Master Thesis

Master's Degree in Energy Engineering

Partial Open-Source HVDC Control

Author: Mohamed Elhadi Idris Abdulgadir

Supervisor: Eduardo Prieto Araujo

June 2022

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

ETSEIB

Abstract

High voltage direct current (HVDC) transmission, with the help of cutting-edge power electronic technological advancements, is envisioned to be the leading mode of transmission of electric power, superseding the traditional alternating current (AC) transmission. HVDC transmission allows for the transmission of large amounts of power over much longer distances in a more efficient and environmentally friendly way than AC transmission. Moreover, HVDC technology paves the way for the integration of renewable energy sources (RES) into the electric power grid. The main attractive feature possessed by HVDC systems that allows for the integration of RESs into the electric power grid is the ability to connect two unsynchronized AC networks. This allows for a seamless transition to renewable energy power generation as opposed to traditional generation methods. HVDC systems will inevitably be responsible for the expansion of power systems in a more controlled and stable way.

When it comes to the design and implementation of HVDC systems, several factors must be taken into account; namely, the architecture of the HVDC system (point-to-point or multi-terminal networks), the converter technology (voltage source converter, line commutated converter, hybrid VSC-LCC, etc.), and the VSC converter topology (2-level, 3-level, or multi-level converter topology). The main focus of this thesis revolves around the converter controls. It has been seen in several commissioned HVDC projects that interoperability plays a massive role in the successful operation of multivendor HVDC systems. Moreover, in multivendor HVDC systems, the converter control software pertaining to each vendor is kept closed. This inaccessibility of vendor-specific converter information leads to inefficient methods of handling interoperability issues.

This thesis aims to propose a partially open converter control software that is hypothesized to ease investigations into converter control interactions, interoperability, and system stability issues. Functional models of the control systems are designed with the help of the software Modelio using the systems engineering language known as SysML in order to provide a higher-level perspective of the system, aiding in the understanding and proper navigation of complex HVDC converter control elements.

ETSEIB

List of Figures

List of Tables

INDEX

ETSEIB

1. Introduction

With the rapid increase in the integration of renewable energy systems around the world, high voltage direct current (HVDC) systems are becoming a focal point of interest in the transmission of electric power. Sustainability is beginning to play a much larger role in placing more importance in the reduction of the global carbon footprint, and the reduction of fossil fuels resulting in a cleaner environment. Although there are many factors that contribute to achieving a more sustainable environment, more focus is placed on the generation of electric power. Renewable power generation is envisioned to be a more suitable replacement for traditional power generation methods in the future. In addition to maintaining a low carbon footprint, the United Nations Framework Convention on Climate Change (UNFCCC) held a conference in Paris (COP 21) where an urgent importance is placed in the need for a "scaled up global response to climate change" maintaining a target of 1.5°C [1]. In order to comply with such objectives resulting in an active prevention of climate change, renewable energy such as wind and solar power generation systems are expected to be globally implemented. According to the European Commission, the total wind energy capacity in the EU is expected to increase from 210 GW in 2020 to approximately 350 GW by 2030 equating to about 24% of the electricity demand in Europe [2]. The fact that RES's are expected to inevitably replace traditional power generation methods based on fossil fuels and nuclear energy, a greater importance is now placed in the optimization and reinforcement of the infrastructure relating to this power generation technology.

While traditional power generation methods are classified as non-ideal for environmental purposes, they have been the primary drivers of electric power generation for a very long time. Major stakeholders in the electric power industry will need to support a dramatic change in the infrastructure of electric power grids both in technical and non-technical aspects. This is a necessity because traditionally, the grid transmission and distribution infrastructure depend on centralized power plants nearby consumers. However, with the integration of RES's such as offshore wind power plants, the development of newer transmission and distribution lines will be required due to the remote nature of the offshore wind power plants. The presence of distribution and transmission networks are crucial for the integration of RES into the grid. The restricted transmission capacity of the current AC networks, as previously mentioned, is one of the major obstacles to the full integration of RESs. When a transmission path's dependable transfer capacity is exceeded by demand, transmission bottlenecks may occur. Therefore, it is important to note that any integration of significant volumes of RESs will need for sizable expansions of the current transmission and distribution networks. Furthermore, with the implementation of large scale RES's, grid stability, expansion, and reinforcement are now of utmost importance.

ETSEIB

1.1. Research Background

Now that the need for renewable power generation is convincingly established, the mode of transmission immediately becomes key in maintaining a stable grid. Traditional three-phase AC power transmission has been a staple part of the electric power system for decades due to its efficiency and reliability. However, AC power transmission faces several challenges that arise as a result of the integration of renewable energy systems into the power grid. Renewable power generation raises a great degree of unpredictability in grid operation. Moreover, issues relating to power flow control flexibility and reserve power immediately become crucial challenges that need to be addressed [3]. As a result of this, high voltage direct current (HVDC) becomes an attractive option due to its flexibility & controllability. The flexibility of the system that integrates RES's carries a great deal of weight due to the fact that having an HVDC system means that it comes with the feature of multidirectional power flow (due to having several DC links capable of connecting multiple AC systems). In addition to this, HVDC guarantees a reduction of transmission losses over longer distances. In the case of AC transmission, it is not ideal for power to be transmitted over very long distances due to losses, and the need for severe reactive power compensation along the way. This brings up the solution of DC transmission with the help of key converter technologies. HVDC offers a wide range of solutions such as: lower transmission losses, controllability of active power flow, longer lengths of underground or submarine cables, interconnection between two non-synchronized AC networks or different frequencies, etc. Fig. 1 shows a traditional HVDC system that operates with the help of the AC/DC converter station, DC/AC inverter station, and a DC transmission line.
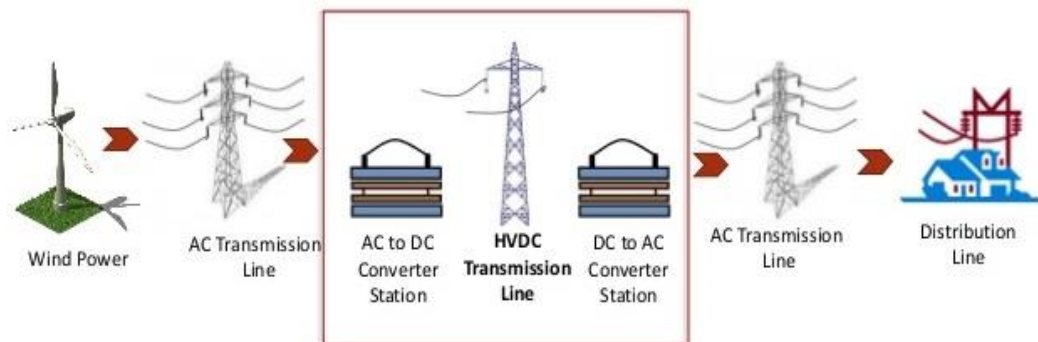
Figure 1: Traditional HVDC System with Wind Power Generation [4]

The main principle of HVDC transmission stems from the advancements in power electronic technologies that enable a clean conversion of AC/DC and then DC back to AC. The main purpose of enabling these DC connections is to integrate volatile energy sources such as wind and solar into the electric power grid. The converter stations that make this possible

come with many advantages that also directly answer some the challenges faced by traditional AC transmission. Applying HVDC (specifically VSC-HVDC) technology in a traditional AC network as seen in Fig. 1 offers benefits such as: independent control of active & reactive power, grid black-start capabilities, ability to connect to weak systems, etc. [3]. The implementation of HVDC transmission, however, depends on the converter technology. Furthermore, the converter technology then depends on the type of topology it uses in order to further optimize the synthesized output voltage in terms of lower harmonic distortion. There are many different converter technologies, however, the two main converter technologies are the line commutated converter (LCC) technology and the voltage source converter (VSC) technology. Lately, the VSC technology has gathered more interest than LCCs due to the realization that the LCC technology possesses key drawbacks that VSCs do not.

The transition to HVDC grids with specific converter technology, while being a crucial step in the advancement of maintaining a cleaner environment, raises many concerns and challenges that need to be strategically and systematically addressed. HVDC networks in their most basic form consist of what is known as a point-to-point transmission scheme; in fact, Fig.1 depicts a point-to-point HVDC transmission system. However, complexities begin to cluster when dealing with multi-terminal HVDC (MTDC) schemes. Fig. 2 shows a commonly adopted MTDC test system by CIGRE.
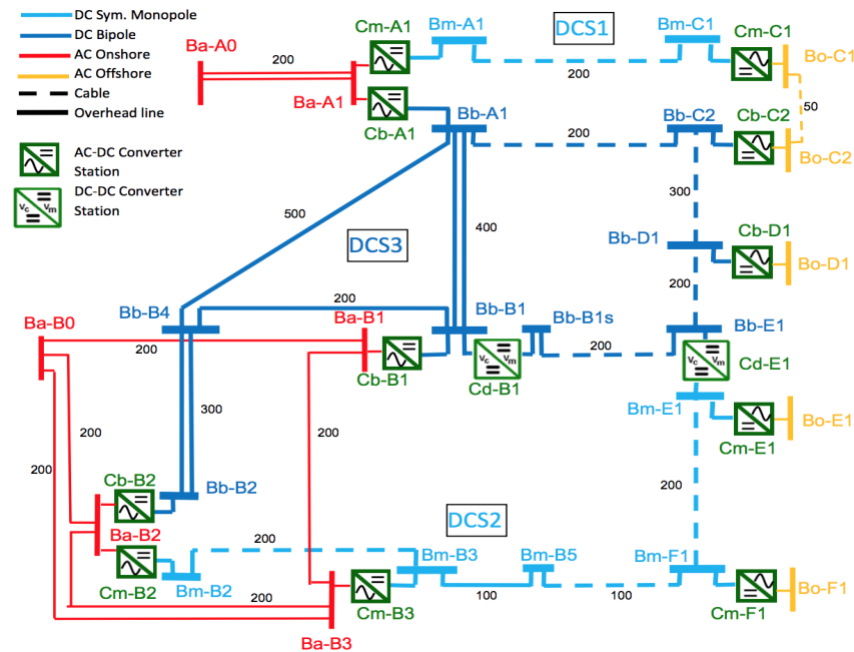
Figure 2: CIGRE MTDC Test System [6]

In MTDC networks such as in Fig. 2, various manufactures involved in individual projects within the network will need to coordinate with each other. Lack of coordination and standardization of technical aspects involved in the system design, testing, and commissioning will unavoidably cause interoperability problems. The interoperability between various technologies between different vendors is, therefore, a crucial next step in the successful development of MTDC grids. Standardization of the fundamental guidelines for HVDC grid design, testing methods, and operation are necessary for interoperability. The ability to interconnect the existing HVDC schemes and build an MTDC grid may not be achievable if the dc-link voltage, protection schemes, control principles, and strategies are not standardized [5]. However, an important point to make is that the standardization of such black boxed information may not be possible for vendors due to issues relating to intellectual property. Furthermore, such standardization could potentially blunt the innovative standpoint that manufacturers would like to ideally maintain.

Apart from the difficulties in equipment coordination, the converter control in MTDC networks will also have to be consequently coordinated in a multivendor scenario. Lack of coordination, as stated above, will undoubtedly cause interoperability issues. There have been observations made in commissioned multivendor HVDC projects where the lack of publicly available knowledge about vendor specific control & protection converter software led to inefficient problem-solving capabilities. The development of complex systems such as MTDC networks will require additional emphasis to be put into the coordination and early stage system design. This is thoroughly achieved with the help of systems engineering tools and principles.

1.2. Main Objective and Scope

Considering the technological challenges and complexities of HVDC systems, this thesis aims to tackle some of the major obstacles faced in relation to interoperability and system coordination. The main objective of this thesis is to investigate the various converter control strategies involved in HVDC systems, and to propose a partial open-source software that will provide stakeholders with much needed resources in addressing system stability & unwanted interactions preventing the need for generic assumptions when dealing with fault in multivendor systems.

The main methodology that will be extensively used to define and demystify the complex nature of the various DC networks will be defined with the help of model based system engineering (MBSE). In addition, several functional models of HVDC control systems will be designed in order to realize where to propose a partial cut for an open-source control. The motivation behind the use of functional modelling is not only for proposing which control elements are to be kept open or closed, but to also establish a clear higher-level system

perspective that will assist manufacturers in assessing the value weight for different control elements. As mentioned above, the complex nature of HVDC networks makes it crucial for manufacturers to ensure that the early-stage design process is as airtight as possible. Therefore, with the addition of an open source scheme, the models designed using systems engineering will simplify the navigation of different control elements, thus enhancing the testing & operational procedures for manufacturers.

1.3. Methodology

In order to best achieve the aforementioned objectives, this thesis is split into multiple chapters providing insight into the theoretical, conceptual, and practical aspects of this project. The final conclusions will consider the feasibility of the proposed solutions. The core chapters of this thesis will be constructed with the goal of covering three major sections: Theoretical background of HVDC systems, literature review of relative issues faced in commissioned HVDC projects, and MBSE principles and theories along with the design of the system functional models.

The outline of the thesis is as follows:

- Chapter 2 presents the theoretical background of the two main HVDC technologies: VSC and LCC along with providing insight into the station construction and configuration of HVDC systems.

- Chapter 3 presents the theoretical background of the different VSC-HVDC topologies.

- Chapter 4 investigates the control of VSCs.

- Chapter 5 delves into the literature review of the different recorded cases of issues pertaining to interoperability.

- Chapter 6 provides an overview of the theoretical principles, modeling language, and project scope of MBSE. This chapter also presents the functional models of the HVDC converter control along with the proposed open-source control model.

- Chapter 7 draws conclusions based on the information that was provided from the previous chapters and suggests for different ways move forward in terms of future work and implementations.

2.   Main HVDC Converter Technologies

The popularity of HVDC technology, over the last few decades, stems from its ability to transmit power over larger distances at a higher efficiency and reliability than traditional AC transmission. As mentioned in the previous chapter, HVDC transmission is made possible with the help of power electronic converters that enable for the conversion of AC to DC (rectifier station), and DC back to AC (inverter station). The two dominant technologies that enable this conversion are the line commutated converter (LCC) technology and the voltage source converter (VSC) technology. In the past, the transverter, electrolytic converter, and atmospheric converter were all earlier AC/DC conversion methods used before the advent of power electronics. Due to technical limitations and intrinsic safety precautions, these endeavors were unsuccessful [7].

Mercury-arc valves, which were ultimately decommissioned in present times, gave AC/DC conversion a brief period of success. The mercury arc valve that was being used at the time has now either been modified to semiconductor converter technology or completely decommissioned [8]. Due to the great switching capacity and ability to withstand high current ratings, power electronic devices have been around since the 1970s and are still a developing technology. Examples of the semiconductor devices include insulated-gate bipolar transistors (IGBT), integrated gate-commutated thyristors (IGCTs), diodes, diacs, triacs, thyristors, MOS-controlled thyristors (MCTs), etc. [9]. The first ever LCC-HVDC project was the Eel River Converter Station, which was commissioned in 1972 in Canada [10]. On the other hand, the first ever VSC-HVDC was commissioned in Gotland, Sweden in 1999 by ABB [11].

2.1. Line Commutated Converter (LCC) Technology

Line commutated converters or current source converters (CSC) are commonly referred to as classic or conventional HVDC. LCCs utilize thyristors to commutate current. Moreover, they operate at grid frequency, and require a synchronous voltage in order to operate. The main advantage of LCCs is that they have a large transmission capacity. However, their main drawback is that they lack black-start capabilities and the risk of commutation failure is high due to their method of commutation. The semiconductor configuration of LCCs usually consists of a 12-pulse thyristor connection with two 6-pulse bridges parallelly connected on the AC side and series connected on the DC side. Fig. 3 shows an example of an LCC-HVDC system. It can be seen in Fig. 3 that the transformers connected to the bridges alternate between a Y-Y and a Y-Δ configuration. This is transformer winding configuration reduces the amount of filtering needed by consequently cancelling the higher-order harmonics present in the AC and DC side bridges.
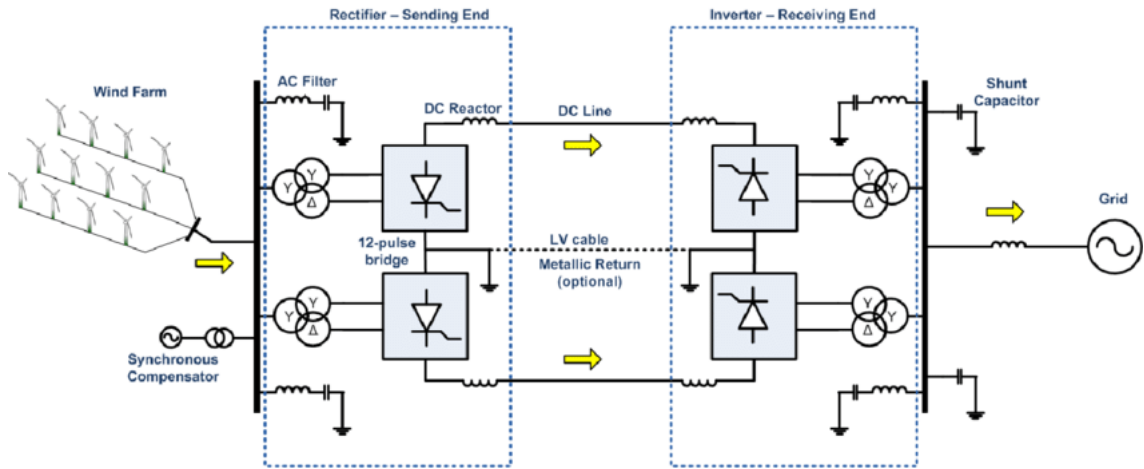
Figure 3: LCC-HVDC System [12]

As mentioned above, LCCs run the risk of commutation failure. This generally happens when the commutation voltage reverses before the current is commutated [5]. This principle directly corelates to the importance of having a strong AC network (with a high short-circuit ratio) for LCC-HVDC systems because voltage disturbances can potentially occur in weaker AC networks causing a short-circuit on the DC side leading to commutation failure. Since it has been established that LCCs require a strong synchronous voltage in order to operate efficiently, reactive power compensation equipment is required when LCCs are connected to weak AC networks. This is why in Fig. 3, it can be seen that a synchronous compensator is connected to the AC side of the system.

Commutation failure is a rather important aspect when considering the commissioning of LCC-HVDC systems, because the strength of the AC networks is not simply assumed to increase over time, but rather, with the integration of renewable energy into the inverter side of the network, the strength of the AC networks could be expected to reduce. An alternative solution to the design in Fig. 3 could be to install series capacitors between the transformers and the thyristors in order to reduce the need for reactive power compensation. This can be seen as an effective way to lower the risk of commutation failure in LCC networks. This configuration scheme is referred to as a capacitor commutated converter (CCC) [5].

It is important to note that the CCC configuration does not negate the generation of lower-harmonics present in the inverter generated AC voltage; therefore, harmonic filtering will still be consistently required. LCC-HVDC systems are controlled mainly by regulating the firing angle $\bar{\alpha}$ (can be seen from equation 2.1) separately on the rectifier and inverter sides. In other words, the DC current of the system can be explicitly controlled by regulating the DC voltage either at the rectifier or inverter side, which can be done with the help of the firing angle reference [14]. The DC voltage equation can be seen below in equation 2.1:

$$V_{dc} = B \frac{3\sqrt{2}}{\pi} V_{L-L} cos\bar{\alpha} - B \frac{3}{\pi} \omega L_t I_{dc} \qquad (2.1)$$

where, V_{dc} is the DC voltage, B is the number of thyristor bridges, V_{L-L} is the line-to-line grid voltage, L_t is the transformer inductance, I_{dc} is the DC current, and α is the firing angle of the thyristors.

2.2. Voltage Source Converter (VSC) Technology

VSCs are commonly referred to as HVDC light (by ABB) or HVDC plus (Siemens). As opposed to LCCs, VSCs use IGBT's (Insulated Gate Bipolar Transistors) in order to commutate the current. The main advantages of VSCs are that they operate at higher frequencies, they possess black start capabilities, they are self-commutating, and they are able to independently control the active and reactive power. These advantages make VSCs the favorable technology for HVDC systems. One drawback that VSCs do possess is the low equipment rating when compared to LCCs. As mentioned above, the AC voltage and current need to be on or off at the same time, and no voltage disturbances should occur otherwise LCCs can run risk of commutation failure. On the other hand, the commutation of the current is independent on the AC voltage in the case of VSCs; this is what allows for black-start capabilities in VSCs.

The semiconductor configuration of VSCs depends on the type of topology that it adopts. The most common VSC topology that is widely considered to be the leading technology in higher voltage applications is the modular multilevel converter (MMC) topology. Most of the VSC topologies, however, are more or less derived from the traditional two-level converter topology. The two-level converter topology is essentially similar to the 6-pulse LCC thyristor valves, but with IGBTs and a DC capacitor instead of thyristors and DC smoothing inductors. The switching of the IGBTs occurs through the positive and negative capacitor terminals. Moreover, the type of topology used also indicates whether or not there will be a need for AC filters. Fig. 4 (can be seen below) shows the typical configuration of a VSC-HVDC system. Since it has been established that in a two-level converter topology, the switching occurs between $\frac{+V_{dc}}{2}$ and $\frac{-V_{dc}}{2}$, two switches cannot be turned on at the same time; this principle is directly supported by the anti-parallel diode connected to the IGBT, which prevents the DC voltage from reversing polarity. This further insinuates that the current can flow either through the IGBT or the anti-parallel diode. This principle of operation in its most basic form serves as the foundation of other VSC converter topologies; however, other VSC topologies pose a higher level of complexity, but offer a better output voltage in terms of quality. The different VSC topologies and their effects on the HVDC system will be investigated in more detail in

the next chapter.
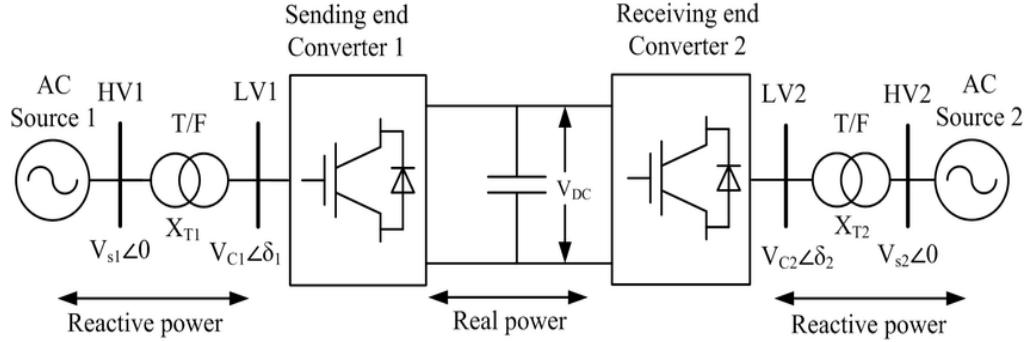
Figure 4: VSC-HVDC System [13]

The fact that VSCs are self-commutating, means that they are able to create their own AC and DC voltages. The VSC-HVDC system shown in Fig. 4 indicates two AC voltages being created: HV1 and LV1. The operational principle of the VSC is that if the phase angle of the AC voltage LV1 is regulated, active power flow in or out of the converter can be directly controlled. Furthermore, if the amplitude of the AC voltage LV1 is regulated, reactive power flow in or out of the converter can be directly controlled. This indicates that the VSC converters have the ability to independently control the active and reactive power flow, which is one of the major advantages of VSCs over LCCs. The VSC active and reactive power flow formulas can be seen below in equations 2.2 and 2.3, respectively:

$$P_s = \frac{V_s V_c}{\omega L} sin\delta \tag{2.2}$$

$$Q_s = \frac{V_s(V_s - V_c cos\delta)}{\omega L} \tag{2.3}$$

where, P_s is the active power, Q_s is the reactive power, V_s is the converter transformer side voltage, and V_c is the converter output side voltage.

Unlike LCCs, VSCs do not require additional reactive power compensation equipment; therefore, lowering their overall costs. One of the issues of VSCs, however, is the fact that losses in VSC converter stations are higher than LCCs. This is mainly due the fact that IGBTs have really high switching frequencies when compared to the thyristors that LCCs use. Although the switching frequencies of VSCs seem to be a problem, there have been some technological advancements, namely, the MMC technology, which is essentially built by using IGBT modules with significantly lower rating that effectively add up together. Table 1 (can be seen below) shows the characteristic data of IGBTs and thyristors. It can be seen that the switching frequency of IGBTs is much higher than thyristors. Furthermore, it can also be seen that the maximum voltage rating of IGBTs is significantly lower than thyristors. This

is what leads LCCs to have a large transmission capacity when compared to VSCs.

Table 1: IGBT and Thyristor Characteristics [16]

Features	IGBT	Thyristor
Maximum Voltage Rating (V)	1700	8000
Voltage Blocking	Asynchronous	Synchronous
Gating	Voltage	Pulse
Conduction Drop (V)	3	1.2
Switching Frequency (kHz)	20	1

Table 2: Comparison between VSC and LCC HVDC Technologies

VSC Technology	LCC Technology
Consists of IGBTs	Consists of thyristors
Does not depend on grid frequency	Depends on grid frequency
Can operate without a synchronous voltage	Requires a synchronous voltage
Possess black-start capabilities	Lacks black-start capabilities
Low risk of commutation failure	High risk of commutation failure
Does not require additional reactive power compensation equipment	Requires additional reactive power compensation equipment
Does not require a strong AC network and can operate weak AC grids	Requires a strong AC network with high SCR in order to operate
Current direction is not constant	Constant current direction
Lower transmission capacity	Higher transmission capacity
Requires little to no harmonic filtering	Requires a large amount of harmonic filtering

Higher converter station losses	Lower converter station losses
Can control active and reactive power independently	Cannot control active and reactive power independently
Has smaller converter station footprint	Has higher converter station footprint
Suitable for MTDC networks due to bi-directional power flow capabilities	Not suitable for MTDC networks
Voltage sags do not impact the system	Voltage sags directly impacts system stability and could potentially cause commutation failure

2.2.1.   Main Components in a VSC-HVDC Station

As discussed above, the VSC technology provides convincing advantages that could greatly contribute towards HVDC systems; therefore, it needs to be thoroughly investigated. Fig. 5 (can be seen below) shows a detailed depiction of a traditional two-terminal VSC-HVDC network.
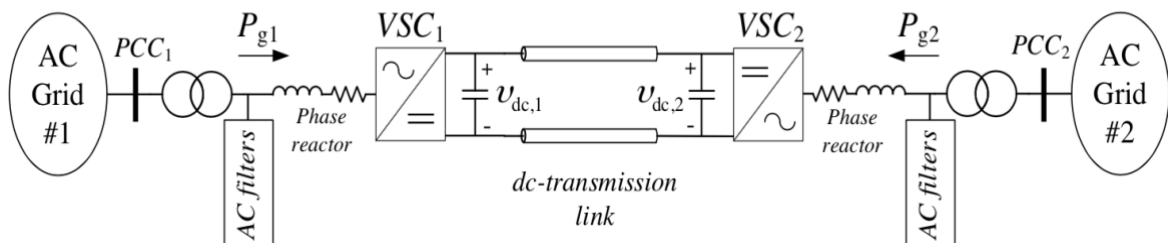
Figure 5: Two-terminal VSC-HVDC Network [17]

It can be seen that there are two AC networks that are connected together via a DC link. The two AC networks can be independent networks [17]. In between the VSC and its adjacent AC network there exists a point of common coupling (PCC). In Fig. 5, VSC_1 acts are the rectifier converter station (converting AC to DC), and VSC_2 acts as the inverter (converting DC to AC). The AC-side filters are present as a measure to smoothen harmonic content present in the output of the HVDC converter. One of the most important components in a VSC-HVDC network are the phase reactors. They are what allow for the active and reactive power transfer between the VSC and the AC network. The main operating mechanism of the VSC stations is to act as controllable voltage sources that are capable of exchanging

active and reactive power between themselves and the AC network [17]. This is accomplished by maintaining the DC voltage in the DC-side of the converters, which is achieved by separating the DC voltage and active power control functions between the two converter stations. Following this, each of the converters can also regulate the exchange of reactive power flow between itself and the AC network independently.

Some of the components present in VSC-HVDC station are as follows [5]:

- IGBT based VSC converters with large DC capacitors.

- Phase reactors.

- AC and RF filters.

- Interface transformers.

- VSC control and protection systems.

- Auxiliary systems.

- DC cables or overhead lines (OHL).

It is also important to mention that in a VSC-HVDC station, there will be protection equipment in place, namely DC circuit breakers (DCCB). This is especially the case in MTDC configurations, where it is critical to interrupt the fault current and isolate the faulty line from the system. DC circuit breakers, namely for high voltage applications, are not commercially and widely available today. There are many significant requirements for the design of efficient and operational HVDC circuit breakers. Some of the HVDC breaker requirements in an MTDC configuration are as follows [18]:

- It is required to create a current zero crossing so as to interrupt the current (in the case of conventional hybrid and mechanical circuit breakers).

- Fast breaking action is required due the fact that the DC fault current rises at a very high rate and could potentially cause a destructive fault current in the system if the breaking action isn't fast enough.

- There should be minimal conduction losses (a small voltage drop across the terminals of circuit breaker should appear and the normal operation losses in comparison to other elements of system should be reasonable).

- There should be a reliable and efficient protection scheme against all kinds of faults including pole to ground and pole to pole faults.

- Redundancy of the switching operation is required.

- Prevention of excessive overvoltage (be able to suppress the switching overvoltage).

- Minimal arcing after contact separation to reduce contact erosion (in case of mechanical or conventional hybrid circuit breakers).

- Provide enough isolation capability due to system ratings.

2.3. HVDC Configuration

Now that the different components of a traditional VSC-HVDC transmission system have been explained, it is important to understand the different configurations that help build these systems. Some of the most common configurations that are a part of the architecture of an HVDC system are as follows:

- Monopole configuration.

- Bipolar configuration.

- Symmetric monopole configuration.

- Homopolar configuration.

- Back-to-back configuration

2.3.1. Monopole Configuration

The monopole configurations, as seen in Fig. 6 & 7, are the most basic configuration of an HVDC system. It consists of two converters that are linked together with a DC line (conductor) with the return path being through either a metallic return or earth ground cables. The DC current flows from the rectifier to the inverter by means of the high voltage conductor. The use of ground return is becoming increasingly unfavorable due to environmental reasons when compared to the metallic return.
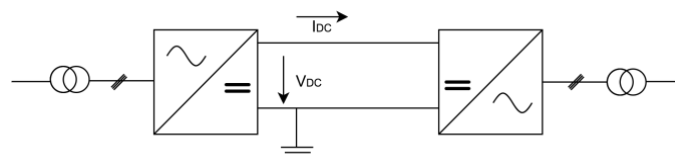
Figure 6: HVDC monopole configuration with metallic return
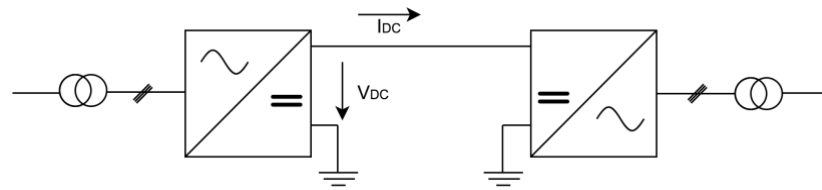
Figure 7: HVDC monopole configuration with ground return

The use of a metallic return in a monopole configuration essentially means having two cables capable of carrying the same DC current, but the metallic return cable consisting of a lower voltage. Modern monopole configurations with overhead lines typically carry around 1.5 GW. One of the major issues with a monopole configuration is that there is no redundancy, which means that if there is a fault in the cable, then the entire system will fail. Moreover, while using a ground return permits the use of only one cable, issues relating to the ground return can arise.

2.3.2.   Bipolar Configuration

The bipolar configurations, as seen in Fig. 8 & 9, consist of a pair of converters at each HVDC terminal basically having two monopole connections in one configuration. This configuration consists of two high voltage lines, and either a metallic or ground return. The immediate benefit of a bipolar configuration is that, unlike a monopole configuration, there is redundancy. In other words, if a monopole and a bipole configuration have the same power rating, then each converter in a bipole configuration will be responsible for 50% of the power. Moreover, since there is twice the number of converters in a bipolar configuration, this indicates that its transmission capacity is twice as much as a monopole configuration. Due to the redundancy in a bipole configuration, if fault occurs in one of the cables, then the network will not experience complete failure and instead run the system using the other high voltage line (essentially operating in a monopole configuration). However, it is important to note that since there is twice the equipment in this configuration, it generally means that costs will be higher than a monopole configuration.
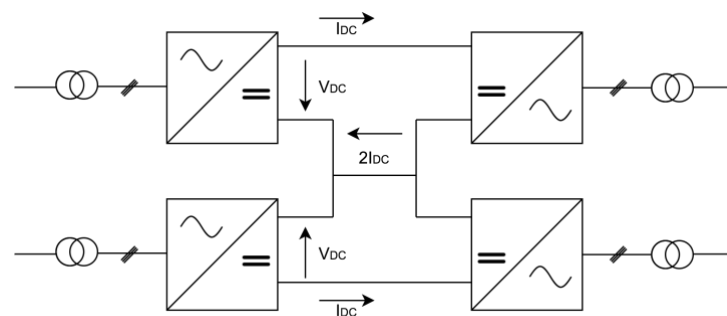
Figure 8: HVDC bipolar configuration with metallic return
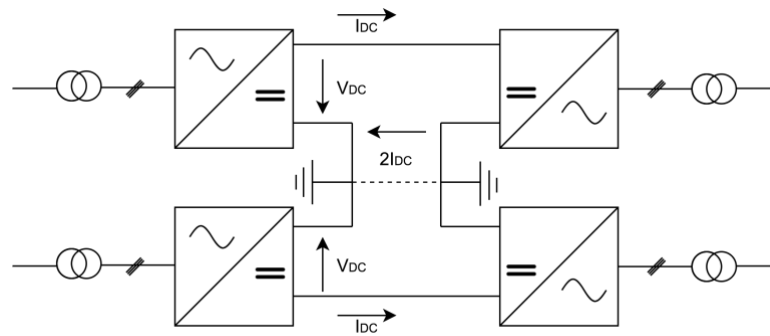
Figure 9: HVDC bipolar configuration with ground return

2.3.3. Symmetric Monopole Configuration

The symmetric monopole configuration, as seen in Fig. 10, is essentially similar to the asymmetric monopole configuration, but with one key difference; there is no metallic or ground return. Instead, the two converters are connected together by means of two high voltage DC cables with positive and negative polarities, respectively. One immediate drawback that can be theorized is again through redundancy; since there is no earth return path, none of the high voltage cables can be used to operate the system if the other fails. However, the use of this configuration removes the need for the voltage polarity reversal to directly cause a change in the power flow. This makes this configuration appealing for VSC-HVDC systems, and in fact, many of the VSC-HVDC projects utilize this configuration.
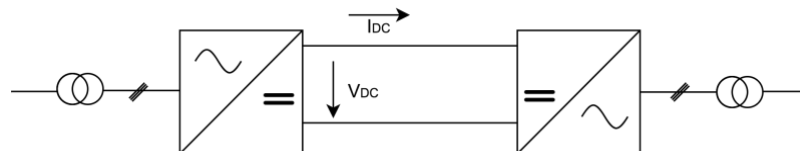
Figure 10: HVDC symmetric monopole configuration

2.3.4. Homopolar Configuration

The homopolar configurations, as seen in Fig. 11 & 12, are essentially identical to the bipolar configuration, but there is major difference. The polarity in each pole of the converters is the same, and in the ground return setup, the current returns through the earth. Due to the fact that each pole of the converter is identical, the insulation costs are thereby reduced [5]. Moreover, the homopolar configuration shares the same benefits as the bipolar configuration in terms of redundancy; the fact that there are twice the number of converters (which are rated at 50% of the overall power rating) means that if a fault occurs at one of the lines, then the system can still be operated. Furthermore, the transmission capacity of this configuration is also twice that of the monopole. One of the major drawbacks, however, is that the return

path contains a high current (basically, twice the rated current goes through the return path since the current flow at each pole has the same path) [5].
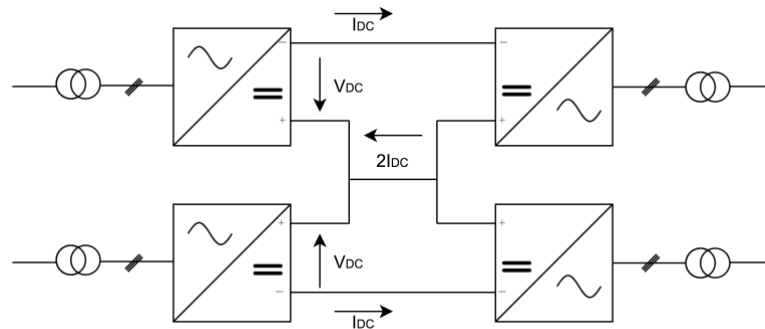
Figure 11: HVDC symmetric homopolar configuration with metallic return
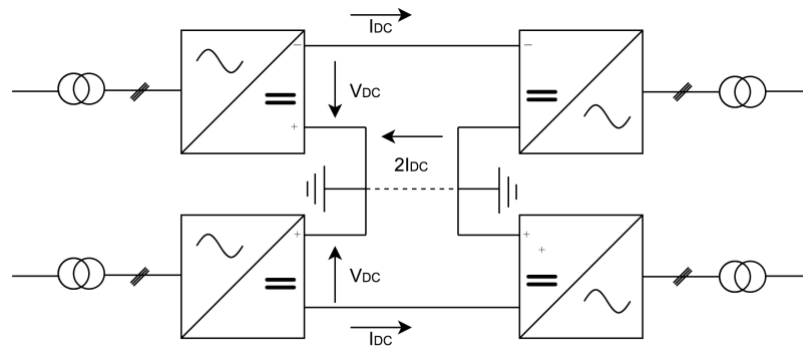
Figure 12: HVDC symmetric homopolar configuration with ground return

2.3.5.   Back-to-Back Configuration

The back-to-back configuration, as seen in Fig. 13, is a configuration where both converters are usually kept in the same area or building. Moreover, DC cables are usually not required, but they are only a few meters if required. Additionally, this configuration can be used to connect two asynchronous networks together. In this configuration, power flow can also be explicitly controlled, and the short-circuit power level is limited. One issue with this configuration, however, is that due to its complexities, costs are usually quite high.
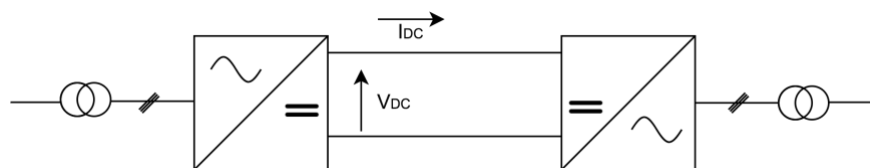
Figure 13: HVDC back-to-back configuration

3. VSC Topologies

It has been established in the previous chapters that the VSC technology is envisioned to be the leading technology responsible for the expansion and success of the integration of RESs into the electric power grid. The components and architecture of a typical VSC-HVDC station have been presented in the previous chapter. Now it is crucial to understand the role that the different converter topologies play in VSC-HVDC systems. The design and topology of the HVDC converters is, in fact, one of the important parts of the VSC technology. There are a large number of VSC topologies, however, most of them are based on the two-level converter topology, which is considered as a basis for operations. The quality of the synthesized output voltage in terms of lower harmonic distortion is directly determined by the topology that the converter uses. Moreover, it is the converter topology that is solely responsible for the conversion from AC/DC and DC/AC.

More complex VSC topologies offer more advantages in terms of controllability, reliability, and system stability. In current times, the topology that is considered the most optimal, for a massive number of reasons, is the modular multilevel converter topology (MMC). The MMC topology is also based on the two-level converter topology; therefore, in order to understand the principles and working operation of the MMC, it is important to understand how a two-level converter works. In this chapter, three major topologies will be explained in detail: the two-level converter, the three-level neutral-point clamped (NPC) converter, and the modular multilevel converter.

3.1. Two-level VSC Topology

The two-level converter is considered to be the most optimal choice of topology for lower voltage applications up to, approximately, 1800 V [5]. This is mainly due to its basic construction. Fig. 14 (can be seen below) shows a three-phase two-level converter. The three-phase two-level converter in Fig. 14 is composed of three parallel branches of two series-connected insulated-gate bipolar transistor (IGBT) modules. The middle point of each branch is connected to inductors acting as lowpass filters and form the connection between the IGBT's and the AC network.

The semiconductor component in all VSC topologies is the IGBT. The IGBT is basically an electronic switch that is capable of turning on and off at a really high frequency. The concept of the IGBT is formed by combing the MOSFET (metal-oxide semiconductor field effect transistor) and the BJT (bipolar junction transistor) together. IGBTs are usually favored due to their high switching frequency and power rating. IGBTs also consist of an anti-parallel diode that conducts current in the opposite direction.
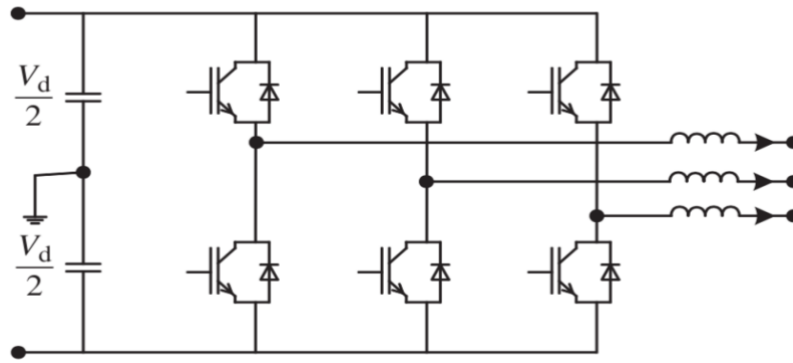
Figure 14: Three-phase two-level converter [5]

The DC terminals of the two-level converter are the two DC capacitors. These DC capacitors essentially act as storage devices and can maintain an approximately constant DC voltage for a fraction of a cycle [5]. The two-level converter switches between the positive and negative DC capacitor terminals $\frac{+V_{dc}}{2}$ and $\frac{-V_{dc}}{2}$, therefore, generating two voltage levels. The output voltage waveform is then transformed into an AC voltage waveform through, what is known as, modulation. Pulse width modulation (PWM) techniques such as sinusoidal PWM (SPWM), and space-vector PWM (SVPWM) are the typical modulation techniques used.

(a) Switch conduction

(b) Commutation from switch to diode

(c) Diode conduction

(d) Commutation from diode to switch

Figure 15: Switching behavior a single-phase two-level VSC [5]

Fig. 15 a,b,c,d shows the four possible current paths in a single-phase two-level VSC. Fig. 15(a) shows that the current is flowing in the negative direction, the current flows through the upper IGBT switch and this forms the voltage $\frac{+V_{dc}}{2}$ at the output. In Fig.15(b), the current is flowing in the positive direction and thus passes through the anti-parallel diode of the lower IGBT switch since the upper switch is bypassed. It is important to note that right before one switch closes and the other opens, there is potential switching state where both the switches are turned on at the same time. This causes a short at the DC side and could cause damage to the components (this phenomenon is referred to as "shoot through"). Seeing as though this is a realistic possibility, a power electronics term known as the "dead time" period must be implemented in order to provide some delay to the switches before one is switched off and the other is switched back on. This effectively prohibits the switches from both turning on at the same time, thus protecting the system. Once the dead-time delay is implemented, the lower switch is turned on and the upper switch is turned off. This forms a voltage $\frac{-V_{dc}}{2}$ at the output. The last state, as seen from Fig. 15(d), is when the lower switch is closed, and the upper switch is turned on, the current will flow through the anti-parallel diode of the lower switch. This happens right after the dead-time delay is implemented once again. From this point where the lower diode is turned off, and the upper switch it turned on, the entire process repeats itself again.
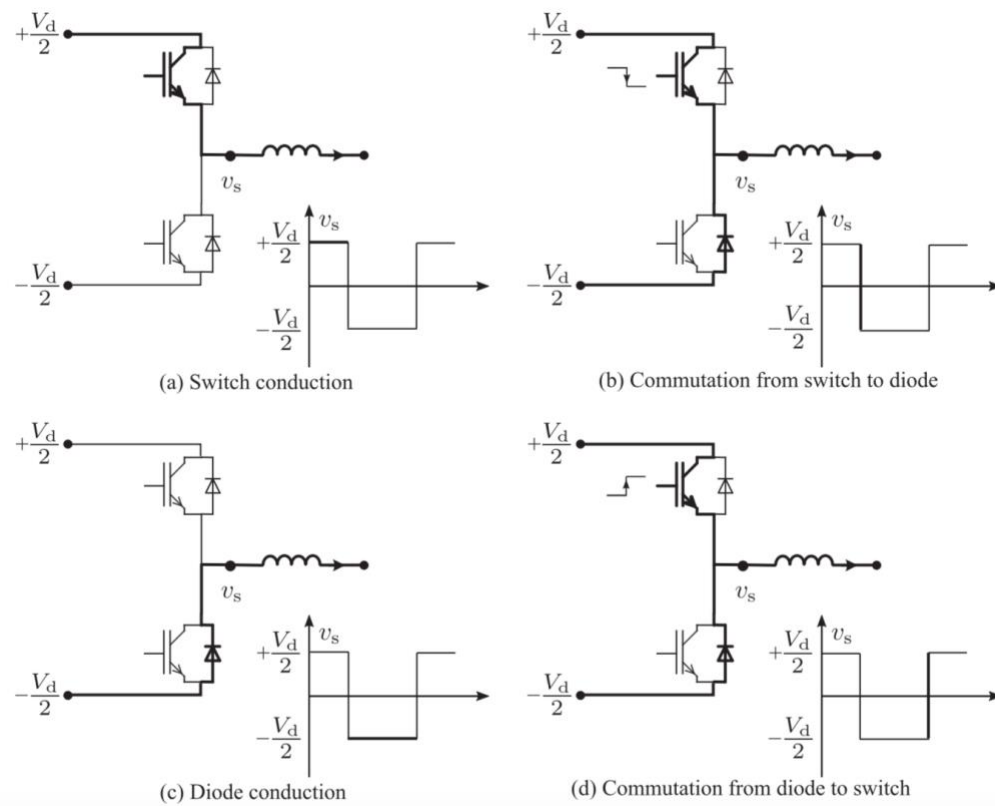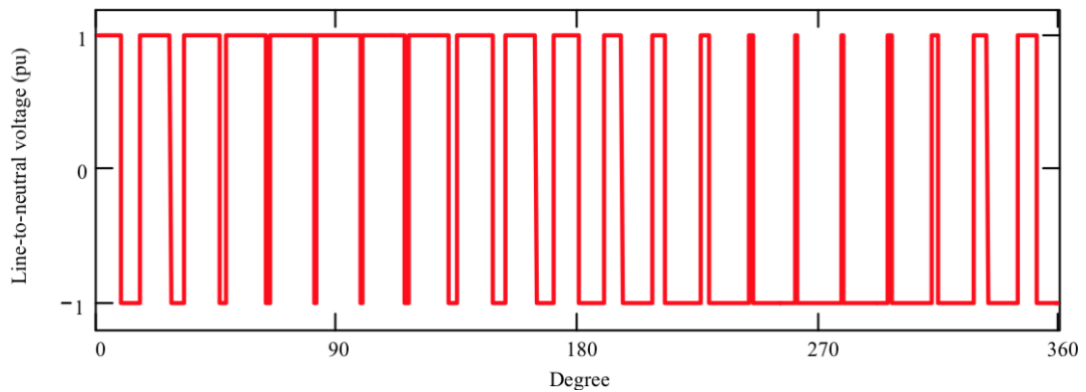

Figure 16: Single-phase two-level VSC output AC voltage waveform using PWM [19]

Once the converter output voltage is established, modulation techniques such as PWM, SPWM, or SVPWM are applied so as to produce an AC voltage waveform. It can be seen in Fig. 16 that the AC voltage waveform of a two-level VSC is discrete and resembles square waves. This indicates a significant presence of harmonic content that requires filtering. However, the two-level VSC is uncontested from an economical point of view; this is because the design of this topology is quite simple with very few components. Moreover, the control of two-level VSCs is far less complex than other multilevel topologies. It is for these reasons that the two-level VSC is heavily relied upon in lower voltage applications with an approximate power rating of 1 MVA [5].

3.2. Three-level Neutral Point Clamped VSC Topology

As a result of the two-level converter topology, the three-level NPC (Neutral Point Clamped) converter was developed in order to reduce the resulting harmonics with the addition of more IGBT switches. The configuration of the three-level NPC converter topology can be seen below in Fig. 17. It utilizes six clamping diodes, and its configuration consists of three branches of four IGBTs with the center point of each branch being center tapped. This converter is now able to switch between $\frac{+V_{dc}}{2}$, 0, and $\frac{-V_{dc}}{2}$. Overall, the three-level converter has successfully achieved a lower total harmonic distortion, reduced losses, and lesser filter requirements, but all at the cost of a higher number of IGBT modules. This dramatically increases the cost and mechanical complexity of this converter topology. However, the three-level NPC VSC is being used extensively for medium voltage applications.
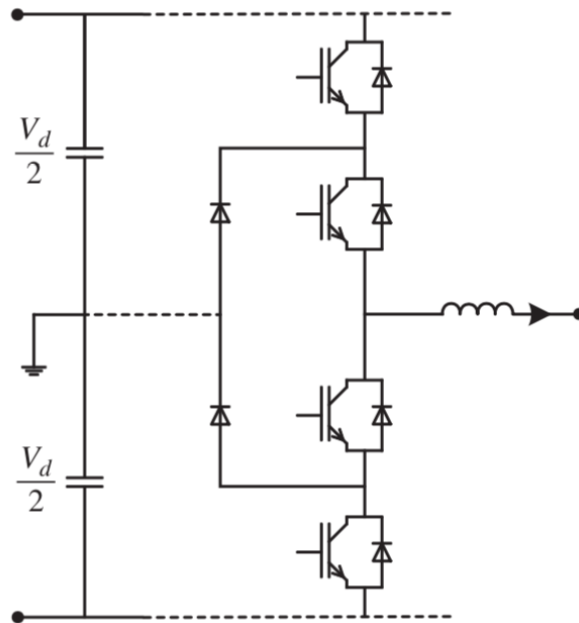
Figure 17: Single-phase three-level NPC VSC [5]

The various switching states of the three-level NPC converter, which can be seen below in Fig. 18, are derived from the working behavior of the two-level converter but instead of two switches, there are four. In the three-level NPC, there are three possible voltage levels that can be created, instead of only two. The switching behavior of the three-level NPC can be directly correlated to that of the two-level converter in the sense that if the upper switches are on at the same time, then the output voltage at the inductor (V_s) becomes $\frac{+V_{dc}}{2}$. On the other hand, if the lower switches are both turned on with the upper switches being turned off then

the output voltage becomes $\frac{-V_{dc}}{2}$. Moreover, if one of the upper and lower switches is turned on at the same time with the other closed, then the output voltage becomes 0. This can be seen in Table 3 below.
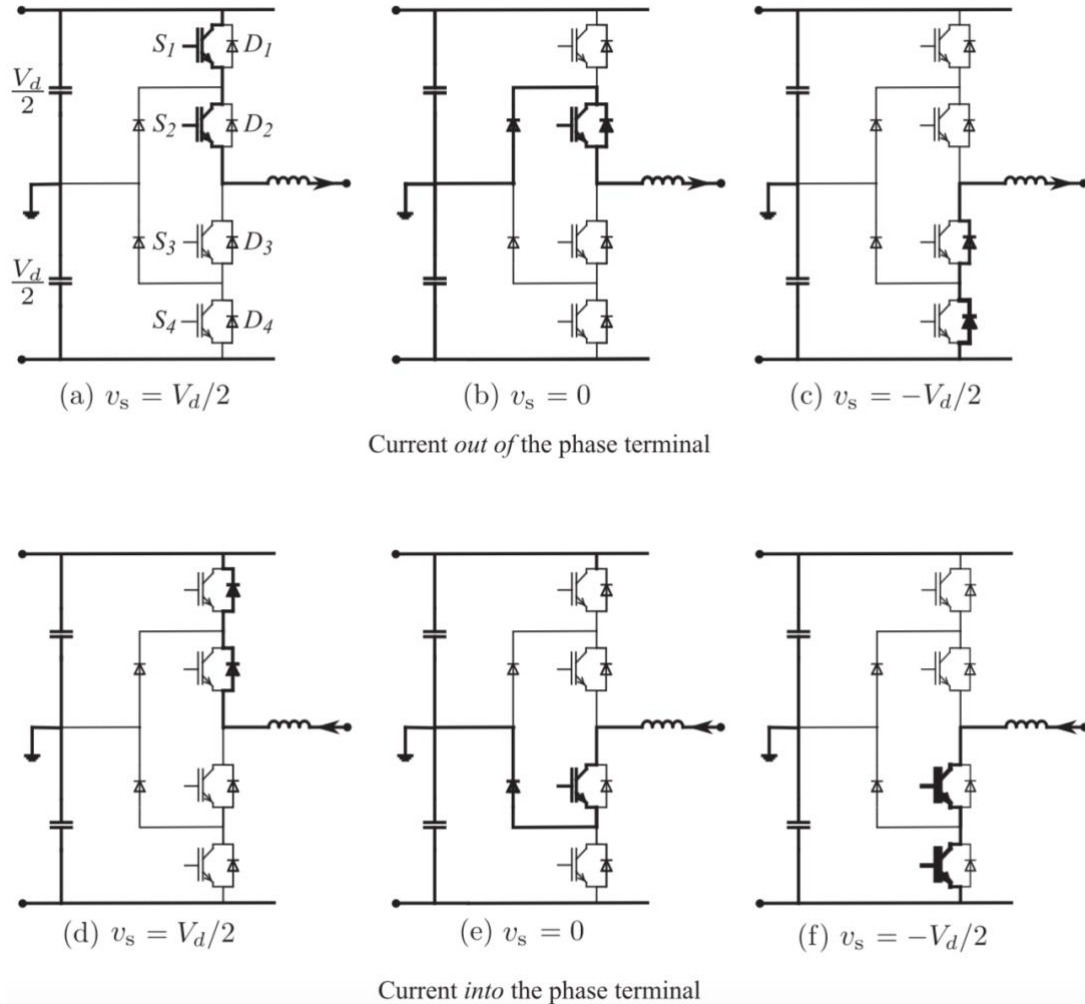
Figure 18: Switching states of a single-phase three-level NPC with two different current paths [5]

It is also important to note that in Fig. 18, there are two different current directions. Fig. 18 (a,b,c) shows the current flowing out of the phase leg. Fig. 18 (d,e,f) shows the current flowing into the phase leg. The path of the current does not determine the switching pattern for a, c, d, & f. This is because these switching states resemble that of the two-level converter with either upper two or lower two switches being turned on and off at the same time. However, for b, and e, it is important to note that the direction of the current does determine the switching characteristic. Moreover, the dead time delay is also applied to the three-level converter in the exact same way as before (right before one switch is turned on and the other turned off).

Table 3: Single-phase three-level NPC switching states truth table

S1	S2	S3	S4	V$_s$
1	1	0	0	$\dfrac{+V_{dc}}{2}$
0	1	1	0	0
0	0	1	1	$\dfrac{-V_{dc}}{2}$
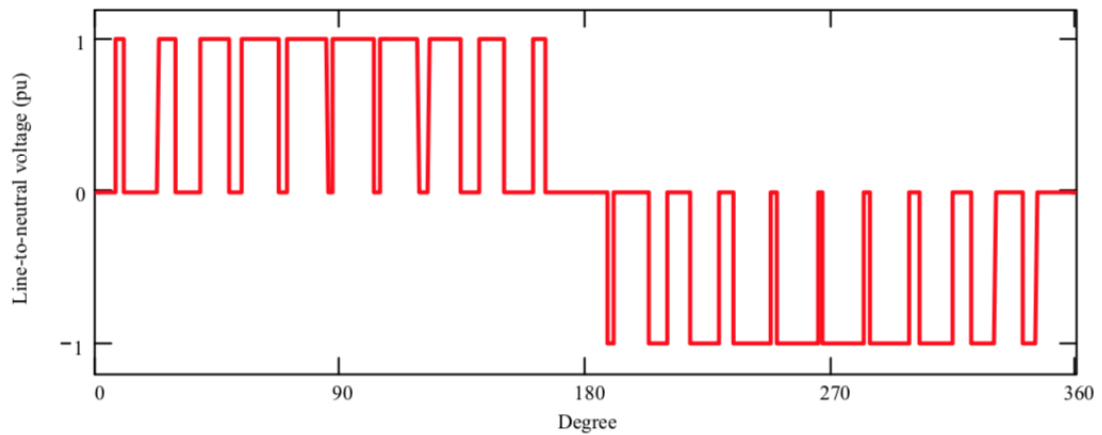
Figure 19: Single-phase three-level NPC output AC voltage using PWM [19]

The resulting output AC voltage waveform of the three-level NPC converter can be seen from Fig. 19 above. The resulting waveform has much lower THD (total harmonic distortion) than the two-level converter. However, one of the drawbacks relating to this is that the upper most and lower most switches (S1 and S4) will experience high losses if the modulation index during operational periods is kept high [5]. Nonetheless, this topology is still widely used in medium voltage applications such as electric motor drive applications.

3.3. Modular Multilevel Converter Topology

Derived from the two-level and three-level VSC-HVDC converter topologies is the revolutionary Modular Multilevel Converter (MMC) topology. MMCs are envisioned to be the leading topology in driving the large-scale implementation of HVDC links and MTDC networks. MMCs are made up of series connected cells or submodules of either half bridge

or full bridge IGBT modules (shown in Fig. 22) each containing a DC bus made up of a capacitor. This is an important point, because instead of having two major DC capacitors (like the two-level and three-level topologies), the MMC has submodules each carrying a DC capacitor. This allows for the rating of each submodule to be much lower, thus using lower voltage devices to realize higher voltage applications (which is favorable). Moreover, it allows for the commutation of current to occur internally, which allows for the separate creation of DC levels inside the converter.

The operational principle of the MMC is that it switches in and out of these capacitor banks using the IGBTs. The configuration of the three-phase MMC shown in Fig. 19 (can be seen below) consists of three 'legs' with an upper arm and a lower arm separated by an arm inductor that helps in controlling the current in the arms and limiting the short circuit current.
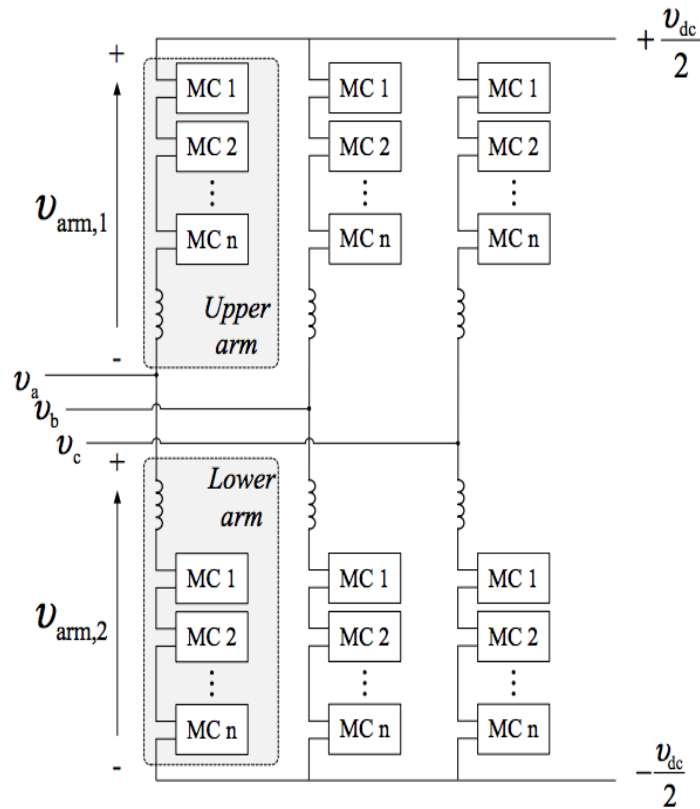
Figure 20: Three-phase modular multilevel converter [17]

Fig. 22 shows the half bridge and full bridge topologies respectively that make up the MMC modules shown above in Fig. 20. The important operational principle of the MMCs consists of three operational switching states: inserted, bypassed, & energized; the inserted and bypassed state being of most importance due to their indication of the functionality of each switch. In other words, when the capacitor is inserted or bypassed it provides two possible voltage levels respectively: V_{cap} or 0, where V_{cap} is the SM (submodule) capacitor voltage.

ETSEIB

The maximum voltage that the MMC switches can safely block is around 4 kV. This voltage blocking capacity of MMC switches is crucial in the appropriate design of MMCs. For example, if an MMC only consists of only one half-bridge configuration (in Fig. 22) then it would be impossible to operate the MMC at large voltages, because the switches will not be able to block them. Thus, a logical consideration could be to design the MMC in a way where multiple switches are connected in series with another in order to, theoretically, increase their voltage blocking capacity. However, this is not feasible due other major concerns.

For example, if the DC bus voltage is 40 kV, and 10 switches (with a 4 kV rating each) are connected in the upper arm and the lower arm then all of the switches in one arm will have to synchronously turn on and off at the exact same time. If this does not happen for any reason, or if one switch is late in its switching, then that one switch will have to be responsible in blocking all of the 40 kV compared to the other 9 switches. This will immediately cause the switch to fail, thus causing the entire system to fail. This is one of the major reasons as to why a series connection of IGBTs is not feasible. Another reason could be that the on state resistance of each switch in a series connection could be different causing different voltage drops thus requiring an additional voltage sharing circuit to be added to the system. It is for these reasons that the multilevel configuration is so crucial for higher voltage applications.

Figure 21: Resulting MMC AC voltage waveforms [17]

Figure 22: Half bridge and Full bridge topologies [17]
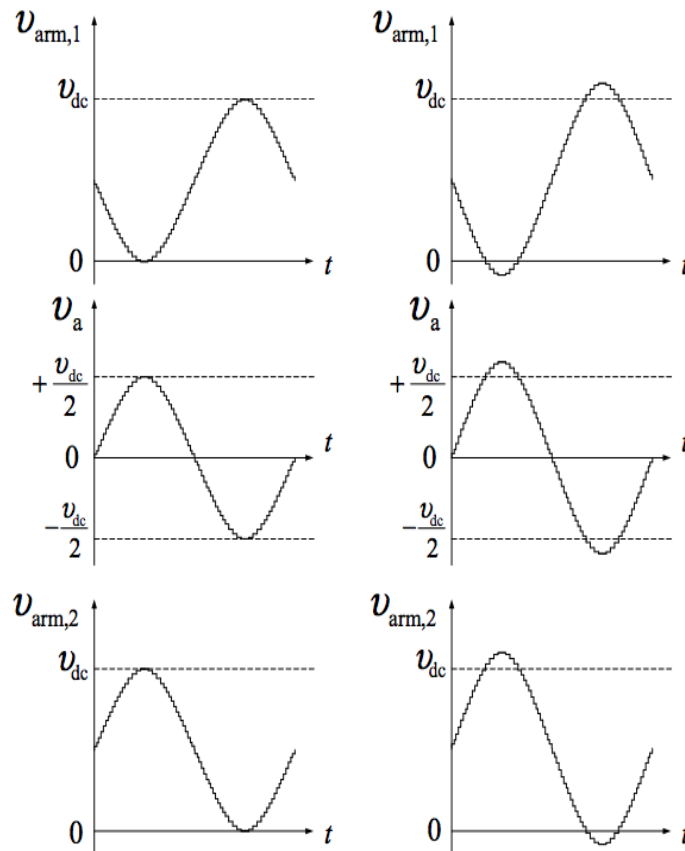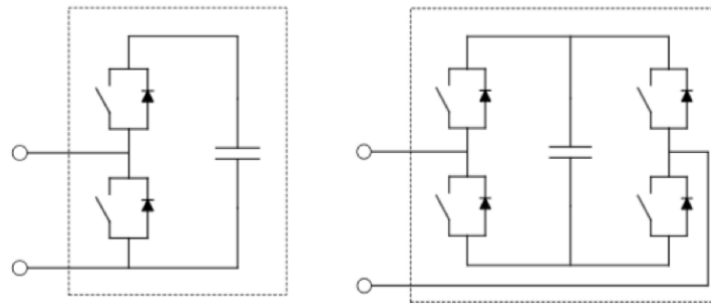
Considering the half-bridge MMC configuration, if the upper IGBT switch is turned on and the lower switch is turned off then the capacitor is inserted, and the voltage at the submodule terminals will be equal to the DC capacitor voltage (V_{cap}). The charging and discharging of the DC capacitor are directly dependent on the direction of the current. If the lower switch is turned on and the upper switch is turned off, the capacitor is bypassed resulting in the submodule voltage being zero. Therefore, the arms of the MMC can act as controllable voltage sources, where a voltage change variation in the upper and lower arms becomes responsible for the converter output voltage.

The last MMC state is the energized state, where both the upper and lower switches are turned off resulting in the capacitor energization. This state is usually only beneficial in the start-up of the MMCs because if both the upper and lower switches are turned off then the capacitor cannot discharge, and the only possibility for the capacitor is to charge or remain constant. Table 4 (can be seen below) shows the different switching stated of a single-phase MMC considering the upper arm submodule switches. It is important to note that the upper and lower arms of the MMC are identical to one another and will essentially operate in the same way. Furthermore, the switching process in an MMC occurs with one SM at a time. The switching states shown in Table 4 are how the output AC voltage is produced in an MMC.

Compared to the two-level and three-level topologies, the MMC contains multilevel half bridge or full bridge modules which allow the converter to provide great harmonic performance, low *dv/dt*, no limit on the DC bus voltage, etc. Moreover, the MMC uses low voltage devices to realize high voltage applications. Therefore, this allows for the submodules to be of lower rated voltages. Furthermore, the fact that there are more than just one DC link capacitor allows for separate creation of DC levels inside the converter and allows for the voltage & power rating to be increased without direct series connection of semiconductor elements. However, the challenges that the MMC raises are that there are a large number of capacitors that must be controlled separately, the circulating currents created need to be controlled, and the physical design is largely complex.

Table 4: Single-phase MMC switching states truth table

S1	S2	S3	S4	Capacitor State	Converter Output Voltage (V_{out})
1	0	1	0	Inserted-Inserted	$\dfrac{+V_{dc}}{2}$
0	1	0	1	Bypassed-Bypassed	$\dfrac{-V_{dc}}{2}$
1	0	0	1	Inserted-Bypassed	0
0	1	1	0	Bypassed-Inserted	0

4. VSC Control

It has been established in the previous chapters that the voltage source converter (VSC) technology is key in HVDC networks. In the previous chapter, the three major converter topologies were presented. It is apparent that the modular multilevel converter (MMC) topology is the ideal choice of converter topology for high voltage applications suitable for the large-scale integration of renewables into the grid. However, it was also mentioned that the internal structure of MMCs is extremely complicated; this further translates into their control. This chapter delves into the control of VSC systems focusing on the MMC-VSC systems.

The essence of MMC-VSC control comes from the understanding the generic VSC control strategies. The reason for this is, regardless of the topology, all VSCs have some common points as seen below [19]:

- The VSC is connected to the AC network by means of inductors (can be seen in Fig. 14)

- The IGBTs can create an AC voltage at a fundamental frequency using DC voltage.

The above points indicate that any VSC can control the magnitude and phase of the fundamental frequency component of the generated AC voltage at the inductor connected side of the VSC system. This is done by regulating what is known as the "modulation index, λ", which is the quantity that creates a direct proportionality relationship between the DC side voltage and the fundamental component of the AC voltage. This is illustrated in equation 4.1 seen below:

$$v_s = \lambda \frac{V_{dc}}{2} \tag{4.1}$$

where, v_s is the fundamental component of the AC voltage, and V_{dc} is the DC side voltage seen in the previous chapter.

The modulation index can be between 0 and 1. If the modulation index is 1, and the magnitude of the voltage, v_s is greater than the AC side voltage then reactive power will flow into the AC side. However, if the modulation index is lower, and v_s is lower than the AC side voltage then reactive power will flow in or out of the converter. This is directly how the magnitude of the fundamental component of the AC voltage controls the reactive power flow. On the other hand, the phase angle of the fundamental frequency component of the AC voltage directly controls the active power flow. The phase angle, δ is controlled by phase shifting the fundamental frequency component of the AC voltage with respect to the phase locked loop (PLL), which is synchronized with the AC grid voltage. Thus, regulating this

phase angle will cause active power to flow in or out of the converter. Therefore, a voltage source converter (VSC) can act as a generator of reactive power that supports the grid in terms of proving black-start capabilities. This specific VSC control capability also allows for the independent control of active power. Therefore, the independent control of the modulation index, λ and the phase angle, δ play a key role in the control of VSCs.

Another important control aspect of VSCs is that the DC side voltage can be regulated to control the AC voltage; however, this is not particularly ideal because the DC side voltage is directly proportional to the charging of the DC capacitors. Moreover, the charging of the DC side capacitors does come with a ramp-up setback, which can lead to an inefficient control. Therefore, the DC side voltage is usually preferred to be constant and maintained at the DC side. This is easily accomplished with the help of pulse width modulation (PWM).

In order to independently control the modulation index and the phase angle, two control methods can be utilized: direct control or vector control. Vector output current control is preferable over direct control when considering a higher-level topology due to it making the system less complicated. However, from a generic outer VSC control standpoint, direct control strategies can also be implemented. Fig. 23 & 24 (can be seen below) show direct control and vector control differ from one another. In Fig. 23, the modulation index and phase angle are directly controlled by relative parameters A and B; however, in Fig. 24, the active and reactive power are independently controlled by regulating the modulation index, which is explicitly controlled by means of the phase angle δ. This is done by using a phase locked loop (PLL), and reference frame transformations. The reference frame transformations are what define the vector control strategy as the measured sinusoidal currents transformed from the *a, b, & c* (three phase) reference frame to the *qd* reference frame, which essentially transforms the currents to constant values.
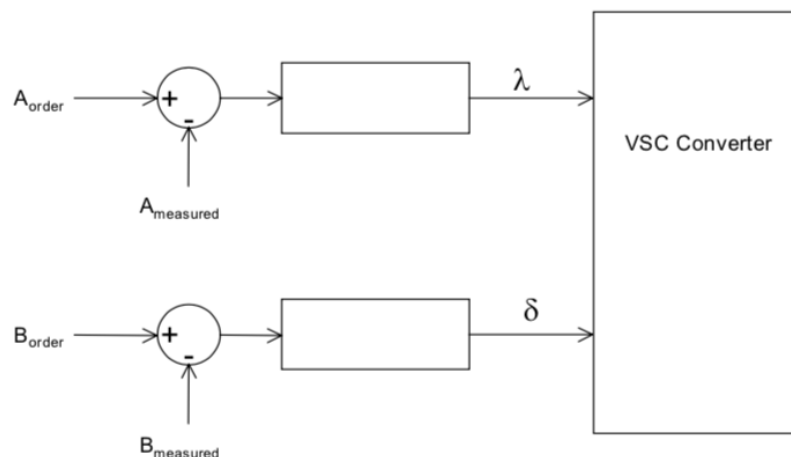
Figure 23: Direct control strategy for VSC-HVDC [19]
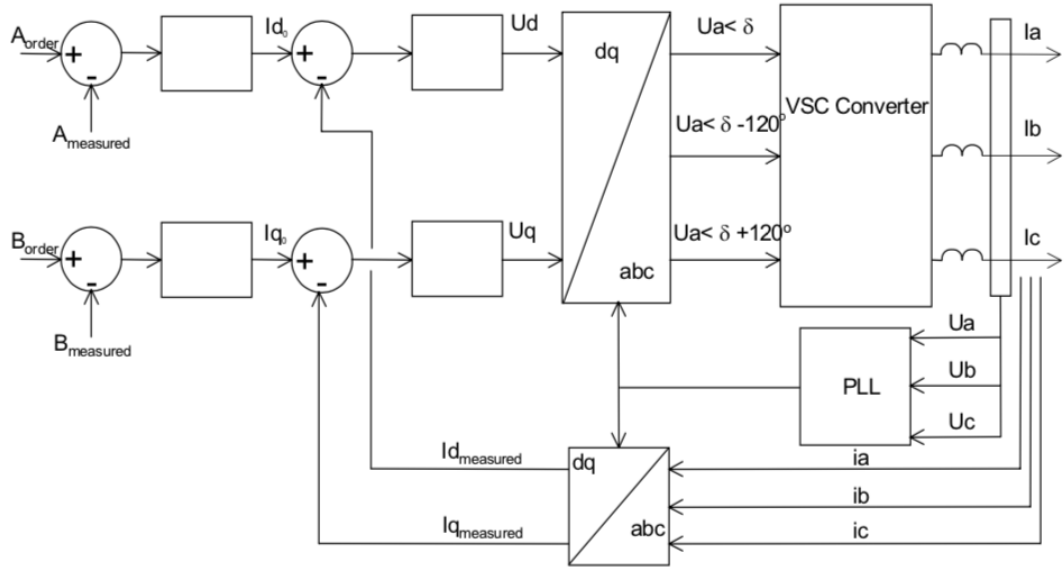
Figure 24: Vector control strategy for VSC-HVDC [19]

4.1. Reference Frame Transformations

As mentioned above, the vector control strategy is beneficial as it reduces the computational complexity of the control system. Moreover, the q and d components of the currents are directly proportional to the active and reactive power. Therefore, reference frame transformations are necessary in achieving a computationally efficient control system. There are two major reference frame transformations that will be explained below:

- Clarke transformation

- Park transformation

4.1.1. Clarke transformation

The Clarke transformation is capable of transforming a three-phase AC system into a two-phase orthogonal system [21]. The Clarke transformation can be seen described in the equations below:

$$[x_{\alpha\beta 0}] = [T_{\alpha\beta 0}]\,[x_{abc}] \tag{4.2}$$

where, $x_{\alpha\beta 0}$ is the vector with the transformed two-phase quantities (α, β), x_{abc} is the vector with the three-phase quantities (abc), and $T_{\alpha\beta 0}$ can be seen in the following equation (4.3):

$$[T_{\alpha\beta 0}] = \frac{2}{3} \begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & -\dfrac{\sqrt{3}}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{2} & \dfrac{1}{2} & \dfrac{1}{2} \end{bmatrix} \tag{4.3}$$

In order to obtain x_{abc}, the inverse of the above transformation (T) matrix should be determined. This can be seen in the following equation (4.4):

$$[x_{abc}] = [T_{\alpha\beta 0}]^{-1} [x_{\alpha\beta 0}] \tag{4.4}$$

where, $[T_{\alpha\beta 0}]^{-1}$ can be seen below in equation 4.5:

$$[T_{\alpha\beta 0}]^{-1} = \begin{bmatrix} 1 & 0 & 1 \\ -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} & 1 \\ -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} & 1 \end{bmatrix} \tag{4.5}$$

The graphical representation of the $\alpha\beta 0$ reference frame transformation vectors can be seen below in Fig. 25.
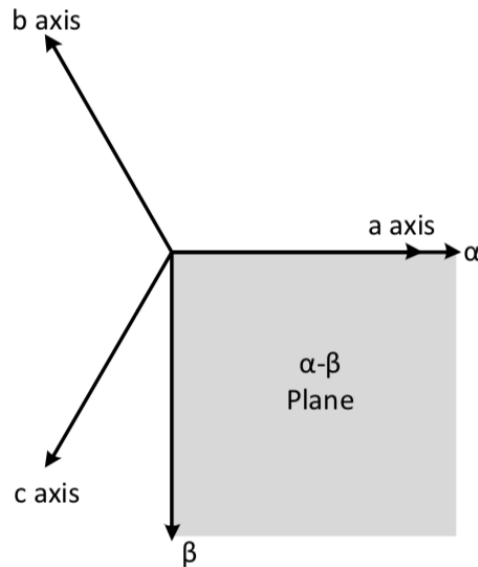

Figure 25: Graphical representation of the $\alpha\beta 0$ reference frame [22]

4.1.2.   Park transformation

Compared to the Clarke transformation, which transforms three-phase quantities into two-phase quantities, the Park transformation takes the transformation a step further. The three-phase quantities are transformed to two constant quantities [23]. This greatly simplifies converter control from a computational aspect. The Park reference frame transformations can be described using the following equations:

$$[x_{qd0}] = [T_{qd0}] [x_{abc}] \tag{4.6}$$

where, x_{qd0} is the vector with the transformed constant quantities (q, d), x_{abc} is the vector with the three-phase quantities (abc), and T_{qd0} can be seen in the following equation (4.7):

$$[T_{qd0}(\theta)] = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4.7}$$

In order to obtain x_{abc}, the inverse of the above T matrix should be determined. This can be seen in the following equation (4.8):

$$[T_{qd0}(\theta)]^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{4.8}$$

The graphical representation of the $\alpha\beta0$ reference frame transformation vectors can be seen below in Fig. 26.
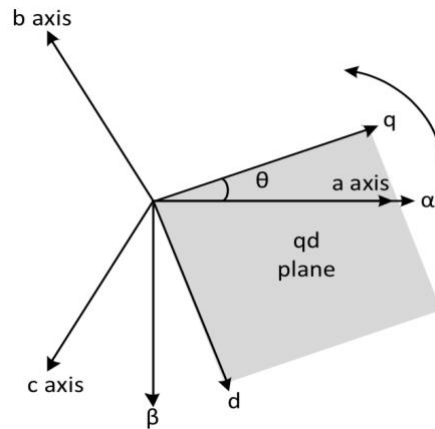

Figure 26: Graphical representation of the qd0 reference frame [22]

4.2. Two-level VSC Control

The basic converter control principles can be easily explained with a two-level converter. Fig. 27 (can be seen below) shows the general control scheme for a two-level converter. With the adoption of the vector control strategy, the two-level converter (as seen in Fig. 27 below) is able to control the active and reactive power independently by regulating the q and d components. The active and reactive power formulas in the qd reference frame can be seen in equations 4.9 & 4.10 below:

$$P = \frac{3}{2}\left(V_q I_q + V_d I_d\right) \tag{4.9}$$

$$Q = \frac{3}{2}\left(V_q I_d + V_d I_q\right) \tag{4.10}$$
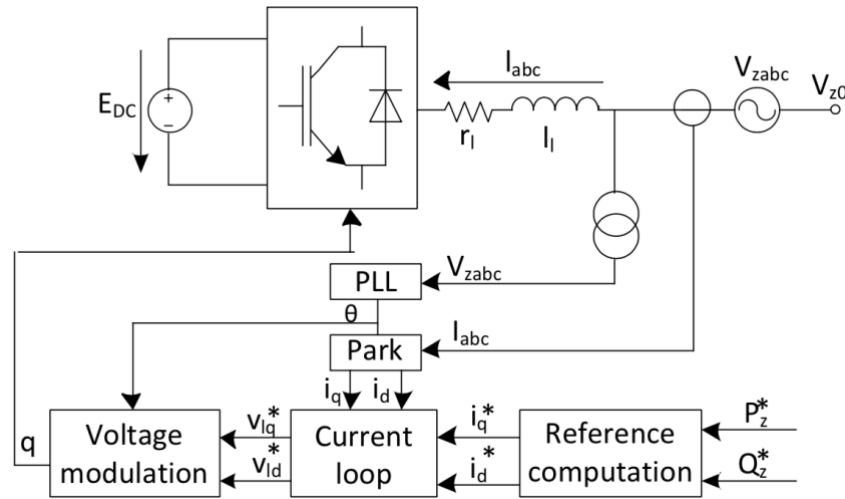
Figure 27: General control scheme for a two-level converter [22]

Fig. 27 shows that, first of all, voltage measurements are taken from the AC network and sent to the PLL (Phase locked loop), which tracks the grid angle, frequency, and provides the qd reference frame voltage magnitudes. In the reference computation block, the reference active and reactive currents are calculated based on the provided reference active and reactive values along with the qd reference frame voltage magnitudes (from the PLL). Once this is done, current measurements are taken from the AC side and shifted into the qd reference frame from the abc reference frame. Then the measured qd currents are compared with the reference qd currents with the help of a PI controller, and the error is tracked. Once this is done, the qd magnitudes are decoupled in order to allow for independent active and reactive power control. The decoupled voltage magnitudes are then shifted back to the abc reference frame, and the desired voltage is then sent to the modulation block, which sends the switching signals back to the converter.

4.3. MMC-VSC Control

Considering an MMC-VSC HVDC system, the control systems of each converter will have to separated and given different functions. Fig. 28 shows the general control scheme for a VSC-HVDC system. The different control functions are separated into: Dispatch control, upper level control and lower level control functions. The dispatch controls are the highest level of controls provided by the system operator. These functions include: the control mode and the converter setpoints. The control mode could either be DC voltage control/Active power control, or AC voltage control/Reactive power control. Furthermore, the converter setpoints include the AC/DC voltage references and the P/Q references. The upper-level control receives the converter setpoints and the control mode from the dispatch control and regulates the grid variables and generates the references for the lower-level control. The lower-level control receives the references from the upper-level control and regulates the internal converter variables (such as modulation, capacitor voltage balancing algorithms, and circulating current control).

Another important factor to consider is the grid-forming and grid-following control approach. The grid-following control, just as the name suggests, utilizes the grid voltage in order to obtain the synchronization reference angle of the AC grid for reference frame transformation, and the frequency with the help of the PLL. Moreover, the active power and the DC-bus voltage are controlled in order to provide the active component whereas the reactive power and AC-bus voltage are controlled to provide the reactive component just as the control scheme presented in Fig. 27. On the other hand, the grid-forming approach does not utilize a PLL in order to provide the grid synchronization angle due to the fact that the angle is provided by a voltage-controlled oscillator (VCO). Moreover, a frequency droop controller is used in order to coordinate the power sharing between the islanded system and AC generation [31].
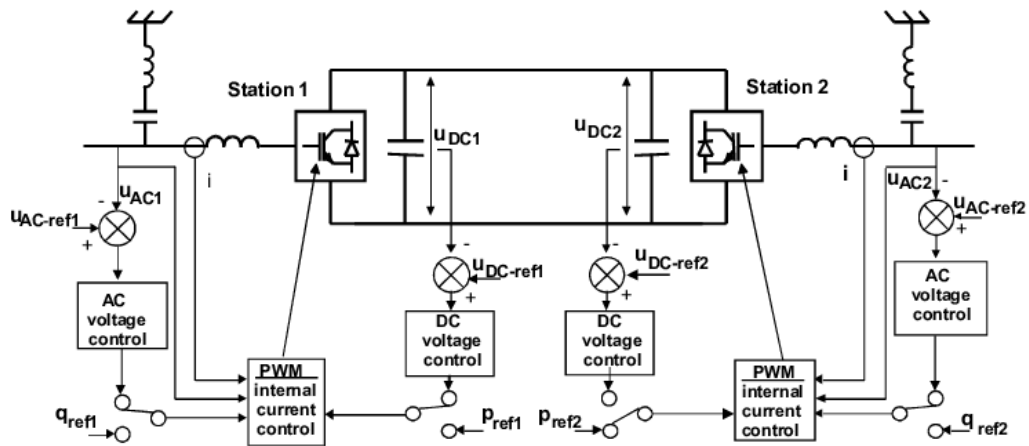
Figure 28: Point-to-point VSC-HVDC Control [32]

The control of MMCs is a highly intricate process due to the number of modules and capacitors present in them. Fig. 29 shows the generic structure of a traditional control strategy for MMCs. As it was explained above, the structure of the control system is normally split into two parts: the upper and lower levels.
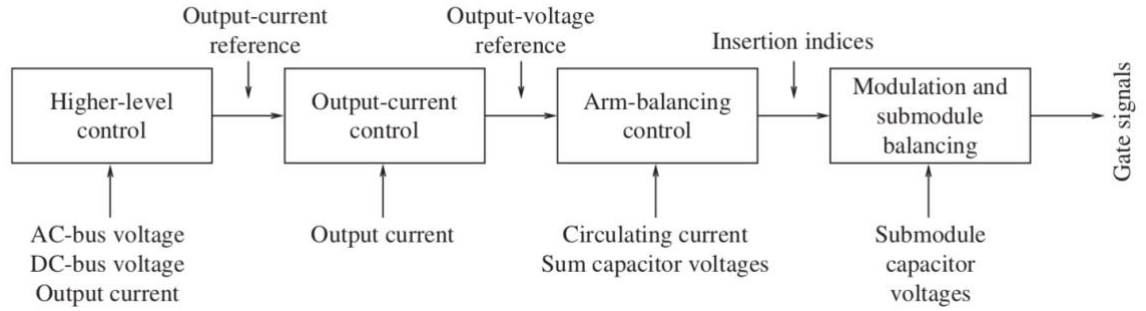
Figure 29: Generic structure of MMC Control [5]

4.3.1. Energy-based MMC Control

The energy-based control strategy of MMCs in a point-to-point HVDC system is where one converter acts as the master MMC and the other converter acts as the slave MMC. The master MMC is solely responsible for control either the AC or DC voltage whereas the slave MMC is responsible for controlling the active or reactive power depending on the control mode. On the other hand, the internal energy is explicitly controlled. The energy-based control removes the need for circulating current suppressors. The energy-based MMC control system can be seen below in Fig. 30.
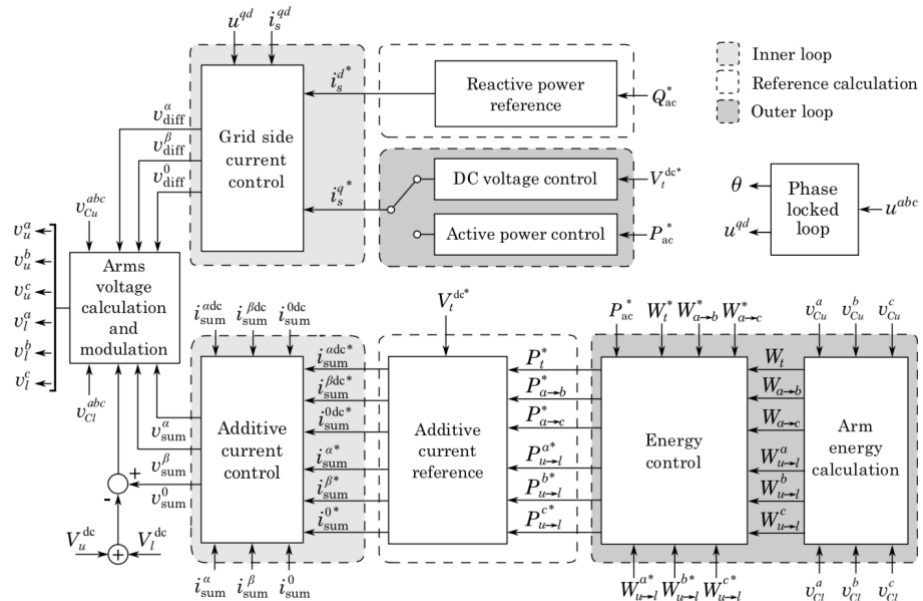
Figure 30: Energy-based MMC control [33]

Similarly to the two-level VSC control, in the energy-based MMC control, there is a PLL that tracks the grid angle, frequency, and provides the *qd* reference frame AC voltage magnitudes. It can be seen from the control system shown in Fig. 30 that there are two possible control modes that can provide the current reference in the *q* reference frame: the DC voltage control or the active power control. On the other hand, the *d* reference frame current reference is provided by the reactive power control. These *qd* reference frame currents along with the *qd* voltage provided by the PLL go into the grid side current controller. Furthermore, the energy control is explicitly controlled and provides current references to the circulating current controller. Both the grid side controller and the circulating current controller provide the voltage references necessary for modulation. However, before the modulation, the arm voltage is calculated and the capacitor balancing process is commenced. This provides the necessary references that go into the modulation, which generates the necessary voltages that are responsible for the converter switching. A real commissioned example of energy-based MMC control is the controller used by the Nan'ao MTDC VSC network, which can be seen below in Fig. 31.
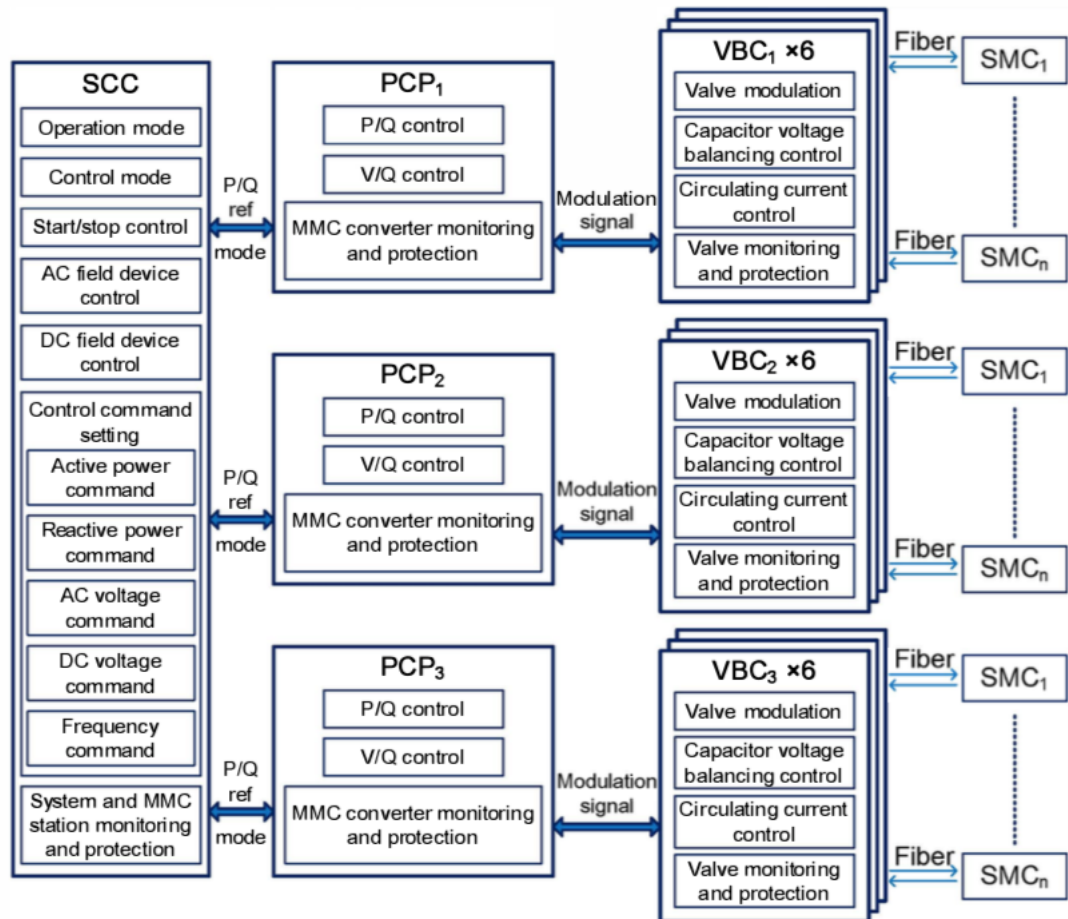
Figure 31: Nan'ao MMC VSC-MTDC Control System [34]

5. Literature Review

It has been seen in some of the commissioned HVDC projects that interoperability between vendors plays an important role in the efficient operation of the network. As the infrastructure of HVDC networks is expected to exponentially expand in the coming decades, it is important to establish standardized principles that will aid in the smooth interconnection of multi-terminal HVDC networks. This chapter will showcase some of the interoperability, harmonic interaction, and stability issues that were faced by manufacturers in commissioned HVDC projects.

5.1. BorWin1 HVDC System

The BorWin1 project is the first ever project to connect an offshore wind farm to an onshore grid by means of HVDC transmission with a total capacity of 400 MW [24]. The HVDC network was commissioned in Germany in 2009. The project is operated by TenneT, which is a German transmission system operator (TSO). Fig. 32 shows the schematic of the BorWin1 HVDC system. The fact that the offshore AC grid is separated from the onshore AC grid by an HVDC network causes a change in the electrical behavior of the offshore grid from the onshore grid. In other words, the frequency is completely controlled by the offshore converter, and is controlled independently from the wind farm.

Figure 32: BorWin1 HVDC system [24]

The main disadvantage of this independent frequency control is that there is no damping of the rotating machines [24]. Moreover, the main issue that occurred in this project is 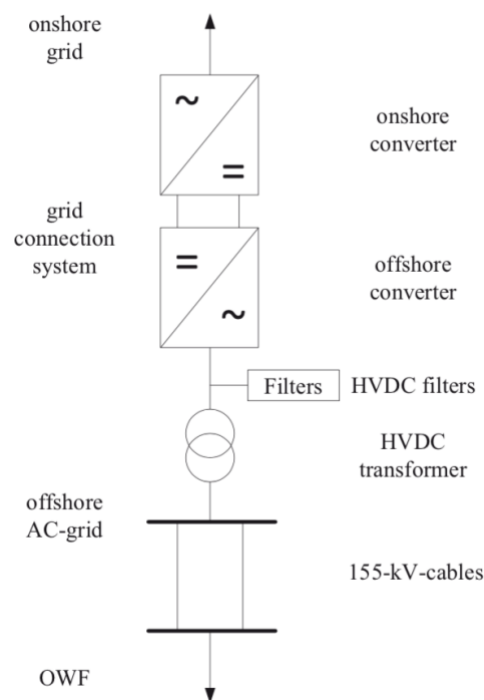a harmonic stability issue that was caused by the converter interactions. The stability issues that are caused by converter interactions were not considered in the design stages of this project, which was the main cause of their occurrence.

When this harmonic instability phenomenon had first occurred, the analysis that was done revolved around the calculation of the frequency dependent impedances at different locations. However, it was found out that the determination of the exact frequency was not at all possible because the manufacturers were reluctant in providing the converter control input data that was necessary for this calculation due to intellectual property reasons [24].

Since it was impossible to gather the necessary converter control input data, other methods had to be utilized in order to make an accurate assumption of this information. Among other investigative methods, the main strategy that was built in order to prevent harmonic instability was the use of a new stability criterion that is similar to the Nyquist criterion [24]. In this criterion, all of the converter control input data was not necessary. Instead, only the frequency dependent impedance of the generation unit needs to be provided. Moreover, this impedance must include all the passive elements along with the active control elements as well [24].

According to [24], the best approach in discovering a harmonic stability issue can only be done in the design phase, and equipment need to be properly adjusted such that resonance issues do not occur in the commissioning. However, the easiest and most efficient way to solve any of these problems is to tune the controls. The way to do that is to set an upper limit in the frequency components of the converter-generated active power. In other words, the converter must control the frequency component of the grid-side active power flow such that it does not exceed the grid resonance frequency.

5.2. Johan Sverdrup Oil & Gas Field

The Johan Sverdrup oil & gas field consists of four AC connected offshore platforms that are supplied by two symmetric monopole HVDC links connected in parallel. The HVDC links are connected to a 300 kV onshore grid. The HVDC links will utilize 200 km cables, and the second HVDC link is a 200 MW MMC-VSC link that is designed by Siemens. The second link is set for commissioning in 2022 [25]. The offshore Johan Sverdrup field itself is located approximately 155 km west of Stavanger, Norway. Fig. 33 shows the single-line diagram of the entire Johan Sverdrup power system. It is important to note that the commissioning of the HVDC systems will be done in two phases. Phase 1 of the system was commissioned in 2018; however, the HVDC converter data is kept black-boxed by its manufacturer.
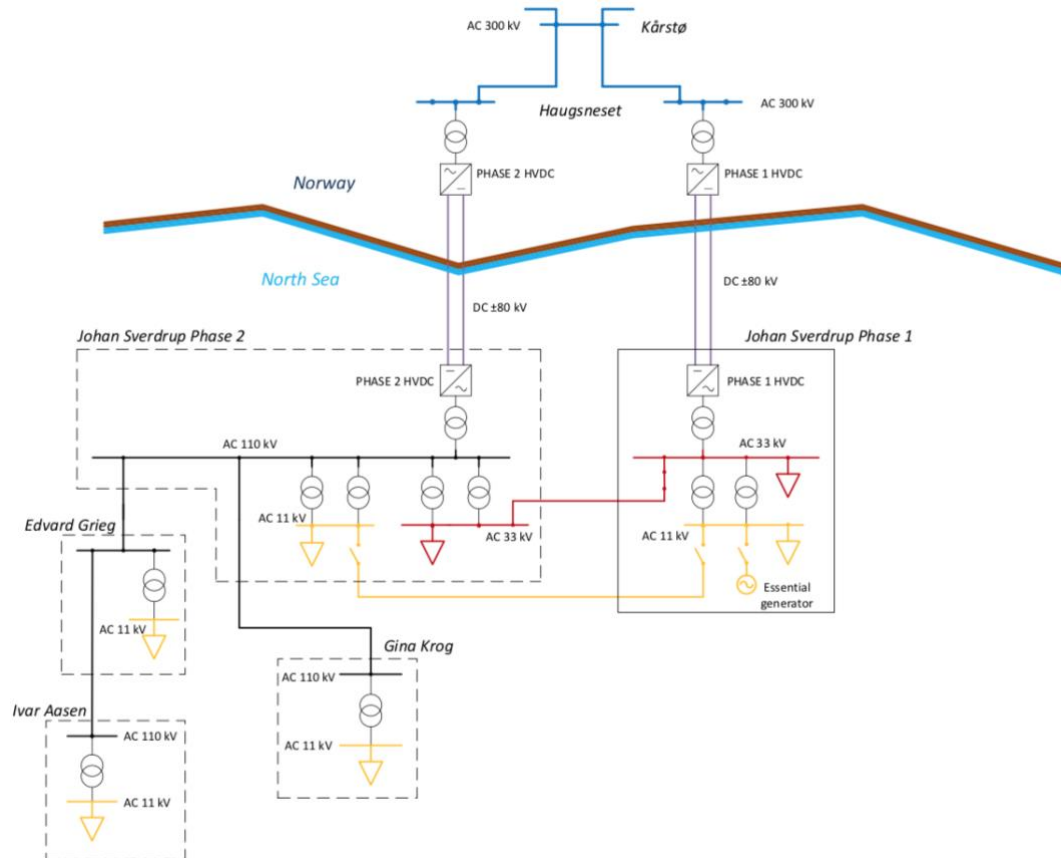
Figure 33: Single-line diagram of the Johan Sverdrup power system [25]

The main challenge in this project is the fact that the design of the second phase HVDC link is done only with public knowledge of the phase 1 HVDC converter. This is due to the fact that the manufacturer of the phase 1 HVDC converter cannot disclose converter data due to intellectual property reasons. Therefore, to work around this, simulations were done in order to determine whether interoperability issues would arise when two converters from two separate links are connected together in parallel. Moreover, the results from these simulations will provide the basis for the real-time tests that will be conducted before the commissioning of phase 2.

It is a real possibility that the interactions between the two offshore HVDC converters will cause harmonic instability to occur. Furthermore, voltage instability can also occur as a result of disturbances in the transmission system [25]. The interactions between the two converters and the passive AC network could cause harmonic emissions and resonances that can spread throughout the offshore network and are not only limited to the equipment. Moreover, these harmonics are also expected to cause overheating of equipment and other interfaces [25]. The core of these issues stems from the interoperability issues caused by having such a large parallelly connected multivendor network with generic converter control assumptions being made due to the lack of standardized vendor-specific software information.

5.3. Yunnan-Luxi VSC-HVDC System

The Yunnan Luxi project is a ± 350 kV/1000 MW back-to-back VSC-HVDC system connecting Yunnan to Guangdong, China [26]. This project was commissioned in 2010 and utilized the highest rated MMCs at the time. The issue that was faced was a 1270 Hz resonance that occurred between the Luxi VSC-HVDC system and the 525 kV AC grid in 2017 after several AC line disconnections. This issue did not affect the stability of the transmission system; however, this issue did cause a phase-ground voltage reaching 68.9 kV as a result of the 1270 Hz resonance [26]. Fig. 34 (can be seen below) shows the Yunnan-Luxi HVDC system as seen from the AC side where the resonance occurred. It was determined that the instantaneous feed forward and long control delay of the impedance of the VSC-HVDC system played a major role in causing the high-frequency resonance issue when AC lines are disconnected.
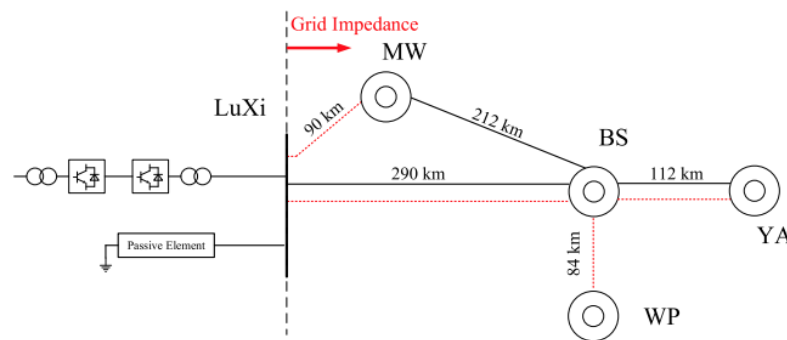
Figure 34: Yunnan-Luxi HVDC system as seen from the AC side [26]

As a result of this resonance issue, several methods were considered to rectify this in order to ensure system stability in [26]. Some of these methods can be seen below:

- Ratio of the grid impedance to the equivalent impedance all parallelly connected equipment was considered.

- Impedance-based stability criterion was implemented in order to analyze the resonance issue.

- Investigations related to improving the control strategy were a major consideration.

- Dividing the major components in a complex HVDC system into different sections and sub-sections during the design-phase so as to simplify stability analysis and to ensure that such issues will not occur.

- Inserting passive and active elements into the system was considered.

5.4. Offshore Windfarms in the German North Sea

There have been many projects in the German North Sea that connect multiple offshore wind farms to the onshore grid through VSC-HVDC transmission. The current overall capacity of these HVDC links is estimated to be over 5 GW [27]. Fig. 35 shows a generic schematic of the projects connecting two offshore windfarms to an onshore grid by means of VSC-HVDC transmission.

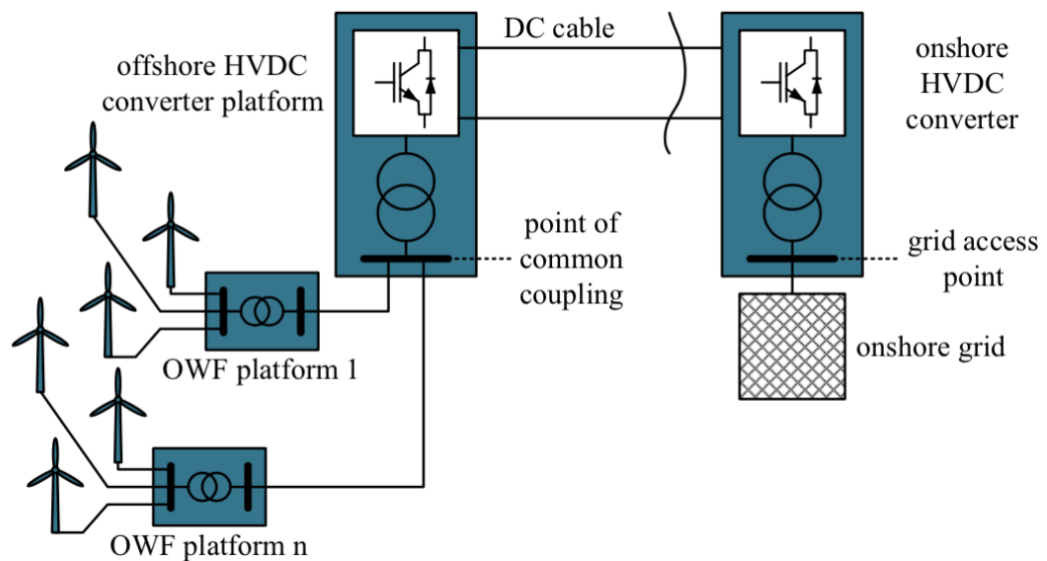*Figure 35: Schematic of the two offshore windfarms connected to an onshore grid by means of VSC-HVDC transmission [27]*

One of the issues that occurred in one of the projects was as a result of a switching event that occurred in the form of busbar decoupling [27]. This ultimately resulted in a high frequency resonance developing in the grid (around 1500-1800 Hz). This busbar decoupling phenomenon also caused a continuous harmonic current between the onshore converter and the onshore grid [27]. This resulted in the converter protection system tripping the entire grid connection.

In order to rectify and analyze this issue, several investigative methods in the form of simulations and tests were implemented. Furthermore, it was established that in one of the grid access points, there needs to be a special switching state in order to avoid overloading of equipment. Therefore, due to this special switching implementation requirement, two HVDC converters were connected to the onshore transmission system via one overhead line [27]. The manufacturers of the converter then proceeded to make changes to the control system (calling it a converter software update) [27]. Once this was done, the busbars were coupled & decoupled several times under different working conditions, and this did not result in any harmonic instability issues.

5.5. Kristiansand HVDC Station

The Kristiansand HVDC station is located in Norway and it is the station that connects Denmark and Norway through the Skagerrak LCC-HVDC transmission system. The total capacity of the Skagerrak HVDC transmission system is 1040 MW with a 300 kV bus. Fig. 36 shows the schematic of the Kristiansand HVDC station. The station consists of three poles, with the third pole being commissioned in 1993 [28].
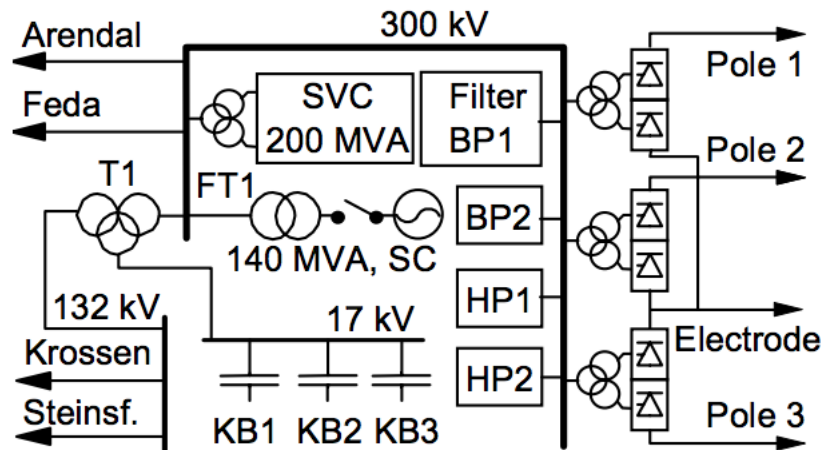

Figure 36: Kristiansand HVDC station [28]

During the operational period of the Kristiansand HVDC station, there were a few occurrences where low order harmonics were detected. These harmonics were responsible for several power system interruptions and trips. Furthermore, there were also some recorded cases of the T1 transformer (can be seen from Fig. 36) also being tripped by the overload protection system [28]. At the time, it was not clear what the exact cause of the issue was; moreover, recreating the same scenarios was extremely difficult. Therefore, several simulations of the HVDC system were done in order to properly grasp the issue at hand [28].

It was also noticed that, even though, the resonance frequency of the DC side was lower than the fundamental frequency, there were interactions present in the system, which ultimately gave rise to a 50 Hz DC side oscillation. As a result of this, simulations were done in order to try and replicate this phenomenon. With the help of the simulations that were done, it was determined that adding specific damping functions to the converter control would rectify this instability phenomenon. In addition to this, it was properly identified that the station suffered from two different types of harmonic issues: core instability and third harmonic resonance [28].

6. Model Based Systems Engineering

6.1. Introduction

Systems engineering serves as the backbone of countless complex systems in almost every engineering discipline. Technological advances are being made every single day, and it is inevitable that it will continue to grow even further in the coming decades. With this predicted growth of technology comes the expectation that the systems involved will also become increasingly complicated. It is for these reasons that systems engineering exists. Systems engineering addresses systems that have a high degree of complexity, not just in the internal design, but from an external point of view as well. In other words, systems that require the multi-operational functionality of several stakeholders pertaining to the successful system outcome are properly coordinated and pre-planned through organized process-based systems engineering. Model based systems engineering (MBSE) is an extension of systems engineering as it directly addresses the different tools provided by systems engineering; these tools are directly made available with the modelling language: SysML. The systems engineering methodology has been a part of many industries such as the automotive, aerospace, telecommunication, rail, etc. This is only as a result of systems engineering providing an increased functionality, interoperability, reliability, and performance of highly complex systems. The growing and strict electric power industry is yet to take advantage of the various benefits offered by the systems engineering methodology.

As it was mentioned in Chapter 1, renewable energy sources are expected to see a massive expansion in the coming decades. The reason for this is due the heavy requirements made in relation to ensuring a clean environment moving forward. It was presented that it is specifically for this reason that large-scale HVDC transmission is envisaged as the leading technology in guaranteeing the expansion and integration of renewable energy systems. However, it was seen in Chapter 5 that some of largest commissioned HVDC projects experienced several issues that can be directly correlated to the interoperability of the system. It was seen in multiple projects that there were power interruptions caused by harmonic instabilities caused by the converter interactions. The manufactures involved in some of these projects suggested the tuning of the converter controller. However, other manufacturers in multi-vendor projects had to resort to making generic assumptions about the converter control scheme based on publicly available knowledge about it due to the manufacturers not being able to disclose data due to intellectual property reasons. It is for these reasons that it is proposed to create a partially open software that will be able to assist in solving the problems by requesting manufacturers to provide data that will not expose the inner and more delicate part of their converter control data. The determination of exactly

which parts of the HVDC converter control system to open is what MBSE will be used for. Moreover, it was also mentioned by manufacturers (seen in Chapter 5) that more focus needs to put into the design phase of future HVDC projects. This serves as validation for the crucial need of implementing the systems engineering methodology in the electric power industry.
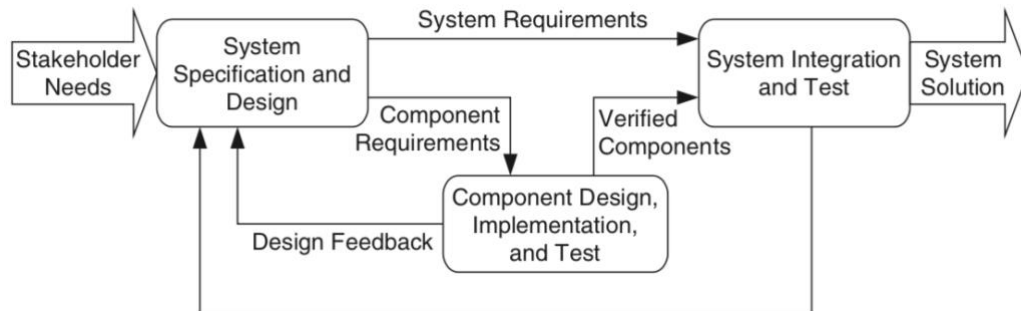

Figure 37: Systems engineering early design process [29]

The above figure (Fig. 37) shows the earliest stage of the systems engineering design process. It involves the identification of the different stakeholder needs that are required before the system specification and design is implemented. The diagram shown in Fig. 37 represents the general external and internal processes involved in the design of a system. All the elements involved are shown in an organized manner; by understanding the exact stakeholder needs, the entire specification of the system can be designed, and only after this, will the internal process involving the component design will be commenced. Results obtained from these internal processes will feedback to the early-stage system specification and design, which appropriately adjust any inaccuracies in the system before recommissioning. This early-stage design process is essential in the success of complex projects, which was validated in the cases presented in Chapter 5. Taking the example of a multi-terminal multivendor HVDC system, this early-stage systems engineering design process must be executed in the following manner:

- Identify stakeholder needs of the HVDC system, the goals that the system is expected to meet, and the evaluate whether these goals effectively satisfy the stakeholder needs.

- Define system specifications in terms of functionality and interoperability to ensure system reliability and performance.

- Split the system specifications into different sections and create alternate solutions in each section.

- Perform the required analysis and tests with respect to all the created solutions and

select the most appropriate solution based on maximizing performance.

- Maintain proper traceability between the above stages in order to address issues in a more coordinated manner.

The last point in the aforementioned design process is crucial especially in complex HVDC systems. This is because the identification of the stakeholder needs along with the specification of the different components, requirements, external and internal control and protection functions, etc. can become excessively convoluted. Therefore, the traceability between all of the different elements, sections, and subsections can greatly simplify the analysis of the system during scenarios where unexpected phenomena occurs.

6.2. SysML Model Design Tools

SysML, just like any other language, provides the user with the necessary tools in order to produce behavioral, structural, requirement, and parametric models of a system. SysML is, however, a graphical language; this means that instead of language syntax, SysML offers a dynamic graphical interface that allows for the design of complex systems. In order to properly operate this graphical interface, it is important to understand how and why the different diagrams and model tools offered in SysML are beneficial. In Fig. 38 (can be seen below), it can be seen that the traceability features offered by SysML allow for the view of system model in different perspectives.
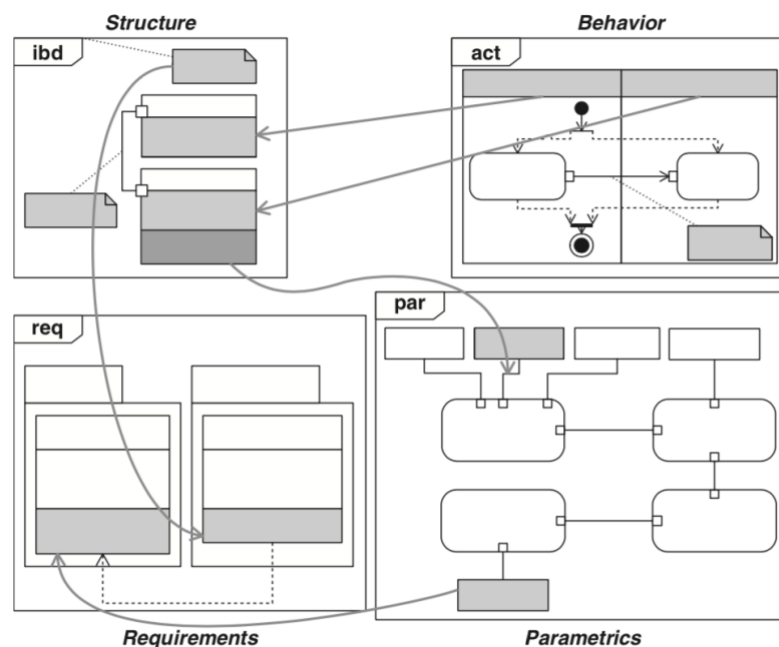

Figure 38: Different perspective views of different SysML models [29]

This model is directly based on the early-stage design process mentioned in the introduction. It depicts the system specification and process (can be seen in Fig. 37). The system specification and design process can be split into the four major sections that directly correlate to the operation of the system. This can be seen in Fig. 38 as four blocks indicating the overall structure of the system, the requirements of the system, the behavior and parametric properties of the system. Fig. 39 (can be seen below) depicts the component and hardware design section of the early-stage design process.
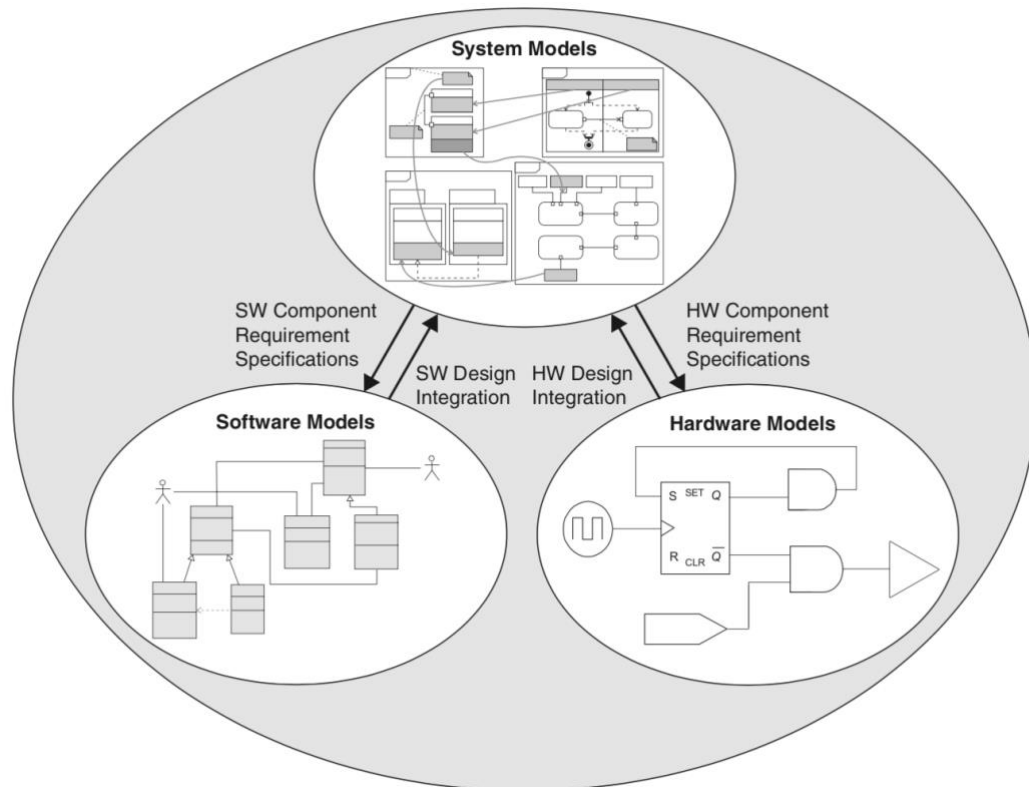

Figure 39: Overall structure of a system in SysML [29]

It can be seen from the above figure that the system models that were created for indicating the behavioral and structural specifications of the system can be linked to the component and hardware models through traceability. The main benefit of having such an intricate process in identifying and modelling the different already known specifications and hardware elements is this traceability feature, which basically demystifies the entire system. Furthermore, information directly extracted from this system model can be integrated with other simulation and analysis software. This is done through the automated documentation features provided by SysML. This documentation can be also be useful in providing data on component and equipment maintenance. It is important to note SysML, just like other languages, has certain rules and requirements for producing certain models. This ensures that the developed models are coherent and concise.
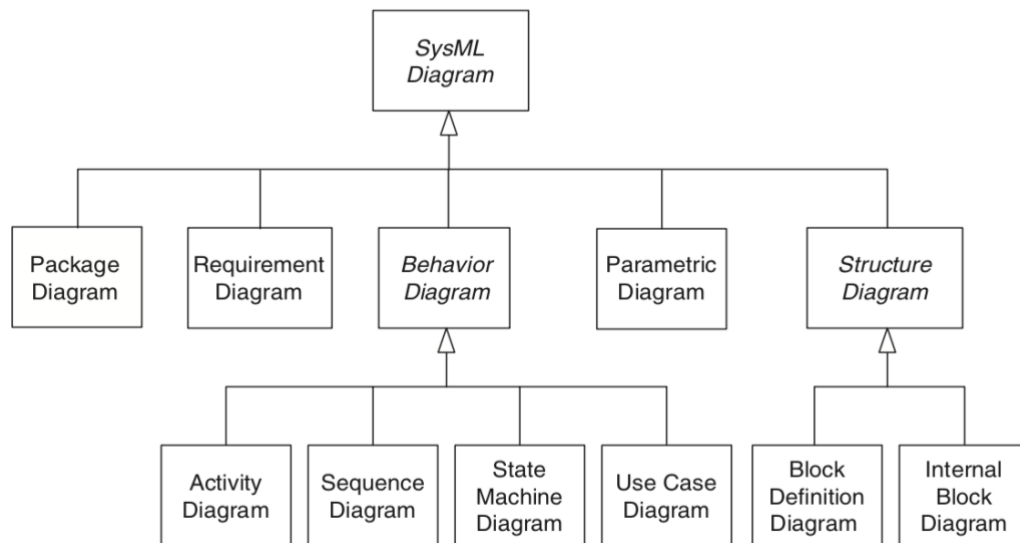
Figure 40: SysML diagram taxonomy [29]

In order to build the aforementioned system model in SysML, the specific diagrams permitted in SysML must first be introduced. Fig. 40 shows the different diagrams provided in SysML. It is important to note that the diagram in Fig. 40 is in fact a 'Block Definition Diagram'. The arrows in this figure signify a "belongs to" relationship. Therefore, Activity Diagrams, Sequence Diagrams, State Machine Diagrams, and Use Case Diagrams all 'belong to' what is known as the "Behavior Diagram". As the name suggests, the behavior diagram is used to describe the behavior of a system. Whereas, the "Structure Diagram" is used for describing the general structure of the system. The Block Definition Diagram (BDD) and the Internal Block Diagram (IBD) both belong to the Structure Diagram. For the scope of this project, the block definition diagram is of great importance due to the complex nature of the HVDC control systems.

6.2.1. Block Definition Diagram

The block definition diagram (BDD) in SysML defines the structure and composition of the system using blocks. Therefore, it is key to understand the main elements and tools available in a BDD. The elements in BDDs are Blocks, Ports, Instance Models, Information Flows, and Links. There are two different usable blocks in a BDD, which can be seen below in Fig. 41. The first block is a regular block that can indicate a structural element in the system. The second block is a constraint block that is meant to indicate a structural element that is strictly constrained. In other words, the constraint block can be used in conjunction with other regular blocks to indicate a constraining relationship between them. These two blocks are the most important blocks for the scope of this project. The other important elements shown in Fig. 41 that are extremely relevant are the three connectors. The arrow with the square

bottom indicates an "association". Therefore, if you connect two blocks together using this item, then it will indicate an association between the two blocks. The arrow with the white diamond indicates an "aggregation" between two elements or blocks. Lastly, the arrow with the black diamond indicates a "composition" between two blocks. These connectors are especially important in providing meaning to a BDD. The three connectors are different from one another, but all serve with the purpose of connecting different blocks in a BDD together. For example, if two blocks are connected together using a composition connection, it means that one of the blocks is composed of the other block. It does not necessarily mean that the two blocks are associated with each other, but rather just that the one block is composed of the other block. The last item shown in Fig. 41 is a signal block, which just like the constraint block is strictly constrained to be a block indicating a signal.
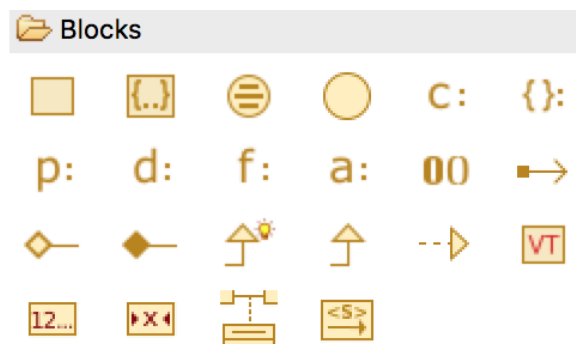

Figure 41: Blocks in block definition diagrams [30]

Apart from the blocks and connectors, there are additional features that are not strictly restricted to a BDD but are a part of it. These are known as information flows which can be seen in Fig. 42 below.
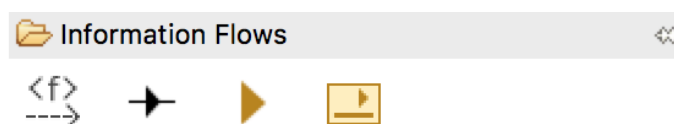
Figure 42: Information flows in SysML [30]

The first item in these tools shown in Fig. 42 is what is known as an 'Information Flow'. It indicates that a certain information/data flows from one block to another. It is important to note that when using the information flow tool, the user must indicate what the information being conveyed is. This is done by connecting two blocks using the information flow tool with the help of a flow port (which is shown below) and then assigning a block specifically to it in the "conveyed" section of the information flow properties. Moreover, the last block in Fig. 42 is an 'information item', which basically creates an additional block containing information relevant to the block that it is connected to.

The ports shown in Fig. 43 below are the items that enable a connection between blocks using information flows. The first port shown in Fig. 43 allows for the interconnection of elements across different diagrams by means of indicating a flow of information in or out of the block.
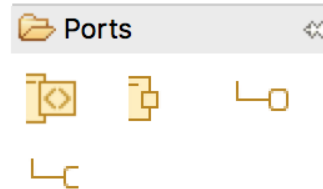

Figure 43: Ports in block definition diagrams [30]

The last set of items shown in Fig. 44 below are the connectivity links. There links are essential in obtaining traceability between different diagrams. The third and fourth items in Fig. 44 are the dependency and traceability links, respectively. The dependency links allow for the dependency connection of elements from different diagrams. It is important to note that this connection does not indicate an association between the two connected elements, but rather strictly a dependency. In other words, certain elements might not have a belonging relationship but might still depend on each another. The fourth item is the traceability link, which serves with the purpose of linking elements or blocks together without establishing a dependency relationship.

Figure 44: Links available in SysML [30]

Information flows, dependency, and traceability links are not items that strictly belong to block definition diagrams (BDDs) and can instead be commonly accessed by any other SysML diagram.

In order to expand on the association and composition connection of two blocks (shown in Fig. 41), a classic example of a car can be seen below in Fig. 45. When two blocks are connected together with either a composition or an association, it is then required to choose a multiplicity (indicated by "0..1"). This multiplicity represents the number instances that the connection makes. In Fig 45, the multiplicity number is set to 1, indicating that there is only one instance of wheels, and one instance of rims. It can be seen that the car block is

connected to the wheel block by means of four composition connections, and the wheels are connected to the rims by means of two association connections. The four composition connections of wheels indicate that the car has four wheels, and the two composition connections indicate that the wheels have two rims. The reason why the rims are not connected to the car by means of a composition is simply because the car is not composed of rims; in other words, the car does not need the rims in order to function properly. The same concept applies to the association connection between the wheels and the rims.

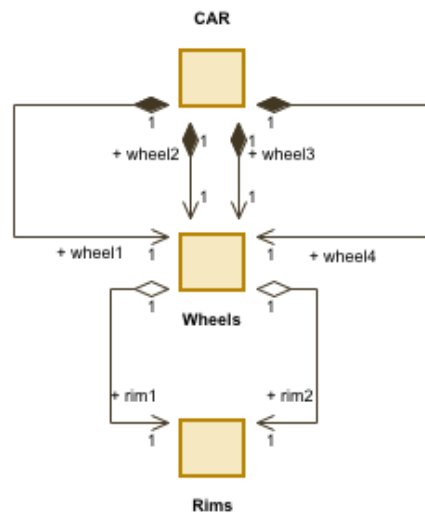

Figure 45: Example of a car BDD

6.2.2.   Use Case Diagram

The Use Case diagram is a behavioral diagram that is mainly used to express the external behavior of a system. The "Use Case Diagram" uses tools such as "Actors" in order to display an exterior entity. Fig. 46 shows the different possible nodes that one could choose from.
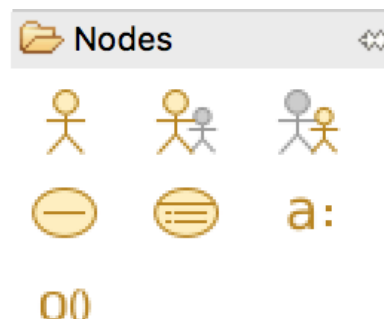

Figure 46: Nodes available in use case diagrams [30]

The first item in the nodes section of the use case diagram indicate the 'Actor' role. The second and third items indicate primary and secondary actors, respectively. The fourth item shown in Fig. 46 is the equivalent of a block in a BDD; it is known as a 'Use Case'. These use cases are generally utilized to depict the relationship between the actor and the operational task that the actor performs. The "a:" shown in Fig. 46 is known as an 'Attribute', and just as its name suggests, it allows the use to create attributes pertaining to a use case.

The last set of elements that strictly belong to use case diagrams are their specific links. They can be seen below in Fig. 47. These links are the tools that allow for the connection of different use cases. The four links being: communication link, inclusive relationship link, exclusive relationship link, and the generalization or inheritance link. The specifications of these links are self-explanatory. The communication link indicates that there is some sort of communication between different use cases. The inclusive and exclusive relationship links indicate either whether one use case includes or excludes the other, respectively. The inheritance link indicates a general link between two use cases.
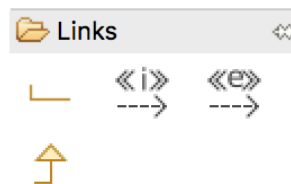

Figure 47: Links available in use case diagrams [30]

6.2.3. Activity Diagram

The activity diagram is another behavioral diagram that provides the tools to construct events and action sequences of a system. The main building blocks of activity diagrams are: control nodes, data nodes, events, flows, and partitions. All of them along with their tools can be seen below in Fig. 48. The first block in the control nodes is the action block, which indicates a specific function that the system must perform. The second and third blocks are the call behavior and call operation blocks, respectively. The fourth, fifth, and sixth blocks are the conditional node, conditional clause node, and loop node, respectively. The three circles are the initial, activity final, and flow final nodes, respectively. These blocks are all control node blocks, just as their name suggest, and indicate the beginning sequence of events. The main event block is the first block in the events tab shown in Fig. 48, which indicates that an event where signals are transported from one point to another. Then there is the data nodes section, which contain blocks that carry data instead of performing an action. In order to connect control nodes and data nodes, different flows are utilized. The first flow is an automatic flow that can basically either connect control node blocks or data node blocks. The sixth and seventh blocks in Fig. 48 are the control flow and the object flow, respectively. They

are responsible for the manual user-based connection of control nodes and data nodes, respectively.
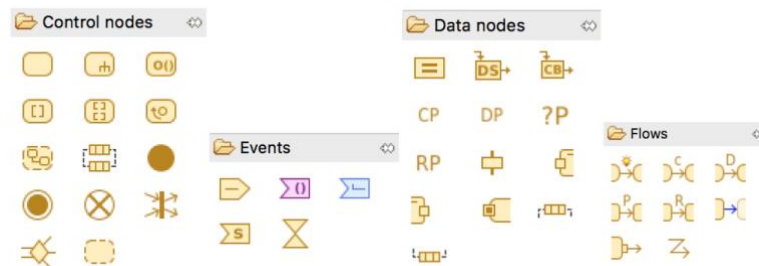

Figure 48: Design tools available in activity diagrams [30]

6.2.4.   Sequence Diagram

The SysML sequence diagram is nothing but a display of the exchange of information/messages between several entities. They contain vertical lines called "Lifelines" that indicate a platform where a message is received, interpreted, and delivered. These messages that communicate through the lifeline platform can be seen below in Fig. 49. The first and second arrows are called synchronous and inner synchronous messages, respectively. The third item is called a 'creation message', where a message is sent from one lifeline to another, and then automatically sends back a message to the previous lifeline. The fourth item is a 'destruction message', and the fifth item is the 'asynchronous message'. The last item is the return, which basically allows the user to manually input a return message in any lifeline instead of relying on the creation message tool.
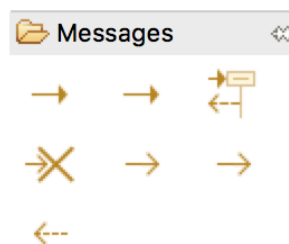
Figure 49: Message tools available in sequence diagrams [30]

6.3. Converter Control Modelling

Now that the representation side of things is clear, the block definition diagram of the control system under study can been seen below in Fig. 50. The strategy involved behind this model is the energy-based MMC control scheme. As it can be seen in Fig. 50, there are two MMC's involved: The master MMC (MMC-1) and the slave MMC (MMC-2). The main idea behind this control strategy is to explicitly control the energy stored in the submodules of the MMC.

Therefore, the control loops placed in the upper-level are the AC/DC Voltage controllers, Active/Reactive power controllers, and the energy control blocks. The control loops placed in the lower level include the current controllers, modulation, and capacitor voltage balancing. Note that the connections within each of these blocks are made using generalization and composition links except for the connection between MMC-1 and AC 'voltage control or reactive power control' along with the connection between MMC-2 and DC 'voltage control or active power control'. This is mainly to indicate an 'association' between the two blocks. Therefore, depending on the control mode that the dispatch operator sets, it is now clear which MMC will operate at which mode. Moreover, there are some elements that are not grouped into the "upper level" and "lower level" sections of the diagram. This is due to the fact that they can be placed at either of the two sections. Though, they will likely be placed in the upper-level due to their insignificant effect on the interior behavior of the converter. These elements can be seen in the bottom section of the BDD.
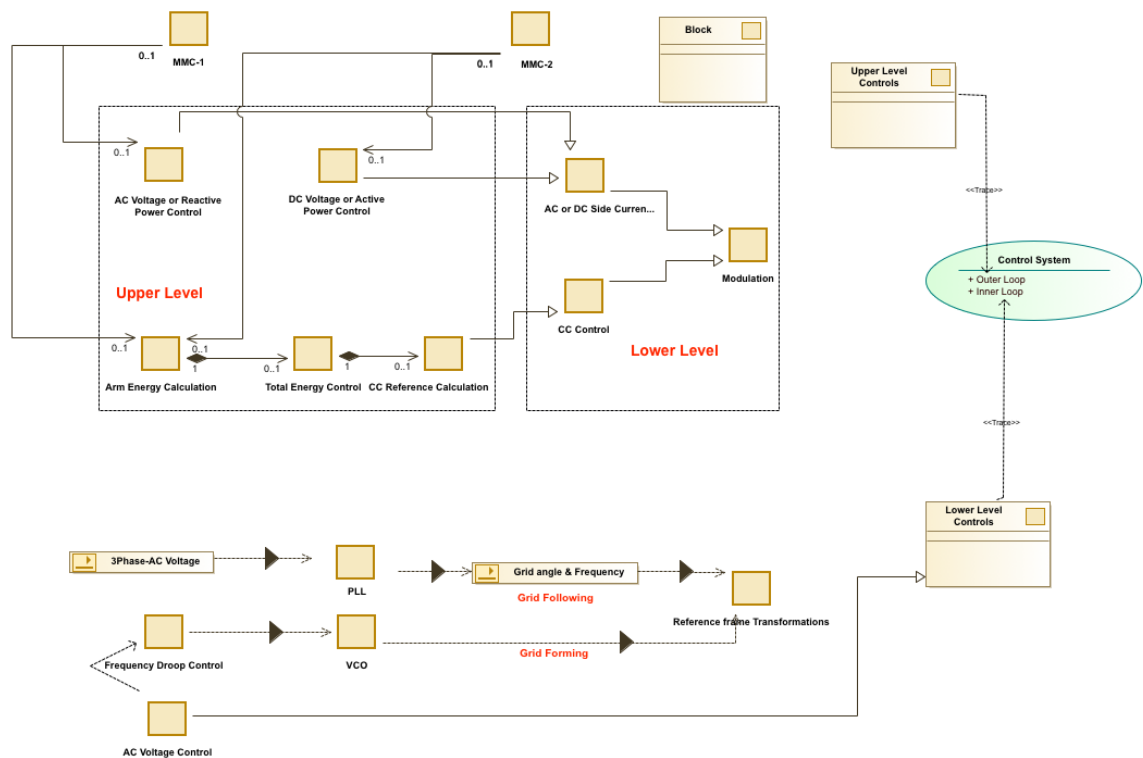
Figure 50: Energy-based, Grid following, and Grid forming converter control BDD

The Grid-Forming/Islanded control approach is also modelled in the bottom section of the BDD. It is important to note that there is no association or dependency links between the PLL and the Grid Forming approach due to the fact that the Islanded system does not utilize the PLL to generate the grid angle and frequency anymore, and instead uses a voltage-controlled oscillator (VCO) for the reference angle. Moreover, it uses an AC side voltage controller, and a frequency droop controller to control the frequency. All of the blocks are

connected by information flows to indicate the flow of information. Note that the green block is not a part of the block definition diagram. It has been pasted from another SysML diagram in order to create flow and traceability among the several models. It creates a link between the upper level controls & outer loop, and lower level controls and Inner loop shown in the use case diagram below.
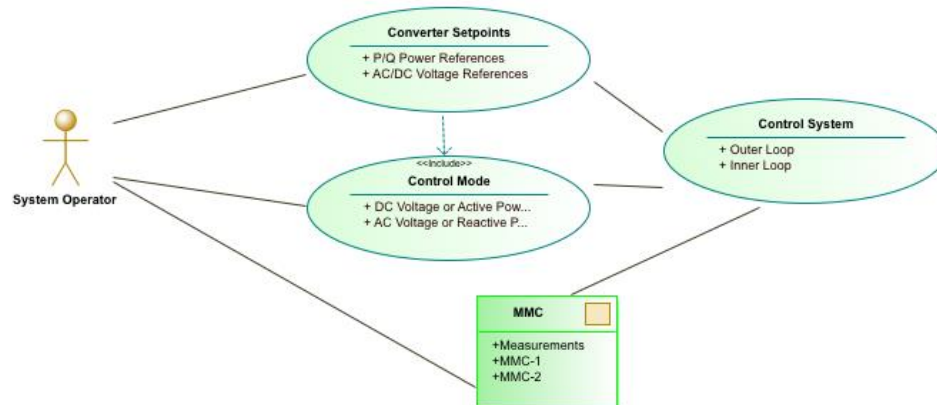

Figure 51: External behavior in an MMC-HVDC system

The system shown in Fig. 51 is quite self-explanatory. The system operator provides the control system with the converter set points and the control mode. Then the control system works and provides measurements that feedback into the system. It is important to note that, in a diagram such as this it would be beneficial to also model the station control approach followed. This is quite important when the HVDC system at hand is a multi-link multivendor system. This sort of system adds more complexity to the model.

There are many proposed ways of sharing power between multiple stations in a multi-link system, but some are less reliable with higher power control/steering, and some are more reliable with less power control. It could be interesting to model the behavior of all of the strategies involved in the station control level of a multi-link HVDC system in order to have a more detailed model. Nonetheless, the control modes taken into consideration now are simply the DC voltage/active power mode and AC voltage/reactive power mode.

The detailed block diagram describing the structure of this system level control can be seen below in Fig. 52. This diagram describes the different references, control modes, and setpoints chosen by the system operator before entering the converter control stage. Note that Fig. 52, 53, 54, & 55 are real control functions provided by a Siemens member of the CIGRE working group B4.85 for the purposes assist this thesis. Therefore, these control modes, references, and setpoints depicted in Fig. 52 are realistic control functions that are
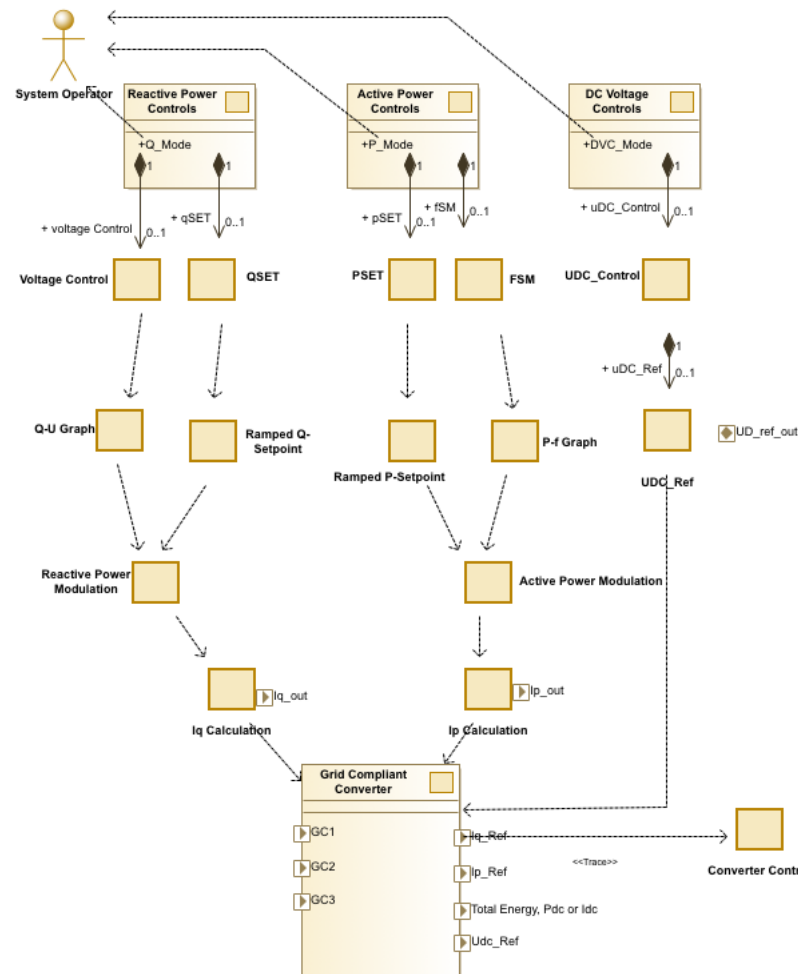
being implemented in the industry.

Figure 52: HVDC system control level

The next stage that proceeds the system level controls is the converter control stage. The BDD design of this stage can be seen below in Fig. 53 and 54. The control functions were split into two levels: the upper and lower level controls unlike the model shown in Fig. 50. It is important to note that Fig. 53 consists of regular blocks that indicate the structure of the control functions and their relationships. However, a constraint block was used instead of a regular block so as to indicate the mode of operation that is selected by the system operator. This serves as a constraint to the system in the upper-level.

It can also be seen that most of the blocks connected to the main upper-level converter control are done so with composition links so as to indicate that the upper-level control system is composed of the other blocks. In other words, if these blocks were not present then the system would not operate. However, the energy control block is not directly connected to the converter control system, although it is instead connected to the AC and DC side controllers with a composition link. Therefore, this indicates that these controllers are

each composed of energy control functions.
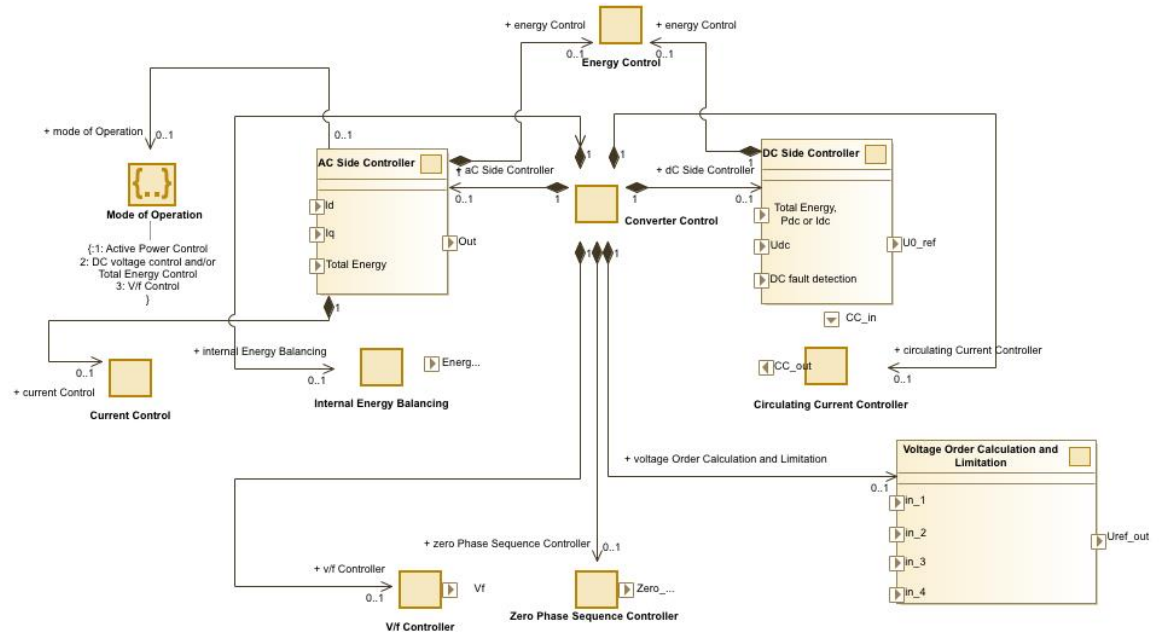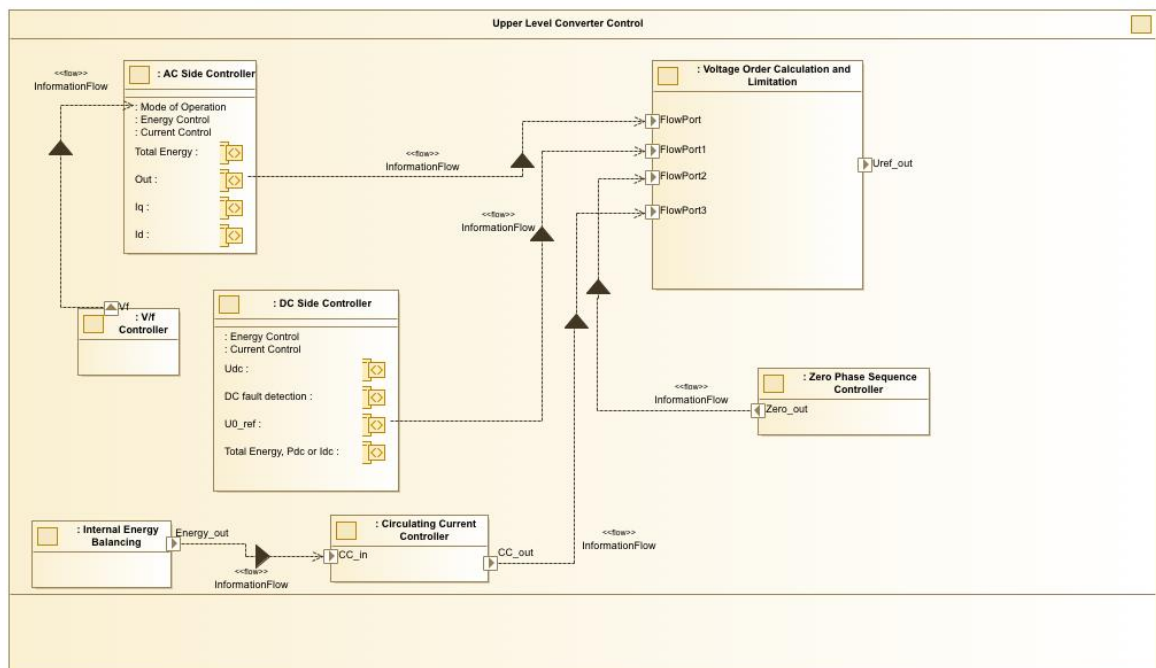

Figure 53: Upper-level converter controls

Figure 54: Internal Block Diagram of the upper-level control system

Another important diagram is the internal block diagram (IBD), which in the above figure (Fig. 54) shows the interconnections of the blocks indicated in Fig. 53 in terms of flow of information. Recall that the in the blocks shown in Fig. 53, the BDD has flow ports connected

to them, which can then be connected together in the IBD using information flows.

Fig. 55 shows the lower level converter control functions. Note that there are only three composite connections between the main lower level converter control block and the control functions. This is because the lower level converter is technically composed of the switching frequency control, the modulation algorithm, and the protection functions. These control blocks are then composed of other control blocks that determine the functionality of the higher-level blocks connected to the main lower level control block.
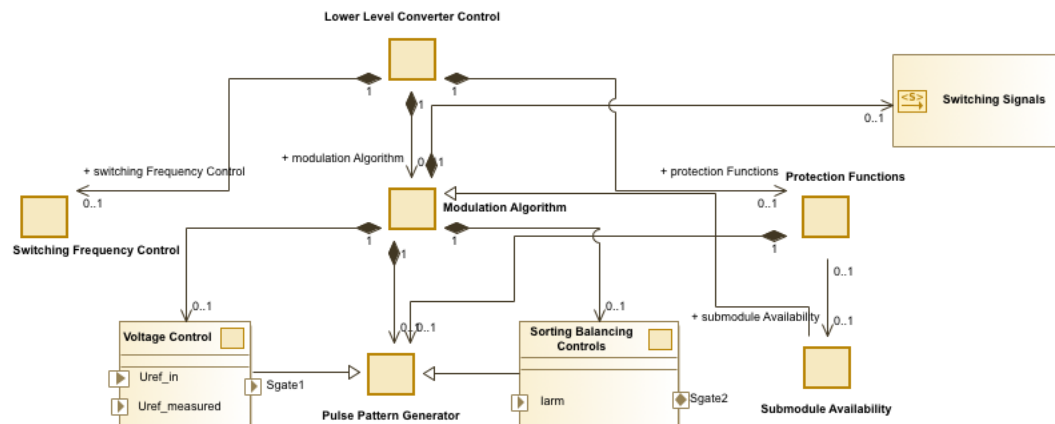
Figure 55: Lower level converter controls

The diagram shown below in Fig. 56 displays the navigation tool in Modelio based on the dependency links between the different system level blocks shown in Fig. 52. This tool is essential for such complex HVDC control systems as it simplifies the system.
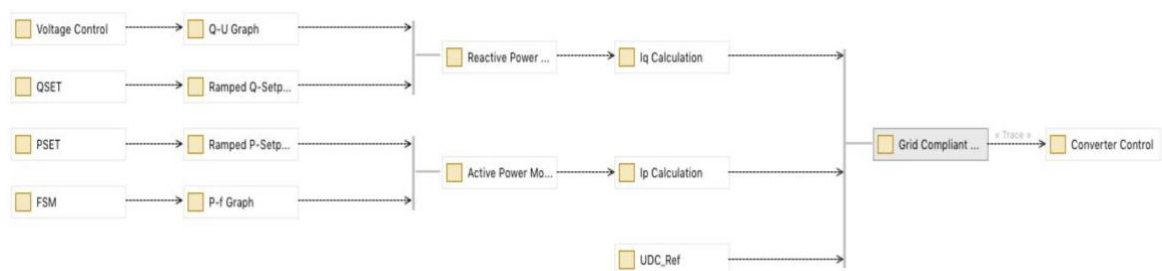
Figure 56: Traceability of system level control functions

A sequence diagram was also designed in order to depict the flow of messages between the system operator and the converter. It can be seen in Fig. 57 (shown below) that there are four lifelines: the dispatch operator, the converter controller, the converter and the AC grid. The information flows first from the operator to the controller (similar to the use case diagram). This information contains the mode of operation and the set-points. The upper level controls generate the voltage and power references for the lower level controls. Furthermore, the lower level controls generate the switching signals (along with the blocking,

and unblocking signals) that will go directly into the converter. Data from the converter also feeds back into the system. The converter then provides the desired voltage and current values that are then fed back to the operator creating a loop.

Figure 57: Communication flow sequence diagram

The last SysML diagram that was created is the activity diagram shown below in Fig. 58. This diagram is based on Fig. 50, and shows the sequ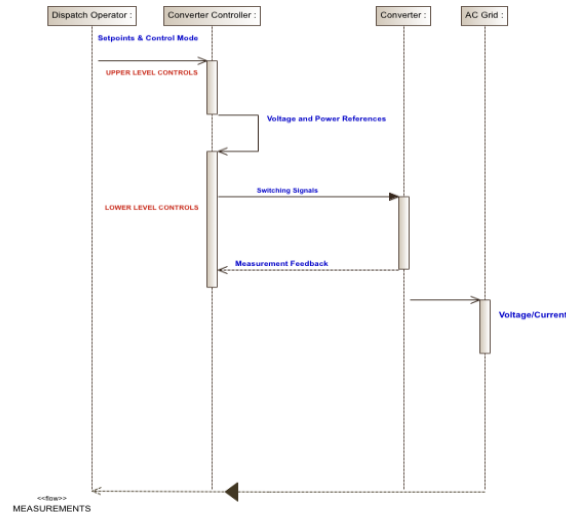ence of actions that are implemented between the different control platforms in order to establish the procedures & actions that need to be met by the converter control system.
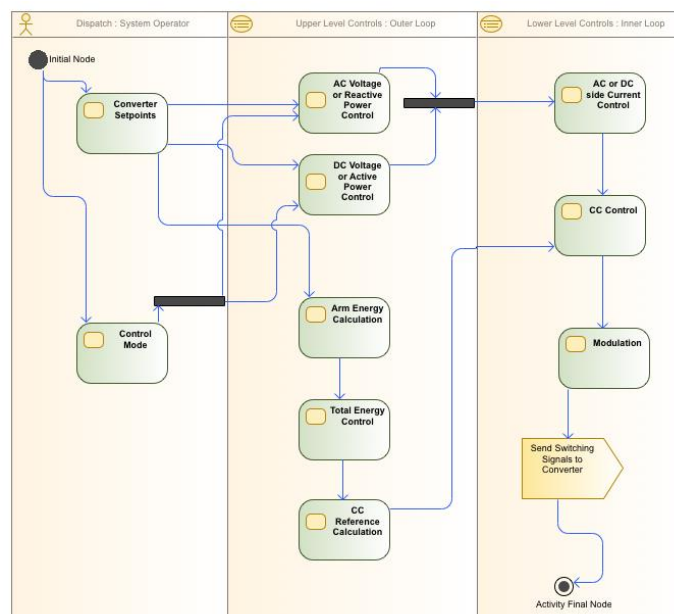

Figure 58: Energy-based converter control activity diagram

6.4. Partially Open Converter Model
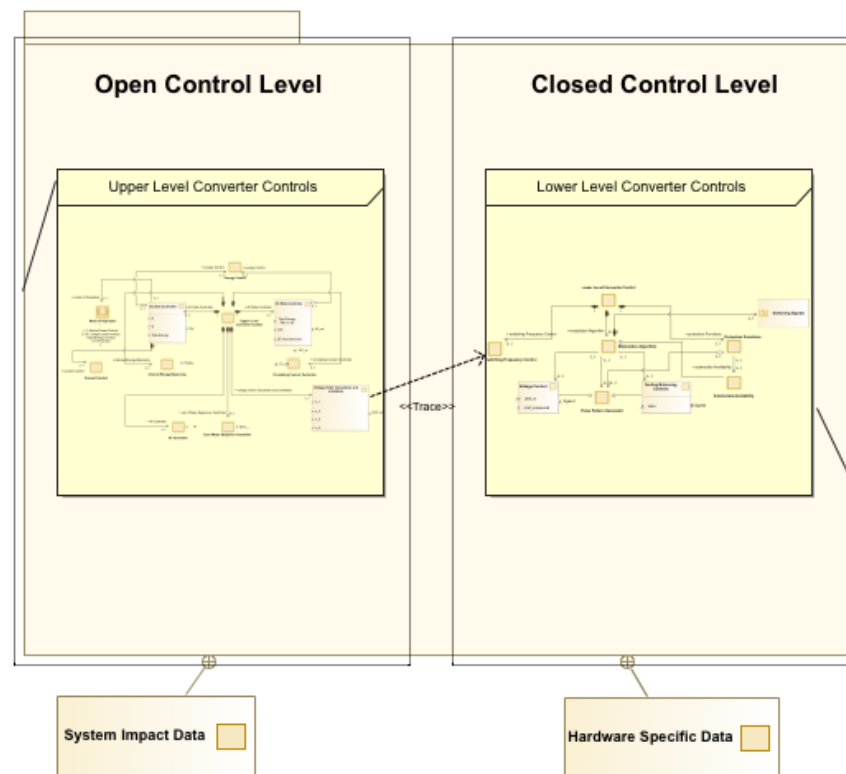
Figure 59: Proposed classification of partially open converter control

In order to consider which elements and functions of the control system to be kept open depends on many internal and external factors. The external factors such as vendor intellectual property is out of the scope of this thesis. However, internal factors that determine which control functions are responsible for causing the interoperability and harmonic instability issues faced by the industrially commissioned HVDC projects seen in Chapter 5 are considered. These control functions were placed in the upper level section of the control system as they pose the highest degree of impact on the system.

On the other hand, the closed functions were placed in the lower level section of the control system as they affect the internal properties of the converter hardware and have a low degree of system impact. Fig. 59 (shown above) depicts this classification, and also includes a traceability link between the upper and lower levels. This is done so as to indicate that even though the lower level is kept closed, it is still important to establish navigational properties between the two levels. Furthermore, this traceability can also be implemented in such a way that it allows for its access by different vendors without revealing specific internal control loops that would be restricted due to intellectual property reasons.

7. Conclusions

VSC-HVDC transmission is predicted to be the leading form of electric power transmission over long distances while ensuring the large-scale integration of renewable energy sources into the grid. This prognosis means that HVDC networks will not only be commissioned in the coming decades, but will be done so in a much larger way. This opens the door to the rise of unexpected issues as the HVDC network expands. The expansion of HVDC networks directly correlates to adopting multivendor multi-terminal HVDC systems. This thesis presented the theoretical complexities involved in the state-of-the-art HVDC technology in Chapter 2, 3, and 4. Chapter 5 introduced real-life cases of industrially commissioned HVDC projects. This chapter provided insight on the various unexpected issues such as: harmonic interactions between converters, interoperability, and resonance problems. The following two major points were directly validated by the manufacturers involved in these projects:

- Access to parts of the vendor-specific converter control software would be the best and easiest way to solve any interoperability issues.

- More focus needs to be put into the early-stage design of HVDC systems so as to ensure efficient system operation.

Chapter 6 was introduced in order to best deal with the aforementioned validated problems with the help of model-based systems engineering (MBSE). Many highly complex industries reap the benefits of implementing the systems engineering methodology in the early-stage design process of their systems, except the electric power industry. With the envisioned expansion of the electric power grid through HVDC transmission, it is strongly recommended in this thesis to adopt the MBSE methodology. Furthermore, in order to provide the best answer to the aforementioned HVDC network issues, it is proposed to create a partially open software of the control system that will improve interoperability in future HVDC projects. This is done in Chapter 6 by introducing the main concepts of MBSE. Moreover, several models of the MMC-based VSC-HVDC control system were implemented in Modelio using the SysML language. These models are expected to ensure the ease in navigation of complex control systems along with providing a simplistic platform where complex control functions can be easily explained.

The most suitable candidate for the open-source part of the control was determined to be the upper-level control due to the fact that they have the least impact on the internal properties of the converter while having a significant effect on the system interactions. This keeps the internal properties of the converter black-boxed, (up to a certain degree due to SysML traceability) thus enabling a straight forward approach for the detection and handling of issues within HVDC converters in order simplify system stability analysis.

ETSEIB

7.1. Future Work

Future work in this area can be done to determine and achieve the following:

- Understand exactly which control blocks carry a greater percentage of responsibility when it comes to diagnosing system interactions by gathering more data from industrial manufacturers.

- Integrate industrial simulations and tests with the functional models in order to further validate the problem and solution.

- Expand the SysML models further by defining the different external stakeholder and system specification needs.

- Further expand the SysML models to larger multi-terminal VSC-HVDC networks considering all of the control systems available in the network.

- Integrate the different system and converter protection strategies along with the control strategies by using SysML.

Environmental Impact

This thesis proposed solutions that directly correlate with the successful operational expansion of HVDC transmission. Therefore, it is important to analyze the environmental impact that this expansion will cause. This is done with the help of the sections seen below.

Renewable Energy Integration

VSC-HVDC directly allows for the seamless transition of grid-connected renewable energy systems. The integration of renewable energy systems into the grid can cause unpredictability due to issues such as: power flow control and reserve power. VSC-HVDC technology greatly reduces, if not completely negates, these concerns. This is because the VSC-HDVC technology is able to independently control the active and reactive power flow; therefore, multidirectional power flow is not an issue. Furthermore, the United Nations Framework Convention on Climate Change introduced a goal of maintaining 1.5°C, inherently reducing climate change. Therefore, the flexibility and reliability of the VSC-HVDC technology supports the transition to a cleaner environment by allowing the integration of renewables and by getting the world one step closer to achieving such climate change goals.

Interoperability

In this thesis, it was theorized that with the expansion of the HVDC transmission system in the coming decades, multivendor HVDC systems will be commissioned more often. However, in the multivendor projects that are already commissioned, it has been seen that interoperability issues were the cause of quite a few unexpected issues. Therefore, this thesis proposed the solution of creating an open-source control software to combat this. Reducing interoperability issues will directly allow for the smooth and efficient expansion of the VSC-HVDC network, which will ultimately impact the environment in a highly positive way.

Environmental Footprint

It has been established that from chapter 2 of this thesis that the VSC-HVDC technology has a low voltage and power rating when compared to LCC-HVDC. Furthermore, the VSC-HVDC technology does not require additional reactive power compensation equipment. This means that the physical & environmental footprint of the VSC-HVDC technology is, and will be low in the future; thus, positively impacting the environment.

Budget

The total budget of this thesis is split into two parts. The first part being the human resource part, which indicates the number of hours the student has spent on the research along with their hourly wage. The second part being the equipment that was required for the successful completion of this thesis. Note that the amounts mentioned below do not include VAT.

Human Resource Budget

Table 5: Human Resource Budget

	Working hours	Hourly wage (€/hr.)	Total (€)
Working Hours of Student	960	9	8,640
		Total	**8,640**

Equipment Budget

Table 6: Equipment Budget

Equipment	Cost (€)
MacBook Pro 13' Laptop	1,000
Access to IEEE and other online databases	150
MATLAB & Simulink Student License	95
Total	**1,245**

ETSEIB

Bibliography

[1] Unfccc.int. 2022. *Climate Action*. [online] Available at: <https://unfccc.int/>

[2] European Commission - European Commission. 2022. *Wind energy*. [online] Available at: <https://ec.europa.eu/info/research-and-innovation/research-area/energy-research-and-innovation/windenergy_en#:~:text=The%20EU%20currently%20has%20the,to%2024%25%20of%20electricele%20demand.>

[3] wang, feng & Bertling Tjernberg, Lina & Tuan, Le & Mannikoff, Anders & bergman, anders. (2012). An Overview Introduction of VSC-HVDC: State-of-art and Potential Applications in Electric Power Systems. CIGRE 2011 Bologna Symposium - The Electric Power System of the Future: Integrating Supergrids and Microgrids.

[4] Electrical Concepts. 2022. *HVDC - Advantage & Disadvantage - Electrical Concepts*. [online] Available at: <https://electricalbaba.com/hvdc-advantage-disadvantage/>

[5] Sharifabadi, Kamran & Harnefors, Lennart & Nee, H.-P & Norrga, Staffan & Teodorescu,. (2016). Design, control and application of modular multilevel converters for HVDC transmission systems. 10.1002/9781118851555.

[6] Vrana, Til & Dennetiere, Sebastien & Yang, Yongtao & Jardini, J.A. & Jovcic, Dragan & Saad, Hani. (2013). The Cigré B4 DC grid test system. CIGRE Electra. 270.

[7] L. de Andrade and T. P. de Leao, "A brief history of direct current in electrical power systems," in HISTory of ELectro-technology CONference (HISTELCON), 2012 Third IEEE, 2012, pp. 1-6.

[8] S. M. Yousuf and M. S. Subramaniyan, "HVDC and Facts in Power System," International Journal of Science and Research, vol. 2, 2013.

[9] B. K. Bose, "Evaluation of modern power semiconductor devices and future trends of converters," Industry Applications, IEEE Transactions on, vol. 28, pp. 403-413, 1992.

[10] Asplund, G.; Carlsson, L.; Tollerz, O. 50 years HVDC Part I, ABB – from pioneer to world leader. ABB Rev. 2003, 4, 6–13.

[11] Hitachi Energy. *Gotland HVDC Light*. [online] Available at: <https://www.hitachienergy.com/me/en/case-studies/gotland-hvdc-light>.

[12] Burman, Kari & Olis, Dan & Gevorgian, Vahan & Warren, A. & Butt, R. & Lilienthal, Peter & Glassmire, John. (2022). Integrating Renewable Energy into the Transmission and Distribution System of the U. S. Virgin Islands. 10.2172/1024523.

[13] Imdadullah, & Amrr, Syed & Asghar, M. & Ashraf, Imtiaz & Meraj, Mohammad. (2020). A Comprehensive Review of Power Flow Controllers in Interconnected Power System Networks. IEEE Access. 1-28. 10.1109/ACCESS.2020.2968461.

[14] L. Chetty, "Lcc Hvdc Control Systems," no. September, pp. 1–128, 2011.

[15] n.d. *HVDC Transmission Systems UNIT-1*. Odisha University of Technology and Research, Bhubaneswar.

[16] O. E. Oni, I. E. Davidson and K. N. I. Mbangula, "A review of LCC-HVDC and VSC-HVDC technologies and applications," 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), 2016, pp. 1-7, doi: 10.1109/EEEIC.2016.7555677.

[17] Stamatiou, G., n.d. *Analysis of VSC-based HVDC systems*.

[18] Mokhberdoran, A.; Carvalho, A.; Leite, H.; Silva, N., "A Review on HVDC Circuit Breakers" 3rd Renewable Power Generation Conference (RPG 2014).

[19] Vovos, Nicholas & CIGRE, WG. (2005). VSC Transmission. ELECTRA. 219. 29-39.

[20] Beddard, A. & Barnes, Mike. (2015). Modelling of MMC-HVDC Systems – An Overview. Energy Procedia. 80. 201-212. 10.1016/j.egypro.2015.11.423.

[21] E. Clarke. Circuit Analysis of AC Power. John Wiley and Sons, 1941.

[22] Egea-Alvarez, A., Junyent-Ferré, A., Gomis-Bellmunt, O. (2012). Active and Reactive Power Control of Grid Connected Distributed Generation Systems. In: Wang, L. (eds) Modeling and Control of Sustainable Power Systems. Green Energy and Technology. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-22904-6_3

[23] R. H. Park. Two-reaction theory of synchronous machines. AIEE Transactions, 48:716–730, 1929.

[24] C. Buchhagen, C. Rauscher, A. Menze and J. Jung, "BorWin1 - First Experiences with harmonic interactions in converter dominated grids," International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age, 2015, pp. 1-7.

[25] K. Sharifabadi, N. Krajisnik, T. Teixeira Pinto, et al., "Parallel operation of multivendor VSC-HVDC schemes feeding a large islanded offshore Oil and Gas grid," in *Proc. CIGRE Session*, Paris, 26–31 Aug. 2018.

[26] C. Zou et al., "Analysis of Resonance Between a VSC-HVDC Converter and the AC Grid," in IEEE Transactions on Power Electronics, vol. 33, no. 12, pp. 10157-10168, Dec. 2018, doi: 10.1109/TPEL.2018.2809705.

[27] M.KoochackZadeh,T.Rendel,C.Rathke,etal.,"Operatingexperience of HVDC links – Behaviour during faults and switching events in the onshore grid," in *Proc. CIGRE Colloq.*, Winnipeg, 30 Sept.–6 Oct. 2017.

[28] Eide, P., Roger Fredheim, Jan Spånberg, Bernt Bergdahl and Lars-Erik., "Simulation of Harmonic Problems in the Kristiansand HVDC Station" (1998).

[29] Friedenthal, S., Moore, A. and Steiner, R., 2015. *A Practical Guide to SysML*. 3rd ed. Elsevier Inc.

[30] 2011. *Modelio*. Paris, France: Modeliosoft.

[31] Mohan, N., Undeland, T.M., and Robbins, W.P., *Power Electronics: Converters, Applications and Design.* John Wiley & Sons, Hoboken, NJ, 1995.

[32] Andersen, B.R., Xu, L., Horton, P., Cartwright, P., "Topology for VSC Transmission." *IEE Power Engineering Journal*, Vol. 16, No 3, pp.142-150, June 2002.

[33] S. Dadjo Tavakoli, E. Prieto-Araujo, E. Sánchez-Sánchez, and O. Gomis-Bellmunt, "Interaction Assessment and Stability Analysis of the MMC-Based VSC-HVDC Link," *Energies*, vol. 13, no. 8, p. 2075, Apr. 2020, doi: 10.3390/en13082075.

[34] H. Rao, "Architecture of Nan'ao multi-terminal VSC-HVDC system and its multi-functional control," in CSEE Journal of Power and Energy Systems, vol. 1, no. 1, pp. 9-18, March 2015, doi: 10.17775/CSEEJPES.2015.00002.