuit faults in the receiving end (inverter side) resulted in considerably high voltage and current peaks and fluctuations for the 3-level converter transmission system. Whereas, for the 5-level and higher converters, the DC link response was significantly better, concerning the post-fault recovery time which was 5 times faster and the voltage peak values which were reduced by third compared to the conventional transmission system.

4.4.3. Comparison between DC and AC Short-Circuit Faults

After conducting a comparison of the obtained results which are shown in Figs. 4.12 and 4.10, it can be seen that fault handling capabilities for 5-level and higher VSCs are much better than three level VSC in case of AC faults, contrarily to that of DC faults. In case of AC faults, increasing operating converter levels will enhance the power transmission system availability and reduce voltage and current fault peak values at minimum. This is observed from results shown in Fig. 4.11 which shows clearly that fluctuations of DC voltage and current signals have been tuned significantly for all high-level converters. In addition, the restoring capability of power transmission system nominal point is guaranteed after every elimination of AC fault for all of the multi-level VSCs transmission systems which mean that AC faults don't pose a problem to the availability of the transmission systems. Unlike the occurrence of DC faults which will present more problems with every increase in the VSC's operating level, increasing the inrush currents and reducing its power transfer performance. Table 4.3 shows a summary of comparison of fault handling capabilities for multi-level VSCs.

Table 4.3: Comparison of Short-Circuit Faults Handling Capabilities of Multi-Level VSCs

	AC Short-Circuit Faults				DC Short-Circuit Faults			
	Restoring capability	Voltage Drop	Current Drop	Fault Peak Values	Restoring capability	Voltage Drop	Current Drop	Fault Peak Values
3-Level VSC	Good	None	Very Low	High	Good	Good	Good	High
5-Level VSC	Great	None	Very Low	Low	None	Bad (Better than higher level VSCs)	Bad (Better than lower level VSCs)	Low
7-Level VSC	Great	None	Very Low	Lower than 5-Level VSCs	None	Bad (Better than higher level VSCs)	Bad (Better than lower level VSCs)	Low
9-Level VSC	Great	None	Very Low	Lower than 7-Level VSCs	None	Bad (Better than higher level VSCs)	Bad (Better than lower level VSCs)	Low

We observe that there are multiple advantages and disadvantages for stepping up operating level of the converters against short circuited faults concerning restoring capability and losing normal functioning as well as voltage and current drop. It is preferred to use 5-level and higher VSCs in transmission systems for better protection against AC faults. But in face of DC faults the transmission system will be exposed to higher possibility of losing nominal functioning.

4.4.4. AC Phase Loss Faults

In this section, a phase loss fault on the sending AC side of the VSC-HVDC link (Network (1) with 60Hz frequency) is selected in order to study the response of these VSCC-HVDC technologies following single-phase loss (Phase A) faults, which frequently occur in AC networks. Two simulations were performed; first one with losing and restoring the phase A of network (1) at different times with different durations. The second simulation concerned the response of the VSC-HVDC transmission systems to permanent loss of phase (A) from network (1). The obtained results are discussed and compared in following paragraphs.

4.4.4.1. Transient AC Phase Loss Fault

First simulation was performed by applying two transient phase loss faults in each of the VSC-

HVDC transmission systems at different times of 1.6s and 3s for 100ms and 200ms respectively. Fig. 4.13 represents the occurring of these faults in the three phase currents of the sending AC side of the transmission systems.

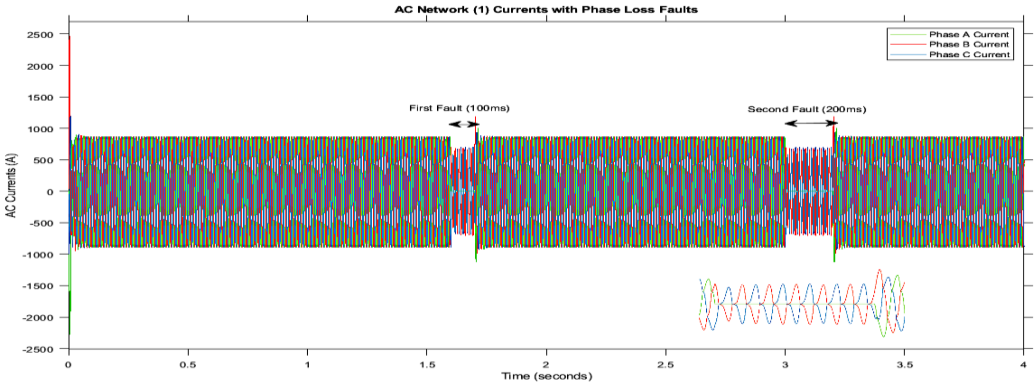


Fig. 4.13: Multilevel VSC Transmission System AC Currents with Transient Phase Loss Faults

As it can be seen from Fig. 4.14, the passage by zero value of phase A current means the elimination and eventual loss of phase A, which is the desired fault. We have performed two transient loss of phase A faults with different duration of 100ms and 200ms to study the effect of the fault duration on the response from the multilevel HVDC transmission systems. Results from the first simulation of the DC voltages and currents of the CHB-based VSC-HVDC transmission systems are shown in Fig. 4.14.

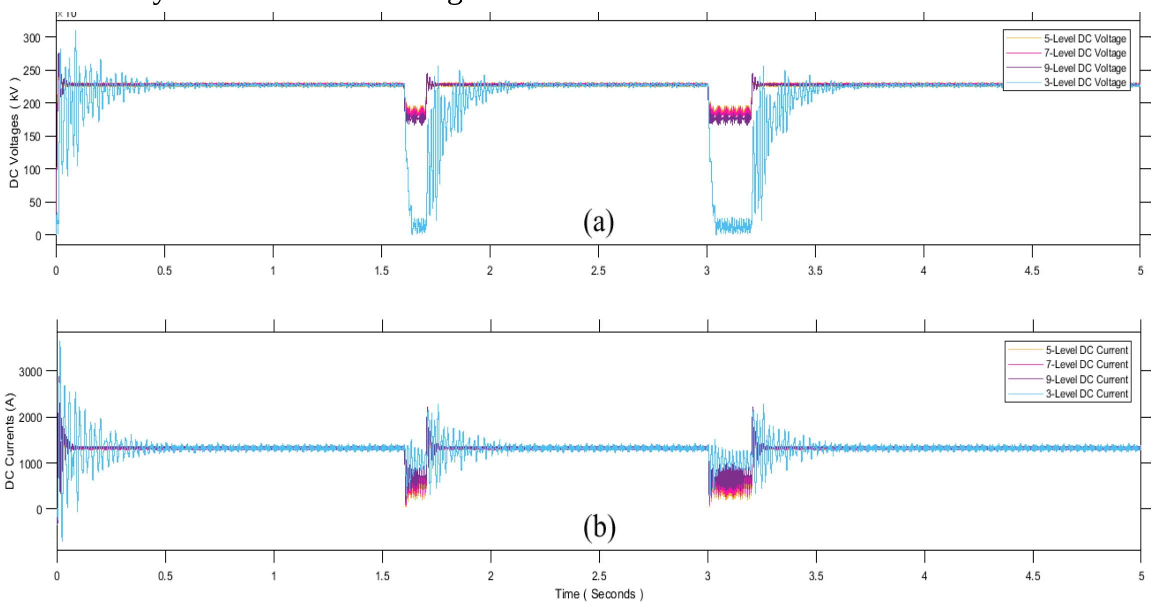


Fig. 4.14: Results of Multilevel VSC Transmission System Response to Transient Phase Loss Faults: (a) DC Voltages, (b) DC Currents, (c) AC Output Currents

It is clear that the transient phase loss faults that had occurred in the transmission systems presented a restoring character same as AC short-circuit faults discussed earlier. As obtained from first simulation results, these faults led to a high drop in the DC voltage of the three level VSC transmission system of an approximate value of 90% which is undesirable for a high-power transmission system.

4.4.4.2. Permanent AC Phase Loss Fault

In order to test the multilevel VSC transmission systems response to the full duration of the phase loss fault, a second simulation is conducted to study the behaviour of the HVDC technology under a permanent loss of phase A in the sending-end AC side. Fig. 4.15 shows the three phase currents of the AC side where permanent loss of phase A has occurred.

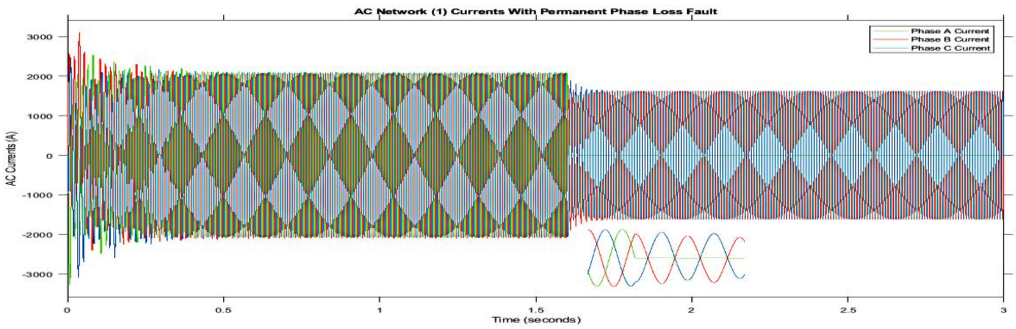


Fig. 4.15: Multilevel VSC Transmission System AC Currents with Permanent Phase Loss Fault

As shown in this figure, the permanent loss of phase A at the sending end starts at 1.6s, which is indicated by passage of phase A current to the zero value. The elimination of phase A resulted in a reduction in phase B and C currents as shown. This will cause changes in the DC link's signals, in which results of the response of the CHB-based multilevel HVDC transmission systems in face of this permanent loss of phase fault are presented in Fig. 4.16.

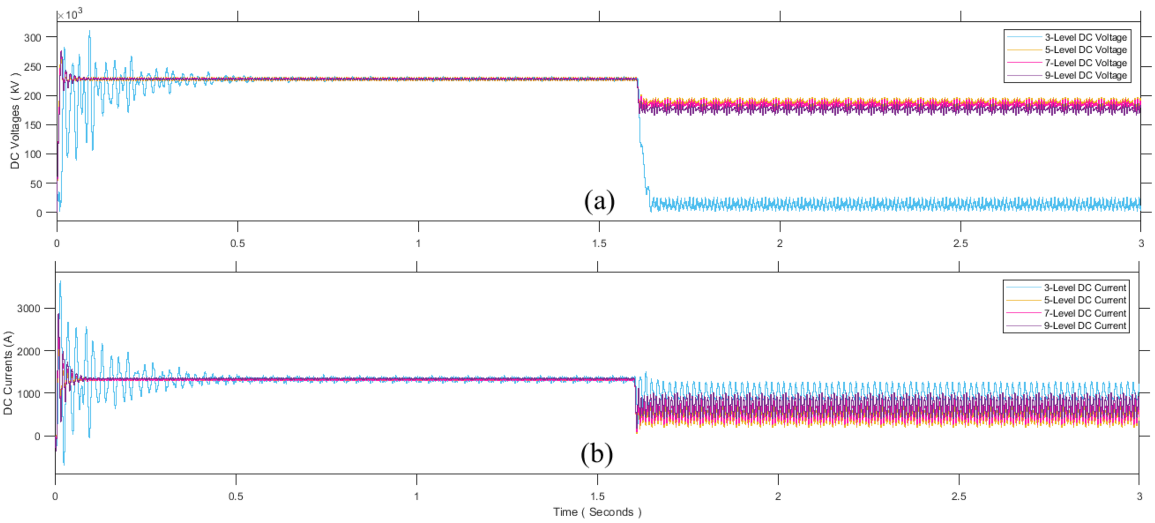


Fig. 4.16: Results of Multilevel VSC Transmission System Response Permanent Phase Loss Fault: (a) DC Voltages, (b) DC Currents, (c) AC Output Currents

One can see that, after the occurrence of the permanent phase loss fault, the HVDC transmission systems have lost their nominal power point functioning with no possibility of being restored to normal. This loss of phase A presented voltage and current drops in the DC side signals along with a deformation in the signal of the AC output currents which have increased after the occurrence of the fault. These fluctuations and deformations in the signal may lead to the appearance of severe problems and damages in the power network or to vital components which are sensitive to the consequences that the occurrences of this type of faults cause. This means that the effects of the fault must be eliminated by the restoring of the lost phase or by presenting other solutions that lead to tuning or eliminating these deformations caused by the occurrence of the fault.

4.4.4.3. Comparison of AC Phase Loss Faults

A simulation study was conducted for the purpose of comparing the responses and behaviours of the multilevel VSC-HVDC transmission systems in the face of transient and permanent loss of phase faults. Also, several variations concerning the capacitance size of the DC filters were applied to each of the transmission systems to analyse their effect in case of the occurrences of the mentioned faults. Simulation results and interpretations are presented and discussed in the following figures and paragraphs.

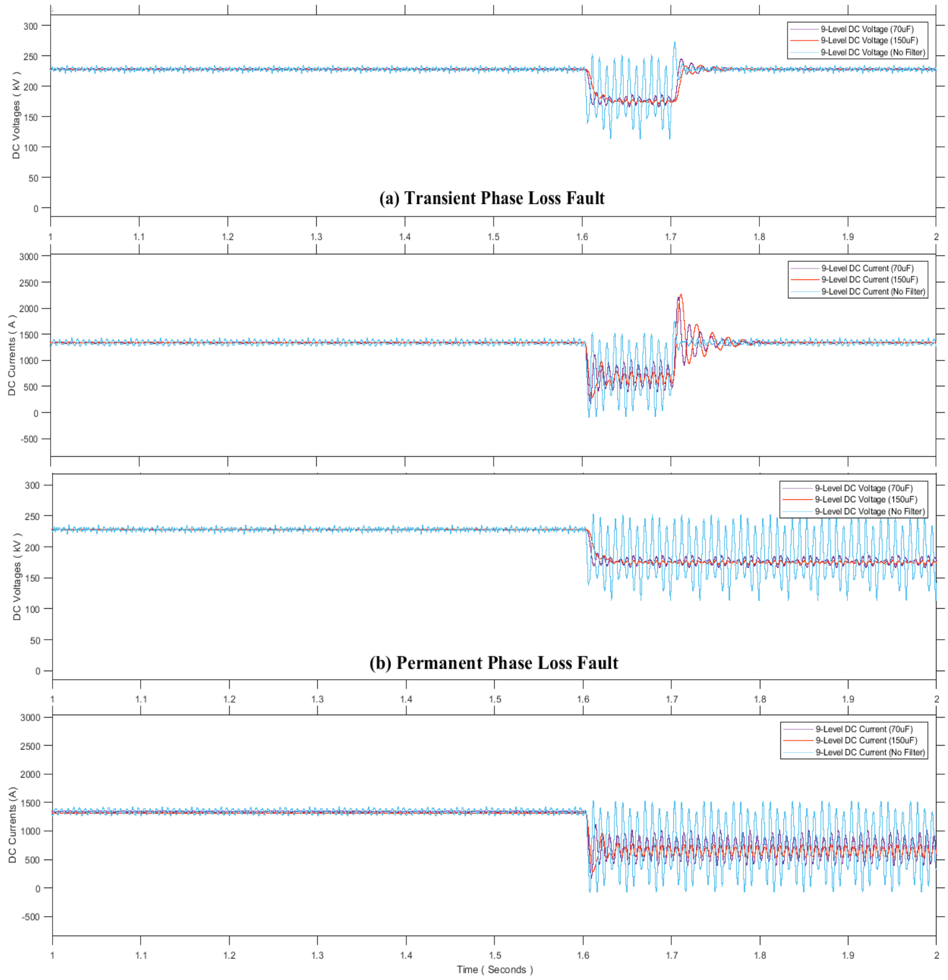


Fig. 4.17: CHB Transmission Systems Response to AC Phase Loss Faults with Different Capacitance sizes: (a) Transient Phase Loss Fault, (b) Permanent Phase Loss Fault

The 9-level VSC-HVDC transmission system has been chosen for the comparison of the effect of DC filters capacitance sizes change when the transmission system is exposed to transient and permanent phase loss faults. A value of 150uF, 70uF, 0uF capacitors for the DC filters of the transmission system were chosen and Fig. 4.117 shows the calculated results of DC signals along with AC output currents. It is observed that increasing the size of the capacitors in DC side filters led to the smoothing of DC signals by eliminating or tuning high fluctuations and deformations that appeared after the occurrences of both of the phase loss faults (starting from 1.6s) as shown in Fig. 4.17. Table 4.4 presents a summary of fluctuations percentages of multilevel VSC-HVDC transmission systems DC signals in the face of transient and permanent phase loss.

Table 4.4: Comparison of DC Signals Deformations After Occurrences of Phase Loss Fault in Multilevel VSC-HVDC Transmission Systems

	No DC Filter		70uF DC Filter		150uF DC Filter	
	Voltage Deformation	Current Deformation	Voltage Deformation	Current Deformation	Voltage Deformation	Current Deformation
3-Level VSC	200 %	180 %	174 %	40 %	138 %	20.6 %
5-Level VSC	49 %	200 %	9.4 %	113 %	2.80 %	44.8 %
7-Level VSC	65 %	242 %	10 %	100 %	3.31 %	40.3 %
9-Level VSC	75 %	247 %	11 %	86 %	3.00 %	34.2 %

This enhancement in the DC signals will help avoiding damages and problems that may be caused by those fluctuations specially from the permanent phase loss fault which will not be eliminated if only the lost phase was restored or by presenting other solutions that offers the same results unlike the transient one which will not pose a problem when normal functioning is restored.

However, changing the DC filter capacitor size did not cause any changes in the AC output current deformation as can be seen in Fig. 4.17 (a) and (b), this means that they may have no impact on the output signal. Concerning transmission systems with converters that have higher operating levels (5,7 and 9) the voltage drop has decreased significantly from 90% to a 20% drop value for systems that contain 9-level VS converters as shown in the previous Fig. 4.14. Table 4.5 shows a brief representation of the signals deformations percentages of the multilevel VSC-HVDC transmission systems in face of transient faults occurrences.

Table 4.5: Signals Drops After Occurrences of Phase Loss Fault in Multilevel VSC-HVDC Transmission Systems

	DC Voltage Drop	DC Current Drop	AC Output Current Deformation
3-Level VSC-HVDC System	93 %	30 %	27 %
5-Level VSC-HVDC System	17 %	48 %	21 %
7-Level VSC-HVDC System	21%	64 %	15 %
9-Level VSC-HVDC System	25 %	70 %	10 %

By comparing Table 4.5 results and curves shown in Fig. 4.14, it is clear that with implementing VSCs with conversion levels that are higher than three levels, the HVDC transmission system will have better fault handling capabilities for both transient and permanent phase loss faults concerning signal drops and fluctuations which will be tuned significantly when faults are occurred. Also, we can see that after eliminating the AC phase loss faults the three-level converter transmission system takes almost 0.4 seconds to regain steady state functioning and stabilize at nominal value whereas for systems that have converters operate at higher converting levels like the 5-level or higher it only takes 0.07 seconds to restore normal operation which is 5 times faster than 3-level VSC-HVDC transmission systems. Extending the duration of the phase loss fault from 100ms to 200ms didn't give any noticeable changes in the behaviour of the HVDC transmission systems in face of the fault.

4.5. Interactions with Weak AC Networks

Generally, the interaction between AC and DC systems depends on the power of the AC network compared to that corresponding to the nominal "Pd" of an HVDC link. To quantify the strength of the AC system at the converter bus of an HVDC system, the concept of Short Circuit Ratio (SCR) is used [50]. The SCR is defined as the ratio of the short-circuit MVA of the AC system at the AC bus to the rated DC power at the DC link. The robustness of the AC network with respect to the latter determines the level of stability of the AC voltage, the voltage of the DC link and its ability to supply reactive energy. It is measured through the short circuit ratio (SCR). This ratio is calculated by the following expression [69]:

$$SCR = \frac{MVA_{sc}}{P_{dc}} = \frac{V_{AC}^2}{Z_{AC}P_{DC}}$$

Where, MVA_{sc} in (MVA), P_{dc} in (MW), V_{AC} in (V) and Z_{AC}in (Ohms). These parameters represent the short circuit level of the AC grid, the rated transmission power of the HVDC link, the rated voltage and the equivalent Thevenin impedance of the grid, respectively. The strength of an AC network with respect to the DC interconnection can be classified according to the SCR value as follows [50]:

$$SCR > 3 : Strong\ AC\ Network$$
$$3 > SCR > 2 : Weak\ AC\ Network$$
$$2 > SCR : Very\ Weak\ AC\ Network$$

A simulation study on 5, 7 and 9-level VSC-HVDC systems was performed to analyse the SCR effect on these systems and their stability. This was discussed in [21], in which, a conventional LCC and 3-level VSC HVDC systems were simulated to test their response to changes in SCR value. In purpose of contributing to the obtained results, in each of the multilevel VSC-HVDC transmission systems, we varied the internal impedance of the 400 kV- 60 Hz network in order to have a strong, weak and very weak AC network connected to the DC link. While the second AC network on the other side of the DC transmission was kept unvaried. The obtained results concerning response of the 7-level VSC-HVDC transmission system to variation of the SCR are shown in the following Fig. 4.18.

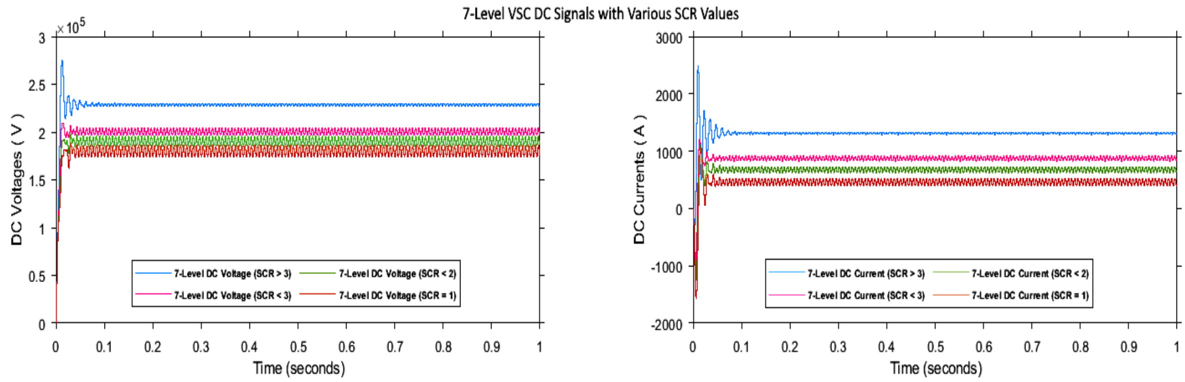


Fig. 4.18: Results of 7-Level VSC Transmission System Response to SCR Variation

Clearly, as shown, the operation of the transmission line is stable since it reaches the steady state in all the presented cases. But we can see that with every variation of the SCR to smaller values there is an increasing voltage and current drops noticed in the DC link of the transmission system. These are due to the rising internal impedance of the AC network connected to the DC link when the SCR is reaching smaller values which will reduce the maximum transmittable power due to this high internal impedance of the AC network. Fig. 4.19 shows comparison of multilevel VSC-HVDC transmission systems response to variation of the SCR in the AC network.

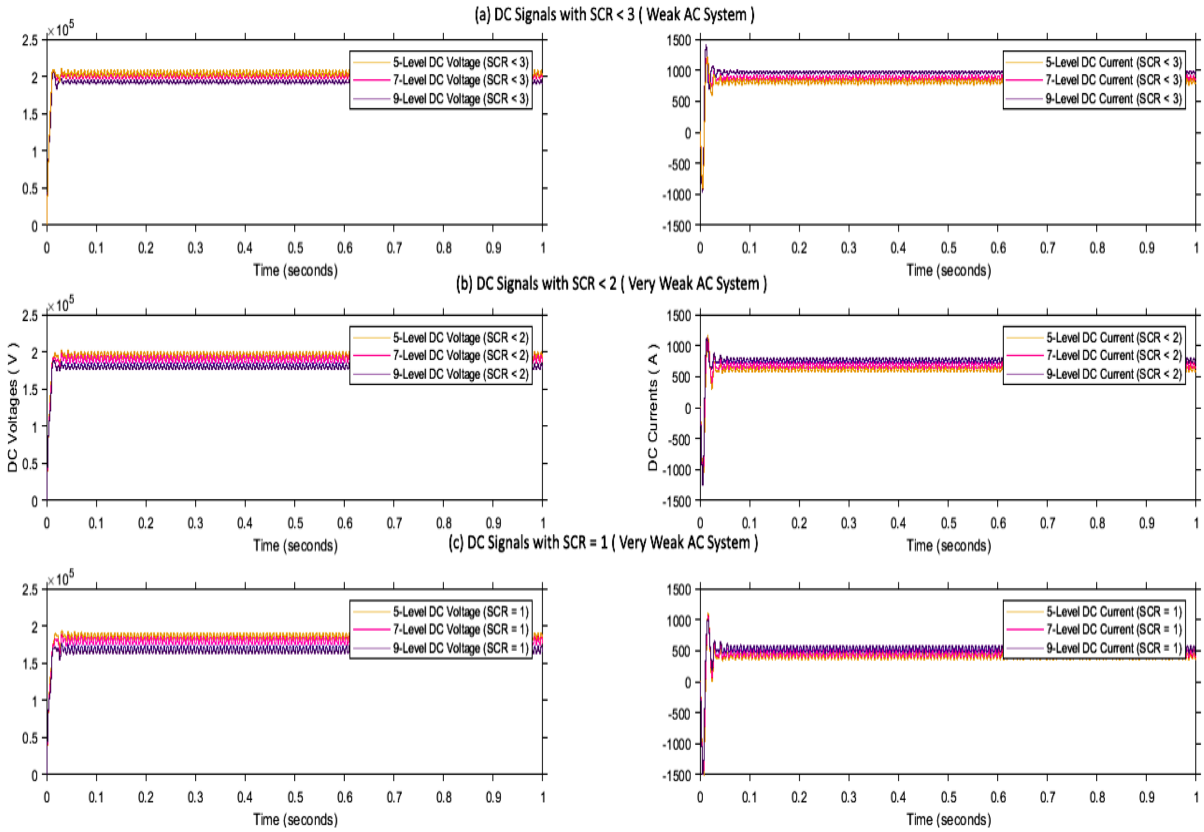


Fig. 4.19: CHB Transmission Systems Response to SCR Variation: (a) DC Signals with SCR < 3, (b) DC Signals with SCR < 2, (c) DC Signals with SCR = 1

By comparing the results of Fig. 4.19 which show different responses from the transmission systems when connecting a weak and very weak AC network to an HVDC link. We can see that concerning DC voltage drops, the 5-Level converter transmission system has the best response with a minimal drop at each SCR value compared to higher level converters (7 and 9). Brief summary of these results is presented in Table 4.6.

Table 4.6: DC Power Drops in Multilevel VSC-HVDC Transmission Systems When Variating SCR Value

	3 > SCR > 2			SCR < 2			SCR = 1		
	DC Voltage Drop	DC Current Drop	DC Power Drop	DC Voltage Drop	DC Current Drop	DC Power Drop	DC Voltage Drop	DC Current Drop	DC Power Drop
5-Level VSC-HVDC	12 %	41 %	49 %	15 %	56 %	64 %	18 %	72 %	78 %
7-Level VSC-HVDC	13 %	37 %	45 %	17 %	52 %	60 %	21 %	69 %	76 %
9-Level VSC-HVDC	16 %	29 %	40 %	21 %	45 %	57 %	26 %	64 %	74 %

These results show that any decrease in the SCR value will cause a drop in the DC signals which will lead to a reduction in the transmissible power by the DC link. Also, we can see that the 9-level VSC-HVDC has the minimum power drop percentage which means that higher operating converter levels will affect the stability of the transmission systems. However, as obtained from Table 4.6, it is highly not recommended to interconnect HVDC links with very weak AC networks (SCR < 2) without implanting a suitable control method that allows the utilization of the full VSC-HVDC potential like the power synchronization control technique discussed in references [70], [71].

4.6. Conclusion

This last chapter presented various comparative studies, where the multilevel VSCs implemented in the HVDC transmission system were simulated using MATLAB/Simulink software under different conditions. Harmonic generation and short-circuit fault as well as an AC phase loss fault analysis were performed to evaluate and compare their performance where the strong and weak points of each VSC technology were drawn. Finally, an interaction of the multilevel VSC-HVDC transmission technology with a weak AC grid was simulated where stability and responses of this technology have been tested by the calculated and obtained results.

General Conclusion

General Conclusion

The HVDC transmission system has many more advantages than the HVAC, in particular by allowing the interconnection of asynchronous networks, the controllability of energy flows, the reinforcement of network stability, the integration of renewable energy, etc. This work focused on the technical assessment study of the HVDC transmission systems between two networks with different operating conditions (frequency and voltage). Based on the model studied by last year's students' work [14], a link between two asynchronous networks 400 kV- 60 Hz and 230 kV- 50 Hz is considered. The line model has been studied for a transferred DC power of 300 MW. The study was based on simulations under the MATLAB/Simulink environment and validated by comparing with the theoretical model.

First, a modelling study concerning the multilevel voltage sourced converters presented a brief understanding of the main and basic components needed in HVDC transmission technology as well as the power control principle. Then an equivalent scheme was drawn to simulate the three level VSC-HVDC transmission system under various operating conditions. The obtained results showed that by increasing the capacitance size of the DC filters the three level VSC-HVDC transmission system will present lower harmonic generation along with reducing the DC voltage ripple which will improve the efficiency of power transferring. Moreover, this technology showed a robustness and reliability in face of AC and DC short-circuited faults where the system regained and re-established its normal functioning in all of the occurrences of the AC faults and in most of the DC fault cases. Where in the presented cases of system failure after undergoing a severe DC short-circuited fault, the transmission system was obliged to be disconnected by AC circuit breakers from both ends to be able to restore its normal operation.

Next, the HVDC transmission was simulated using multilevel voltage sourced converters of level 5,7 and 9 which were implemented in the same transmission system in order to perform a comparative study based on the three-level converter transmission system discussed earlier. The simulation was carried out for a 300 MW line between two asynchronous networks, four converter topologies were used, VSC 3,5,7, and 9-level. According to the results found, the first thing to observe from this simulation is that when increasing the operating conversion levels of the implemented VSCs in the transmission system, the total harmonic distortion will be reduced significantly with each stepping up in the levels from 3 to 9 levels. Where, for the three level VSC system, the THD was up to 53% and was reduced to 28 %, 17 %, 13 % for 5,7 and 9-level VSCs respectively which meant less harmonic generation for these VSCs. This drop in the THD was followed by a decrease in the DC voltage ripple in the same sequence from three level converter topology to the nine level one. The FFT Analysis provided by Matlab/Simulink showed that when increasing the operating conversion levels of the VSCs, it will result in a higher harmonics order group. For the 9-level VSC, the FFT Analysis presented a number of harmonics grouped around the 160^{th} order, whereas for the 7,5 and 3-levels VSCs the harmonics were gathered around the 120^{th}, 80^{th}, 40^{th} orders respectively. The presence of these generated high order harmonic counts as a positive point for multilevel VSC since it is easy to eliminate them by a reduced AC filters compared with those generated by lower level VSCs. Moreover, other results of a comparative simulation study showed that the possibility of avoiding and removing the DC filters is offered when using a multilevel VSC in the transmission system in question. This was presented from obtained results that gave multiple combinations related to the use of different sizes of DC filters with different operating converter levels (9-level VSC with no DC filter, 5-Level VSC with a reduced DC filter, …etc.). Furthermore, fault analysis was performed in order to compare the response of each multilevel VSC topology in the face of different AC and DC faults. First, the results of the DC short-circuit faults simulation showed that VSCs with levels higher than three presented less fault handling capabilities where the transmission system lost its nominal point functioning. Whereas, in case of AC short-circuit and phase loss faults the multilevel VSCs transmission systems gave superior results in stability, reliability and performance. Finally, an HVDC transmission technology interaction with a weak AC grid resulted in the conclusion that multilevel VSCs will present a stable and steady functioning with weak AC grids in condition of providing suitable control methods to fully exploit the VSC-HVDC transmission technology potentials. These discussed results will offer some perspectives that the multilevel voltage sourced converters are the promising future of the HVDC transmission technology and the power transferring techniques in the years to come and much research will be done on the purpose of this topic.

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Appendix
Choice of Simulation Network

The network configurations and parameters of the HVDC transmission elements (LCC and VSC) simulated under the MATLAB-Simulink environment, are based on the "Benchmark" model established by CIGRE [72]. It is a representative reference model of HVDC, which is used as a test system for new control strategies [52]. The schematic of this model is shown in Figure 5.15. The network voltages are 345 kV and 230 kV. The HVDC line is characterized by a transmission power Pd of 1000 MW and a nominal voltage Vd of 500 kV. The HVDC transmission is of the LCC type using 12 pulse converters. It has a DC cable is a distance of 100 km, modelled as a "T", with smoothing coils.

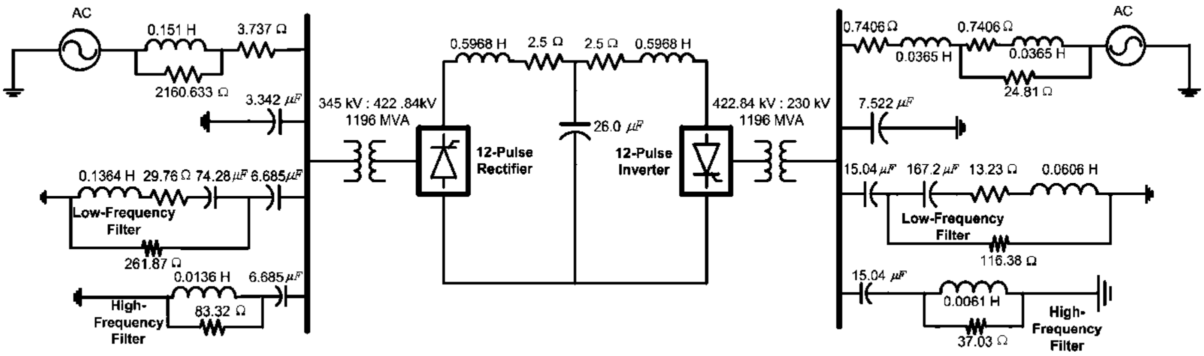

Fig. 4.20: Illustrative diagram of the CIGRE "Benchmark" model [71]

However, by consulting the main VSC HVDC transmissions in the world [50], there is currently no such link in service with the same values of power and operating voltage as those of the model. "Benchmark". Therefore, modifications have been made to this model. The simulation was carried out for the following nominal point: (P_d = 300 MW; V_d= 230 kV). The parameters of transformers and cables in the simulation were taken from references [73], [74].