

Review

Overview of HVDC Technology

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Abstract: There is a growing use of High Voltage Direct Current (HVDC) globally due to the many advantages of Direct Current (DC) transmission systems over Alternating Current (AC) transmission, including enabling transmission over long distances, higher transmission capacity and efficiency. Moreover, HVDC systems can be a great enabler in the transition to a low carbon electrical power system which is an important objective in today's society. The objectives of the paper are to give a comprehensive overview of HVDC technology, its development, and present status, and to discuss its salient features, limitations and applications.

Keywords: High Voltage Direct Current transmission (HVDC), Multi-terminal HVDC, Voltage Source Converter (CSC), Voltage Source Converter (VSC)

1. Introduction

Initially one of the reasons AC systems displaced DC was because transformers allowed efficient conveyance of electricity by increasing the voltage for transmission and reducing the voltage to a level needed for utilization. Regardless of whether AC or DC is used there is always a need to use a voltage level appropriate for transmission distance and power being conveyed. HVDC transmission systems have significant advantages over AC transmission, as will be outlined later. The advances in solid-state device, converter topology and control methods has accelerated the deployment of HVDC schemes in recent years. New converter topologies and control systems and advanced in semiconductor technology is increasing the benefits of HVDC systems. Therefore in the foreseeable future the power system will continue to be AC with the penetration of DC systems increasing over time. Not only is DC well established for High Voltage (HV) systems but there is increasing interest internationally in using DC also for medium and low voltage systems (MVDC and LVDC systems) [1].

High penetration of DC systems in AC transmission and distribution networks will provide many benefits to the transition to a low carbon power system. This is particularly true when considering the connection of off-shore windfarms, where undersea cables are required [2]. Moreover, by connecting two AC power systems the best energy resources can be utilized whereas when uncoupled polluting generation resources would have to be used. A number of HVDC schemes were built to allow hydro generation to be exploited rather than using polluting thermal generation to meet the loading.

In the field of power electronics there are numerous converter technologies and a basic classification of AC/DC converters is given in Fig. 1, however, only those more suitable for HVDC will be elaborated upon in this paper. In order to appreciate the historical developments in HVDC a brief review of HVDC technology is given in section 2. Have set the scene the historical background of HVDC systems is presented in section 3. Some of the innovations made to the standard schemes are detailed in Section 4. Section 5 discusses where further developments are needed in HVDC systems. Finally a few concluding comments are made in Section 6.

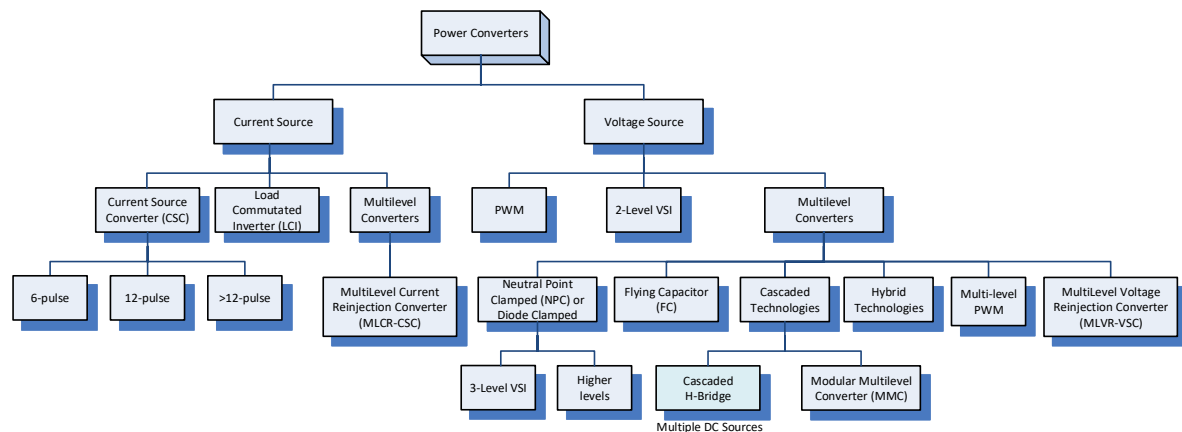


Figure 1. AC/DC Converter classification

The development of HVDC system is of paramount importance in achieve efficient conveyance of electricity, the interconnecting different AC systems, as well as the integration of renewable energy resources [3,4]. The basics of converters are given in various power electronic textbooks [5-12], while references [13-26] are dedicated to various aspects of HVDC transmission systems. The review papers [27-35] are also insightful.

2. HVDC Technology Overview/Background

Before discussing the basic topologies it is helpful to know some of the reasons HVDC is used [36]. These will be elaborated more when discussing the characteristics of the technology.

2.1 Advantages of HVDC

The main advantages of HVDC over HVAC transmission are:

- Asynchronous connection (can connect two ac systems of different frequency)
- Overcome technical limitations. HVDC can supply via a long cable system when an AC system cannot. This is due to the high cable capacitance causing a large capacitive current (reactive power flow) that leaves reduced current capacity for the transmission of real power when AC transmission is used.
- No increase in short-circuit capacity (do not have to upgrade protection equipment due to the link).
- Controllable real power transfer (independent of Z , V & f). Can supply power to any pre-specified criteria (can set the controller to a variety of functions).
- Lower losses (as shown in Fig. 2) [35, 37]
- Higher power transfer for a given conductor.
- No stability distance limitation.
- The lack of reactive voltage drop means better voltage regulation for both heavy loading and light loading (no Ferranti effect).
- Narrower right-of-way (better land use).
- Higher power transfer for a given conductor.
- Advanced control features can improve stability of the ac systems and act as fast generation reserve.

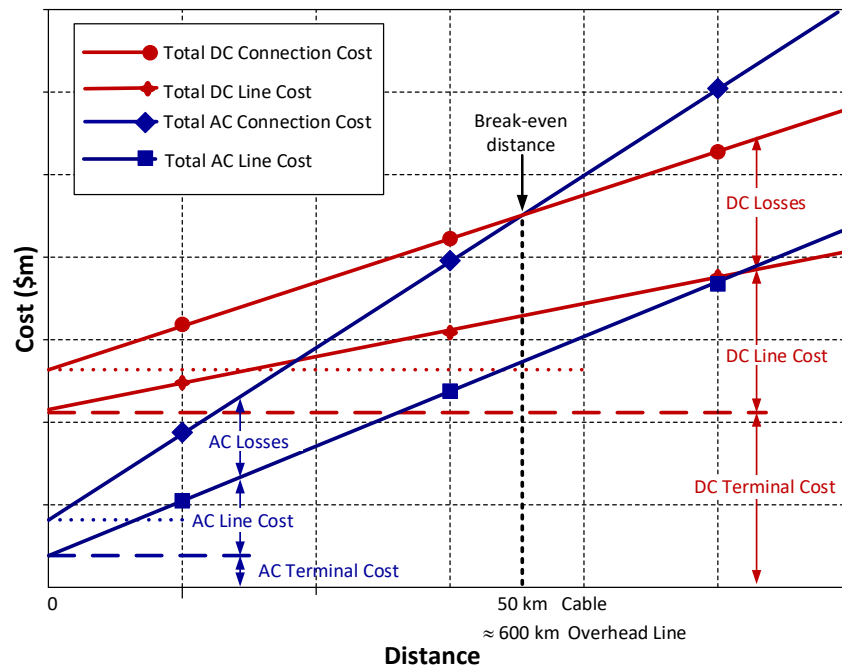


Figure 2. Comparative cost of AC and DC transmission systems

2.2 Power Electronic Switches

The fundamental component in an AC/DC converter is a switch can either be in the “on” (i.e. conducting) or “off” state [38]. The first switches used for HVDC systems were mercury-arc valves. These were replaced by thyristors (shown in Fig. 3(a)). A valve or thyristor is a switch in which turn-on is controlled by a gate pulse but turned-off naturally occurs when the current drops to zero. In other words they cannot be turned-off by a gate signal, and are hence referred to as Line commutated switches. Because of the voltage levels in HVDC schemes one switch in the converter (termed valve for historical reasons) consisted of many thyristors in series.

By contrast Insulated Gate Bipolar Transistors (IGBTs) have the ability to have both their turn-on and turn-off controlled by a gate signal and are termed self-commutated switches (Fig. 3(b)). An anti-parallel free-wheeling diode is usually connected between the emitter to collector to allow bidirectional current flow through the combination. GTO, MCT and IGCT are also self-commutated switches [39].

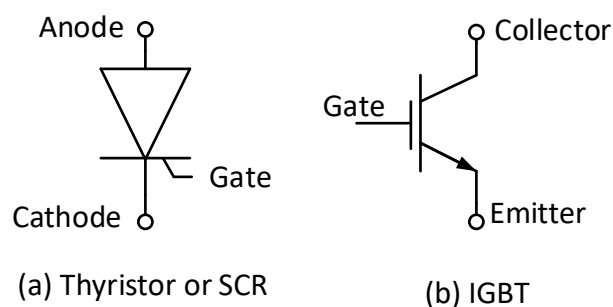


Figure 3. Basic Solid-state switches.

Any figure of device ratings, such as Fig. 4 which displays the voltage current rating of the various devices, quickly becomes out-of-date due to the improvements in technology, nonetheless, it is informative to see the comparative ratings of devices as it gives insight into their application.

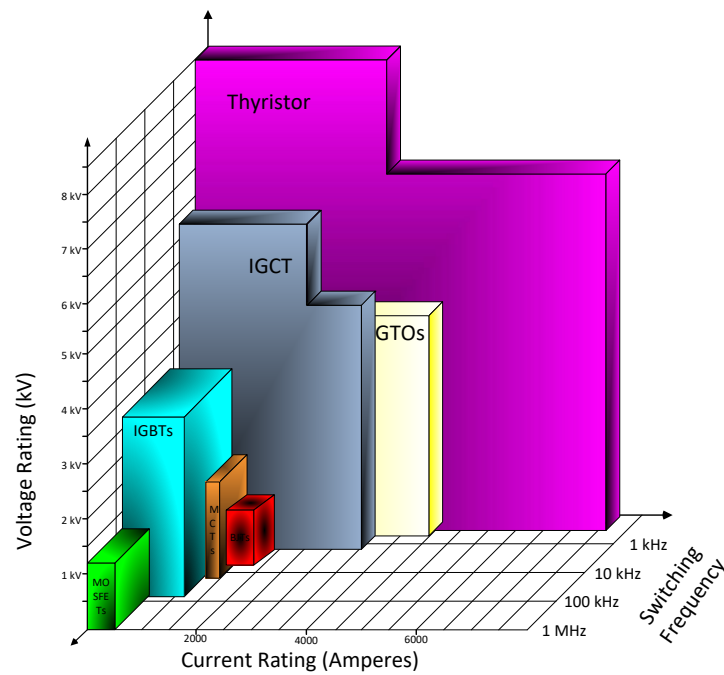


Figure 4. Voltage and current rating of solid-state switches.

2.3 Current Source Converters

Only semiconductor devices with controllable turn-on are required as they naturally turn off when the current drops to zero due to turning on the next device on the same side of the converter. This commutation process depends on the AC system's voltages and impedances and hence are also frequently referred to as Line Commutated Converters (LCC) [16]. Fig. 5 illustrates the DC voltage (V_{dc0}) that results from the converter conversion process. To match ideally a level DC voltage (V_{dc}) a DC smoothing reactor is necessary [16]. This large DC reactor makes the converter current stiff and hence the term Current Source Converter (CSC).

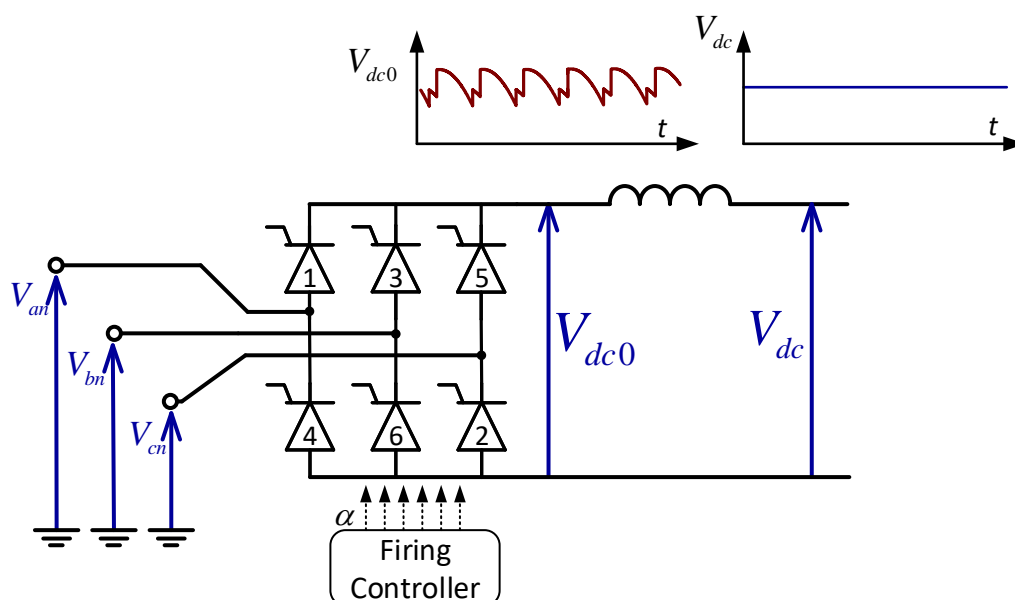


Figure 5. A 6-pulse (Graetz) bridge as a Current Source Converter (CSC).

2.4 Voltage Source Converters

In a Voltage Source Converter (VSC) the capacitance on the DC side ensures that the voltage is stiff. To limit the current due to the mismatch between the AC system voltage and voltage from the

converter, an ac side inductor is used. This is illustrated in Fig. 6. Ignoring the harmonic components the real and reactive power conveyed to the AC system is given by:

$$P = \frac{V_{ac} V_{ac0}}{X} \sin(\delta)$$

$$Q = \frac{V_{ac}}{X} (V_{ac0} \sin(\delta) - V_{ac})$$

Where X is the interfacing reactor and δ the angle between the voltages on either side of the reactor. The switches for this type of converter must be self-commutated and have the ability to control the time instance of turn-on and turn-off, which increases the flexibility of this converter.

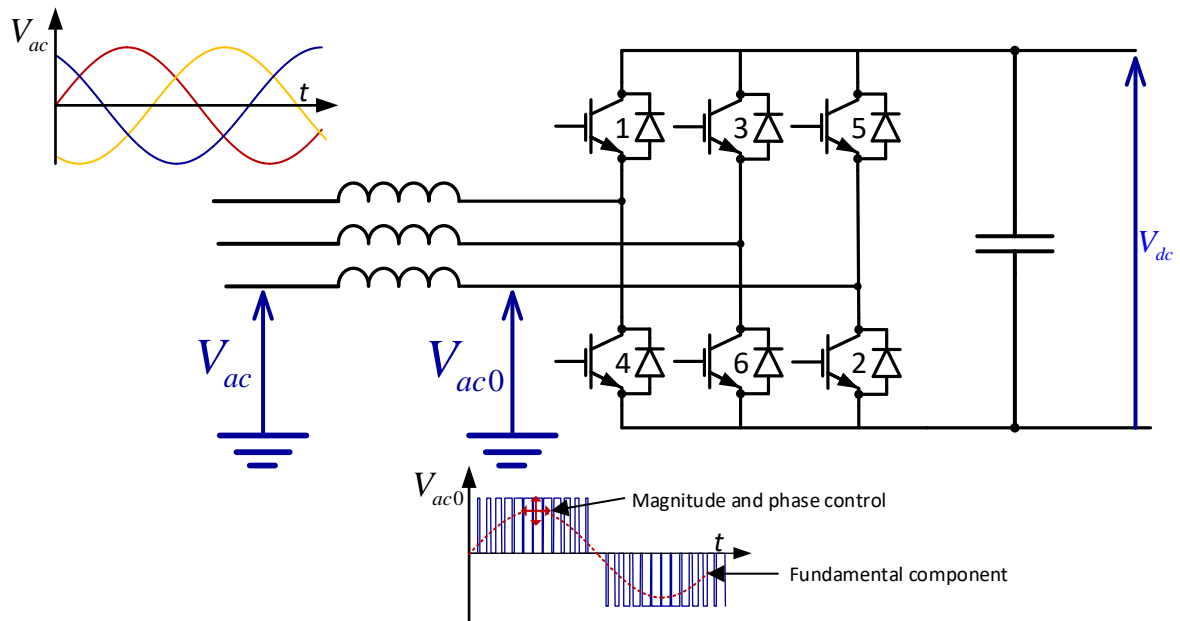


Figure 6. A self-commutated 6-pulse bridge as a Voltage Source Converter (VSC).

2.5 Topologies

For current source converters, normally each converter comprises of two 6-bridges connected in series on the DC side and the AC supplied from transformers with different winding configurations as shown in Fig. 7. This gives harmonic cancellation of some harmonic orders and reduces the filtering requirements. Similarly, two 6-pulse VSC can be connected in series on the AC side and parallel on the DC side to form a 12-pulse VSC converter, however, multilevel topologies are normally favoured.

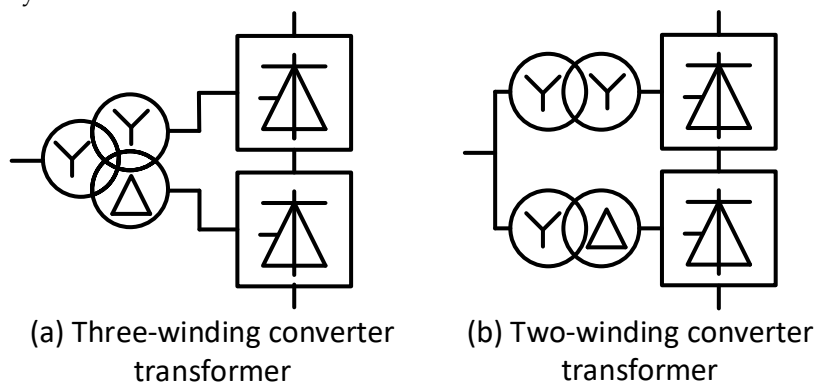


Figure 7. Two 6-pulse bridges forming a 12-pulse CSC.

The simplest topology is a back-to-back scheme as there is no transmission distance. This is used to connected two AC systems asynchronously when their frequencies differ or when the fault level precludes a more direct AC interconnector. The next is the monopole. The return path may be metallic (through a conductor) or to reduce costs an earth or sea return can be used. The problem with a monopole scheme as any malfunction will see the loss of all the capacity. A bipole scheme such as illustrated in Fig. 8 gives increased reliability as a fault in one pole will see only half the transmission capacity. The centre point of the converters may be connected via a conductor, however, since it is only used when a fault occurs an earth or sea electrodes are often used and the return path is through the earth/sea. Fig. 9 displays the current path for normal and when forced and planned outages occur on a bipole HVDC scheme.

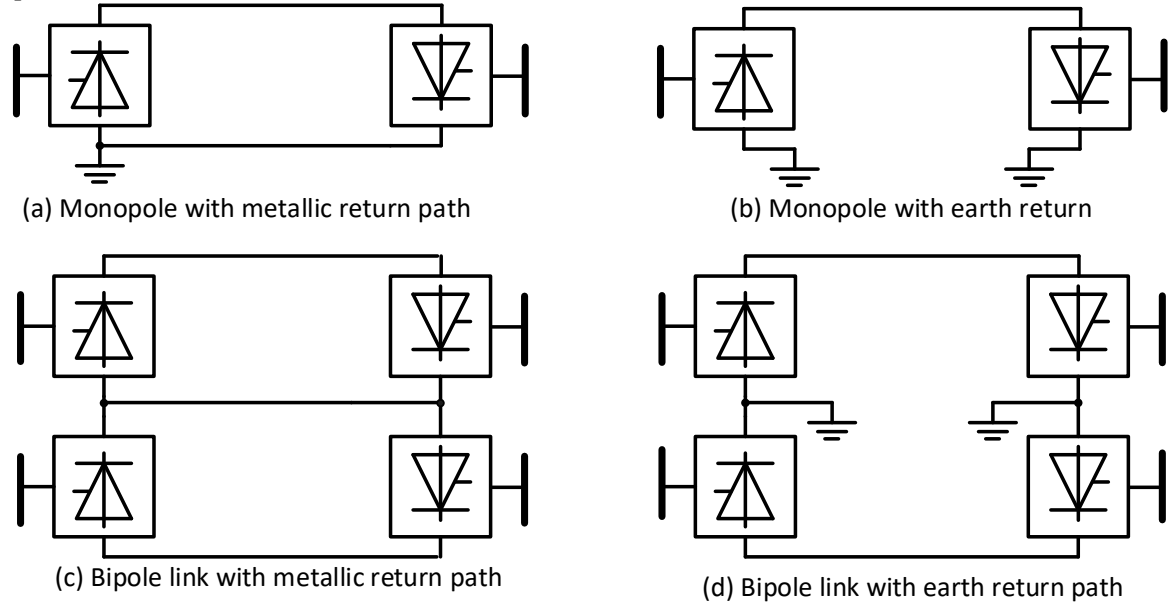


Figure 8. Monopole and Bipole HVDC Schemes

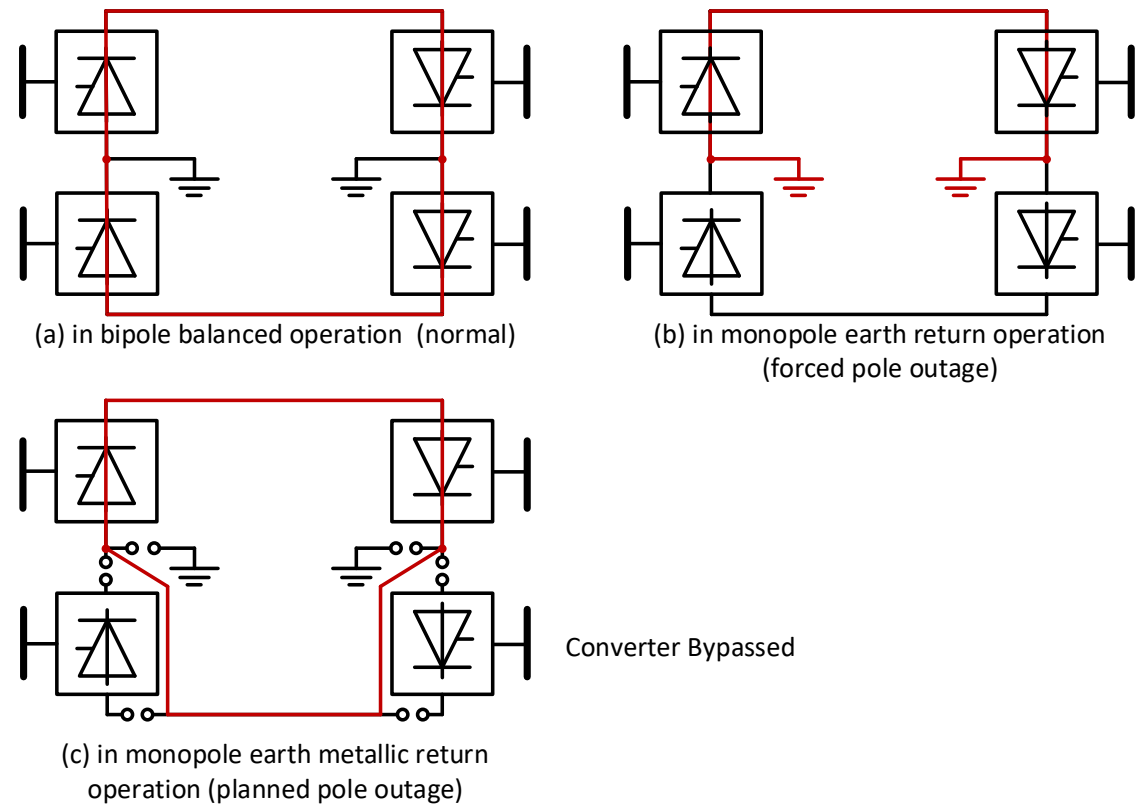


Figure 9. Bipole HVDC Scheme operating states

A number of configurations have been proposed for when the generation resources are far from the load and there is no local load. This removes the need for harmonic filter requirements. Unit-connected scheme is where there is a generator/transformer/converter connected as shown in Fig. 9 and Group-connection reduces the cost by sharing a transformer(s) [40–42]. Although at one time there was considerable interest in these schemes their efficiency, and dependency of the DC voltage on the number of generators running (Unit-connected), has resulted in these schemes not being progressed.

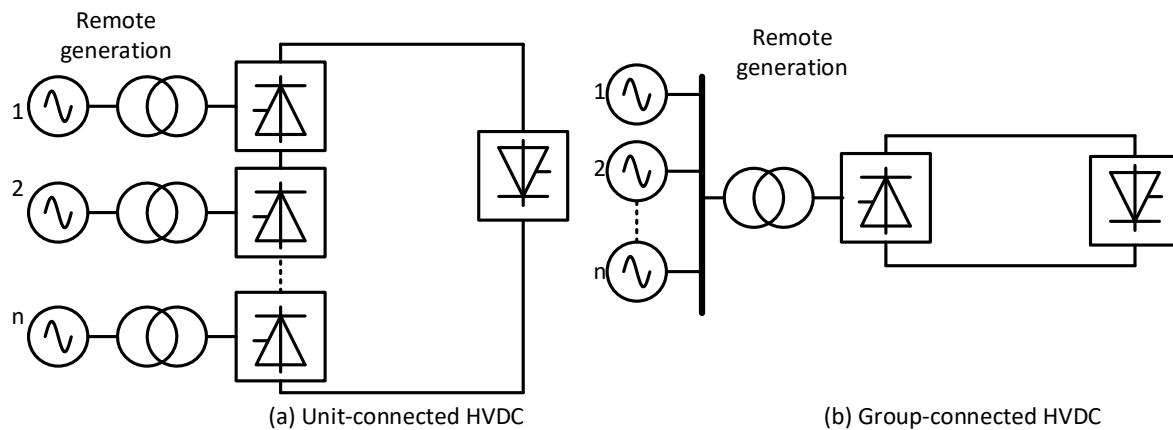


Figure 9. Unit and Group Connected HVDC schemes

The ability to exchange power between more than two places has resulted in multiterminal HVDC schemes [39]. The converters could be either be connected in series or parallel, as illustrated in Fig. 10. One of the biggest challenges is control and coordination of such schemes.

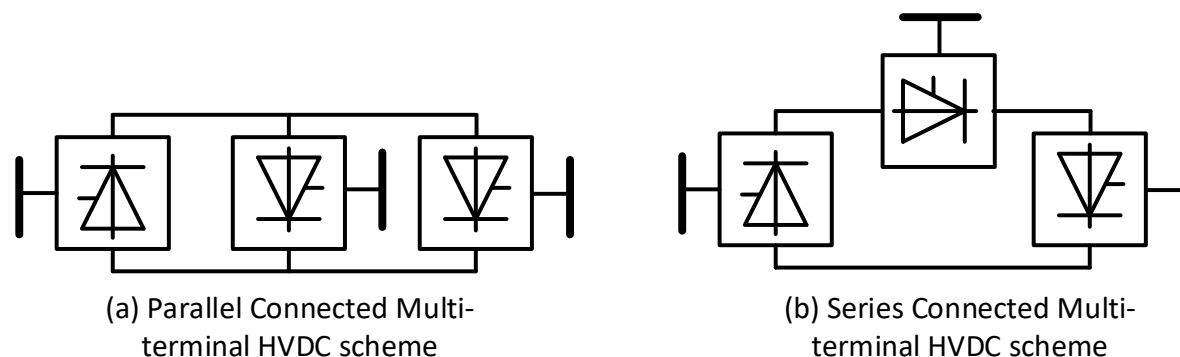


Figure 10. Multiterminal HVDC schemes

3. Comparison of Current Source and Voltage Source Converters

3.1 Introduction

Having seen the basic operation of current source and voltage source converters the main distinctions will be elaborated on, as these will influence where each is best suited.

3.2 Current Source Converters

The characteristic AC current harmonics of the 6-pulse bridge of Fig. 3 are $h = 6n \pm 1, n = 1, 2, 3, \dots$ and their magnitude under ideal conditions is given by $|I_h| = |I_1|/h$. As previously mentioned, with the two 6-pulse bridges connected together using different transformer winding configuration causes the following harmonic orders to cancel $h = 6n \pm 1, n = 1, 3, 5, 7, \dots$. The characteristics AC harmonic currents are therefore $h = 12n \pm 1, n = 1, 2, 3, \dots$ and on the dc side the

DC harmonic voltages $h = 12n, n = 1, 2, 3, \dots$. Thus harmonic filtering is needed both on the AC and DC side [43-46]. The AC current waveform of each converter -transformer and the combined waveform (I_{ac}) is displayed in Fig. 11.

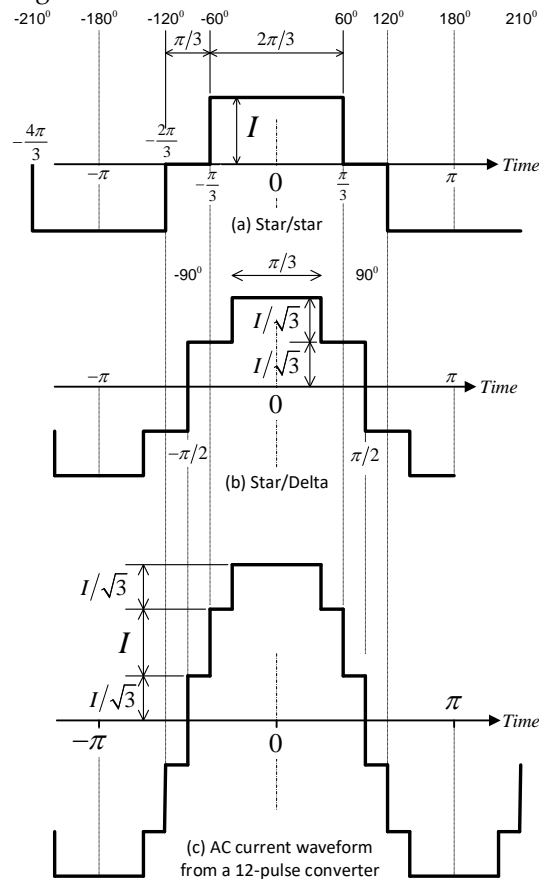


Figure 11. AC Current Waveforms of two 6-pulse bridges and the 12-pulse converter formed from the two.

The numbering of the thyristors in Fig. 5 show their firing order. Each thyristor conducts for 120 electrical degrees. The voltage across the thyristor becomes positive when the appropriate phase-to-phase voltage zero crossing occurs and the firing angle is the delay between this point and when the thyristor receives a gate turn-on pulse. The thyristor only turns off what the current drops to zero (actual below its latching current) and this is achieved by firing another thyristor with a higher phase voltage. This is illustrated in Fig. 12 for a commutation from thyristor 1 to 3 (thyristor 2 is already conducting). Commutation from 1 to three is only possible while phase Y is greater than phase R (between T_1 and T_2 in Fig. 12). The extinction angle is the angle between when a thyristor stops conducting and the next zero-crossing when commutation can no longer occur. Hence $\gamma = 180 - (\alpha + \mu)$. The maximum firing angle is limited by the need to allow for the thyristor to re-establish its blocking ability and a margin to allow for natural voltage and current perturbations that occur in the system. If the commutation from thyristor 1 to 3 has not been completed fully by T_2 then Thyristor 1 will pick up the current again and hence commutation failure has occurred. The term Line-Commutated Converter (LCC) is often used for CSC as it indicates that the conversion process relies on the line voltage of the AC system to which the converter is connected in order commutation from one thyristor to the next.

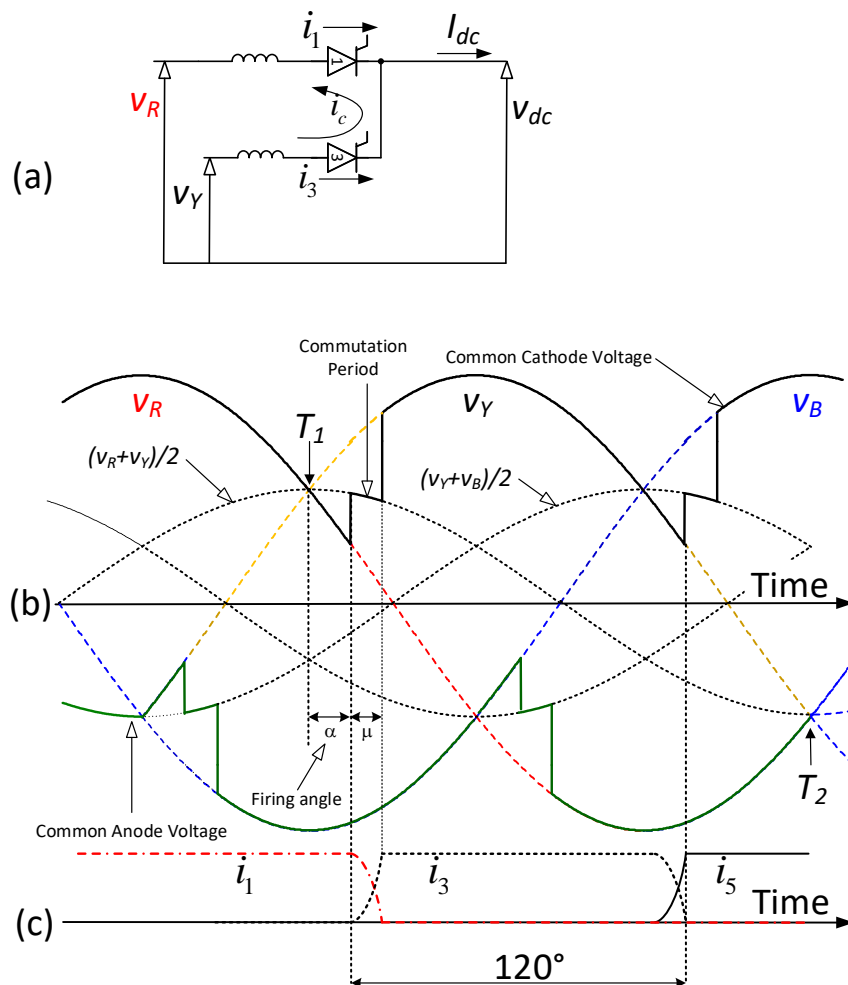


Figure 12. The commutation process in a 6-pulse bridge (a) Equivalent circuit for commutation between thyristor 1 and 3 (b) Voltage waveforms (rectification) (c) the current waveforms.

Only two quadrant operation (P versus Q) is possible, with the CSC always requiring reactive power regardless whether rectifying or inverting. The reactive power required is approximately proportional to $\sin(\alpha)$ therefore an On-Load Tap Changer (OLTC) is normally provided on the converter transformer to minimize the firing angle when rectifying (or extinction angle for inversion) to minimize the reactive power required by the converter. The harmonic filters required to improve the AC current waveforms also perform the dual purpose of supplying some of the reactive power required by the converter [43].

3.2 Voltage Source Converters

Table 1 provides a comparison between VSC based and CSC based HVDC Systems [36]. Clearly when the AC system is weak or passive and/or independent control of real and reactive power is required VSC is preferable [36]. For the transmission of bulk power over long distances the CSC based HVDC system, with its lower losses has the advantage. The VSC based HVDC is improving with a decline in losses per converter over time: 3% (Gotland, 1997), 2.2% (Eagle Pass, 2000), 1.8% (MurrayLink, 2002), 1.4% (Estlink, 2006), 1% (Trans Bay, 2010, Superstation, 2014 & Dolwin 2, 2015). This is compared with a typical loss of 0.7% for CSC based HVDC [31].

Voltage Sourced Converter (VSC) topologies for HVDC power transmission either use 2 or 3-level converters with Pulse Width Modulation (PWM), multilevel topology to achieve a better waveform with lower losses or a hybrid [28]. The use of 2 or 3-level converters requires series strings of semiconductor devices (IGBTs) to form one switch and switched together to achieve the required voltage and power ratings. Multilevel converters connect individual bridges or cells in series and

avoid the need to simultaneously switch a large string of series IGBTs. This is because each cell is switched at a different time and a lower voltage is switched. This section will review the main topologies used for HVDC transmission and their characteristics.

Table 1. Comparison of CSC based LCC and VSC HVDC systems

Title 1	LCC HVDC	VSC HVDC
Store energy in	inductance	capacitance
Semiconductor	withstand voltage in either polarity	Combination can pass current in either direction
Semiconductor switch	turned ON by control action	turned ON & OFF by control action
DC Voltage	changes polarity reserves the power flow direction	Direction does not change
DC Current	direction does not change	direction changes to reverse the power flow
Turn-OFF	commutation relies on the external circuit	independent of external circuit
P & Q	P & Q dependent	independent P & Q control
Quadrants	2 quadrant operation	4-quadrant operation
Real Power capability	Very High	Lower than LCC
System Strength	Requires minimum SCR to commutate thyristors	Operates into weaker AC systems (or passive)
Overload capability	Good	Weak
DC line faults	Copes well. Control action can extinguish arc	More challenging as diodes provide path.
Harmonic generation	Significant, AC & DC harmonic filters required	Small, minimal filtering required.
Reactive power	Needed	Fine reactive power control in both directions
“Black” start	requires additional equipment	capable

The basic 6-pulse VSC is displayed in Fig. 13. The switches are power electronic devices, such as IGBTs, which conduct in one direction and the timing of the both turn-on and turn-off are controllable. If a fundamental frequency switching is performed then the waveforms displayed in Fig. 14 are obtained.

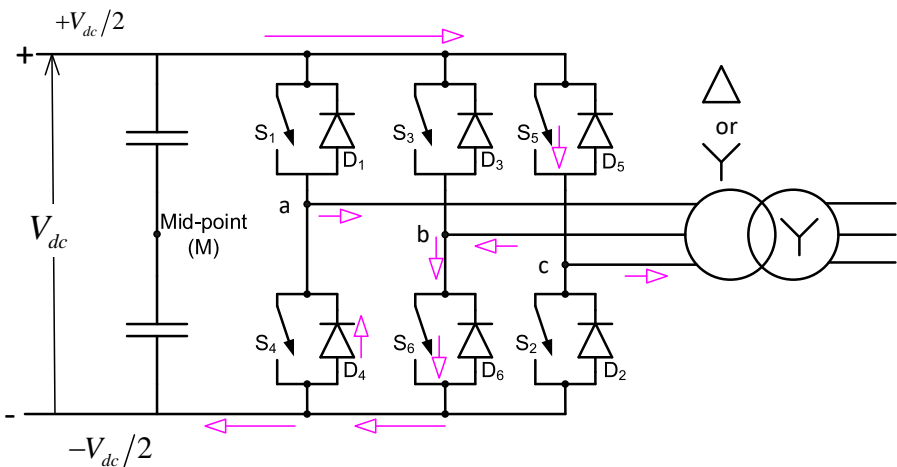


Figure 13. Basic 6-pulse VSC

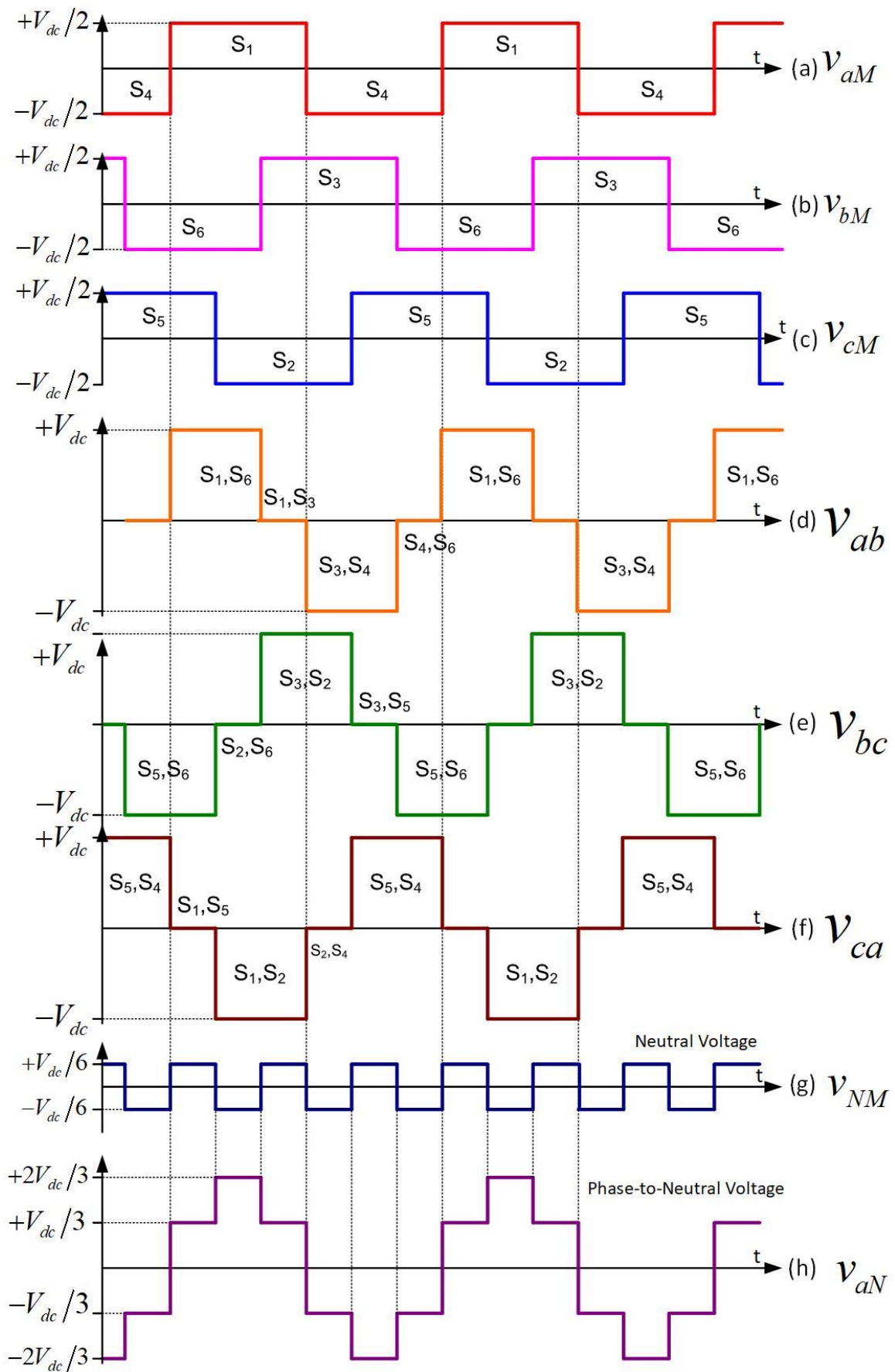


Figure 14. Voltage waveforms for the basic 6-pulse VSC using fundamental frequency switching. Waveforms (a),(b) & (c) phase-to-DC-midpoint voltages; waveforms (d),(e) & (f) Phase-to-phase voltages

However, the real benefit of using devices with turn-off ability is the ability to use Pulse Width Modulation (PWM) techniques. To illustrate PWM consider one arm of a converter, shown in Fig. 15. Depending on which devices are conducting, the output voltage (between voltage at the mid-point of the arm and DC mid-point of the capacitors) is either $V_{dc}/2$ or $-V_{dc}/2$. To improve the output voltage waveform the periods of $V_{dc}/2$ or $-V_{dc}/2$ would be modulated to approximate a sinewave. In sinusoidal PWM a triangular or carrier waveform is compared for a sinusoidal control/reference signal and the devices are switched when they cross as illustrated in Fig. 16. Note there are two control variables, amplitude (by changing the modulation index, M_a) and phase angle (ϕ) (by changing the control sinusoidal phase angle) and this allows independent control of the real and reactive power transferred to/from the AC system. In theory the operational area in a P/Q diagram is circular, however, constraints on voltage and current modify this shape as illustrated in Fig. 17, which shows the four quadrant operation of typical VSC in a PQ diagram [49]. In Fig. 18 the single-phase PWM of Fig. 16 is expanded to show three-phase PWM and the resulting phase-to-phase voltage waveform. PWM can also be used in multilevel converters, with a lower switching frequency required with more levels.

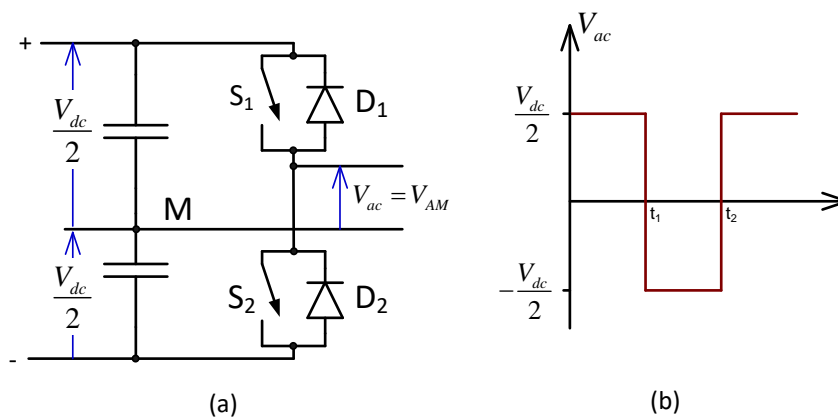


Figure 15. One arm of the basic 6-pulse VSC.

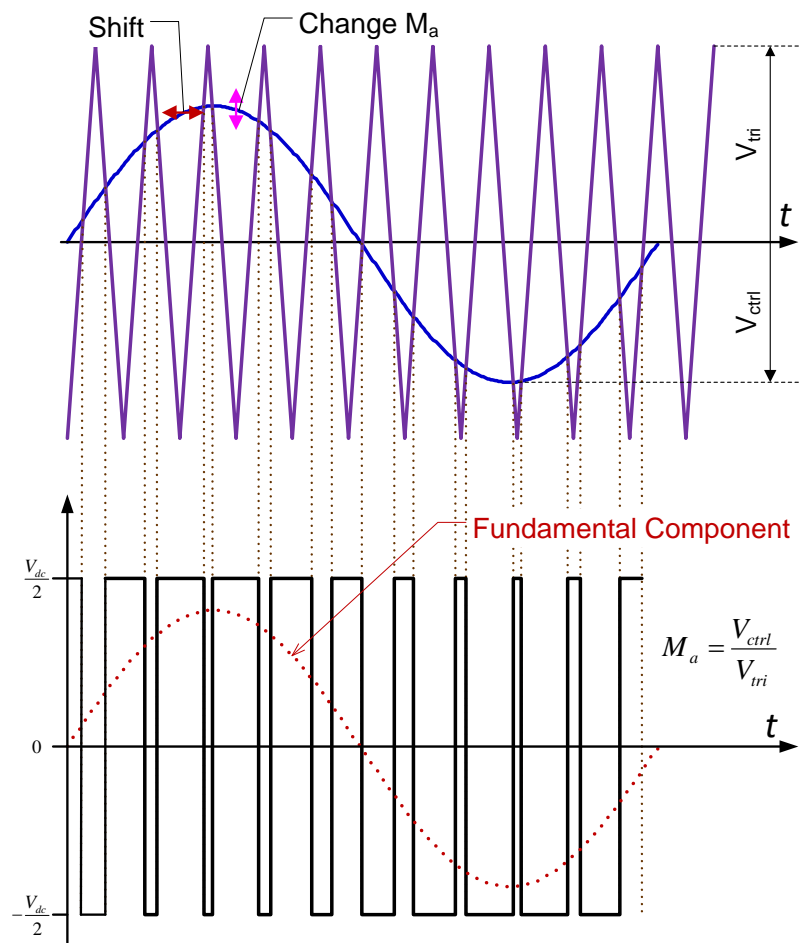


Figure 16. Sinusoidal Pulse Width Modulation (PWM).

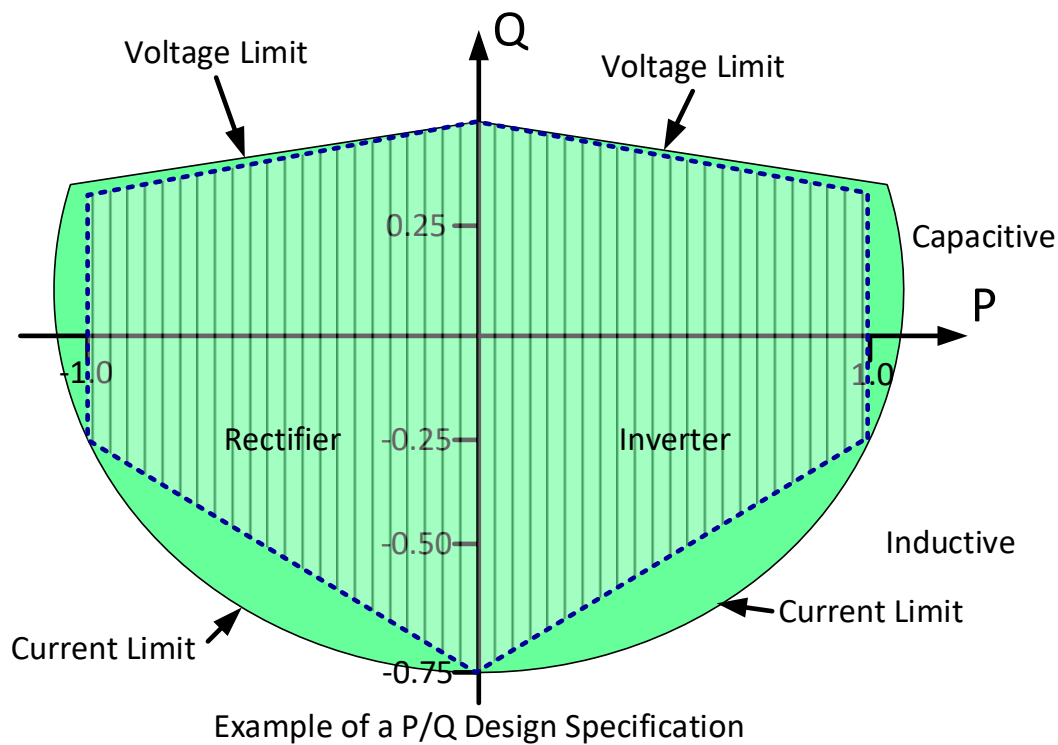


Figure 17. PQ diagram of VSC operating area.

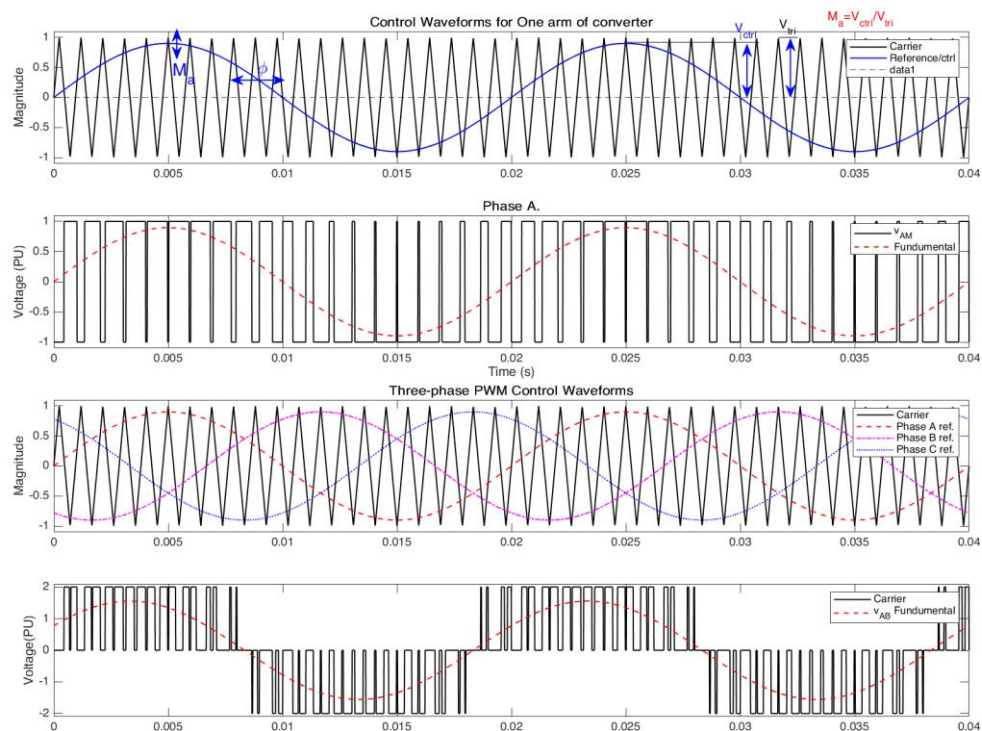


Figure 18. Three-phase PWM

There is a trade-off between waveform distortion and losses as the higher the switching frequency the better the waveform but the higher the losses [50]. Various refinements to the standard sinewave PWM have been made to achieve different objectives. For example rather than a pure sinewave control waveform a zero third-harmonic component is added to the sinusoidal reference voltage, as illustrated in Fig. 18. This reduces peak AC converter voltage in order that, an approximately 15% increased AC-side fundamental-frequency voltage is available with the same DC voltage. The Cross Sound Cable HVDC system uses this while MurrayLink does not [51]. Other optimized PWM schemes have been developed. For example minor non-linearities in the valve switching can create low-order harmonics. To prevent their amplification, a special controller has been designed to act on the PWM pattern in order to minimize the low order (5th and 7th) harmonic currents [52]. If the converter is near to generators there may be a need for sub-synchronous damping control [53]. AC and DC filtering is normally provided [54, 55].

Another way to improve the waveforms is to use a multilevel topology. Some of the multilevel converters topologies are:

1. Neutral-point clamped circuit (also called a diode-clamped circuit)
2. Flying Capacitor
3. Cascaded H-bridge
4. Modular Multi-level Converter (MMC)

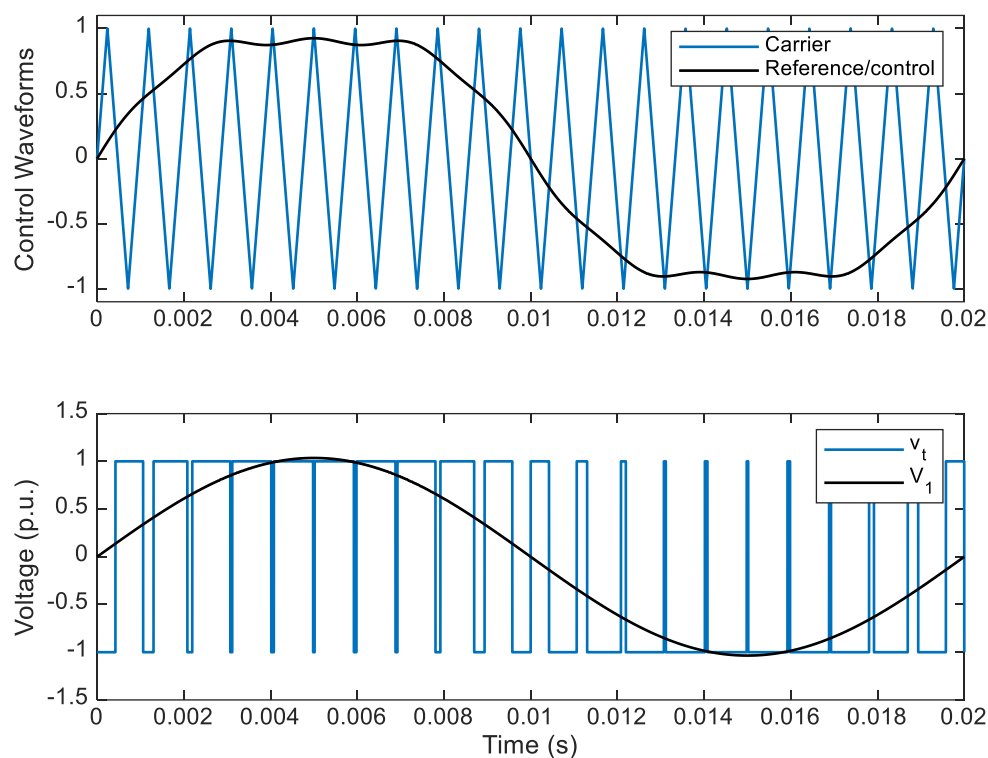


Figure 18. PWM with 3rd and 9th Harmonic

The cascade H-bridge and Flying capacitor converters each have features that discourage their use at high voltage and power levels. The 3-Level Neutral-Point Clamped (NPC) converter, shown in Fig. 19, is a more suitable topology for such applications [56]. One of the issues is the asymmetric loss distribution in the semiconductor devices and the Active Neutral-Point Clamped (A-NPC) converter overcomes this deficiency and has been used in HVDC schemes [57,58].

The Modular Multi-level Converter (MMC), displayed in Figs. 20 & 21, was introduced to the world in 2003 [59] and now widely adopted due to its many advantages. Some of these advantages are the modular design, making it scalable to different voltage and power levels, and multilevel waveform expandable to any number of voltage steps, low total harmonic distortion and low losses [60–62]. For these reasons it is very well suited for many applications such as HVDC. Note that

- Circulating currents are inherent in the MMC topology.
- These currents cause variations in the capacitor voltages and increase converter losses.
- Capacitor voltages variations increase with increase in load current and circulating currents.

To aid understanding the MMC's operation Fig. 22 displays the output voltage from one phase of the MMC and Fig. 23 the corresponding arm switching pattern for a given output voltage.

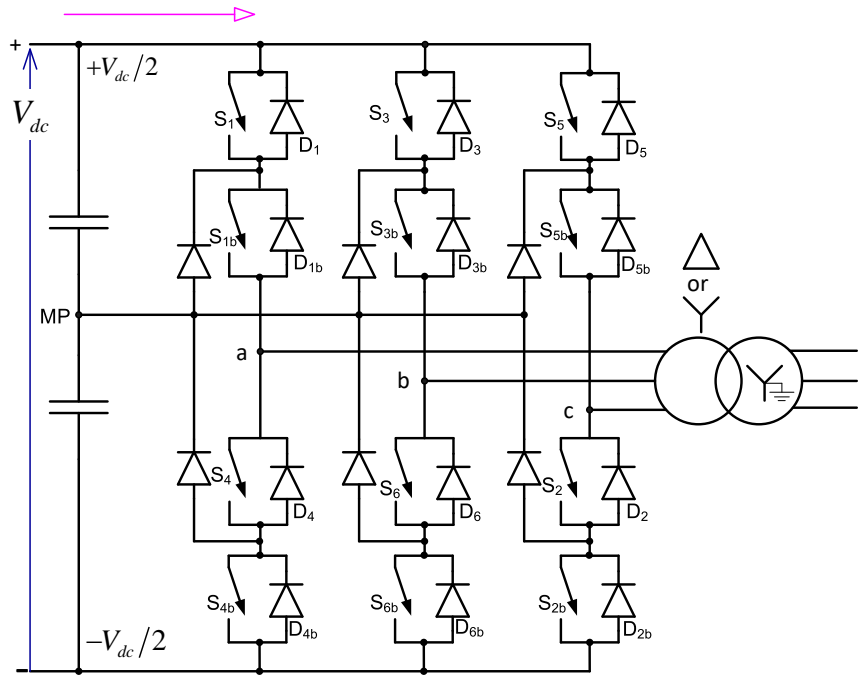


Figure 19. 3 Level Neutral-clamped converter.

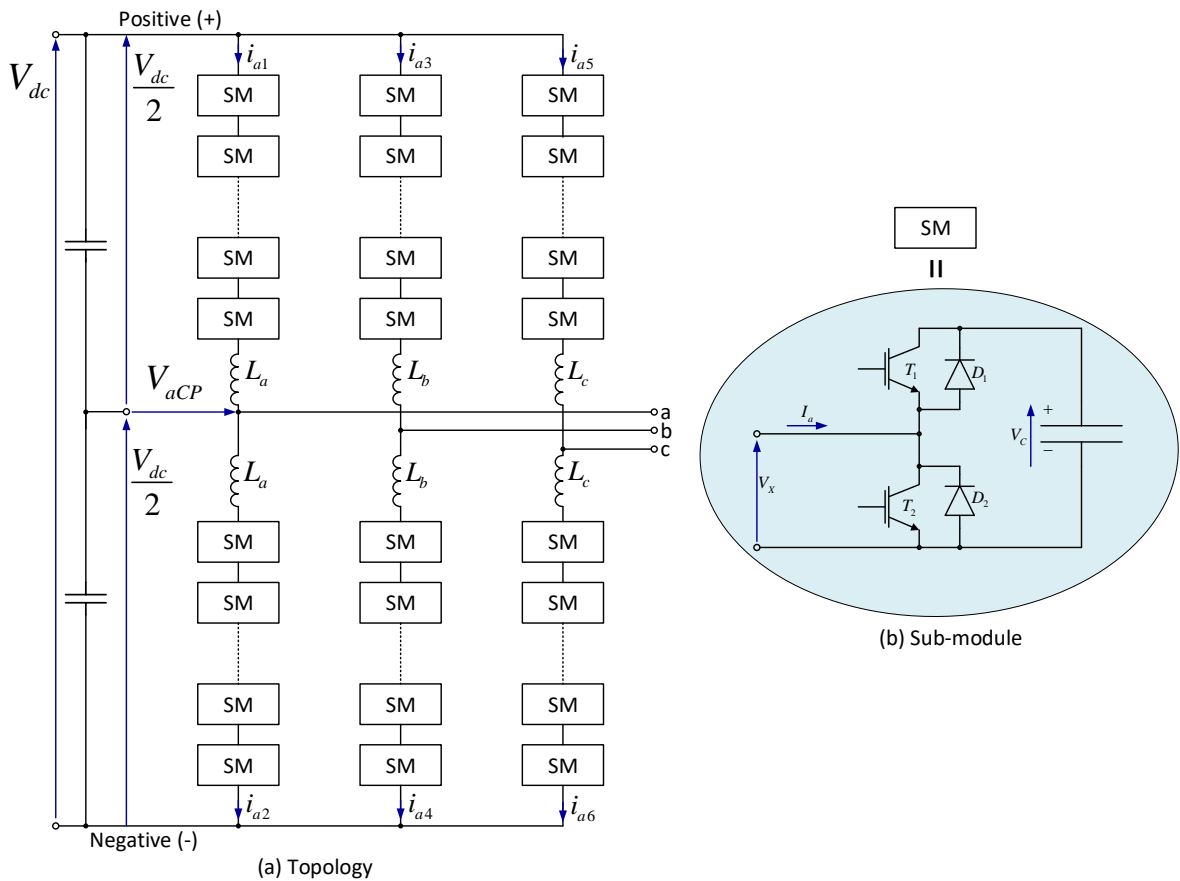


Figure 20. Multilevel Modular Converter (MMC).

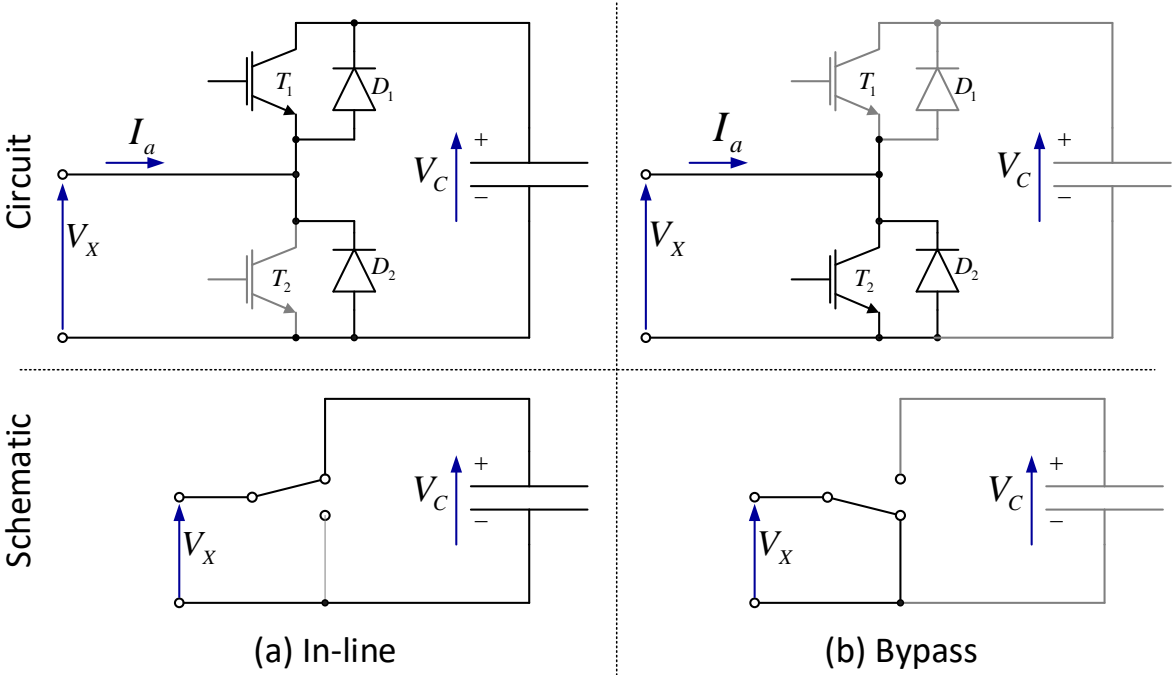


Figure 21. Sub-module Operation

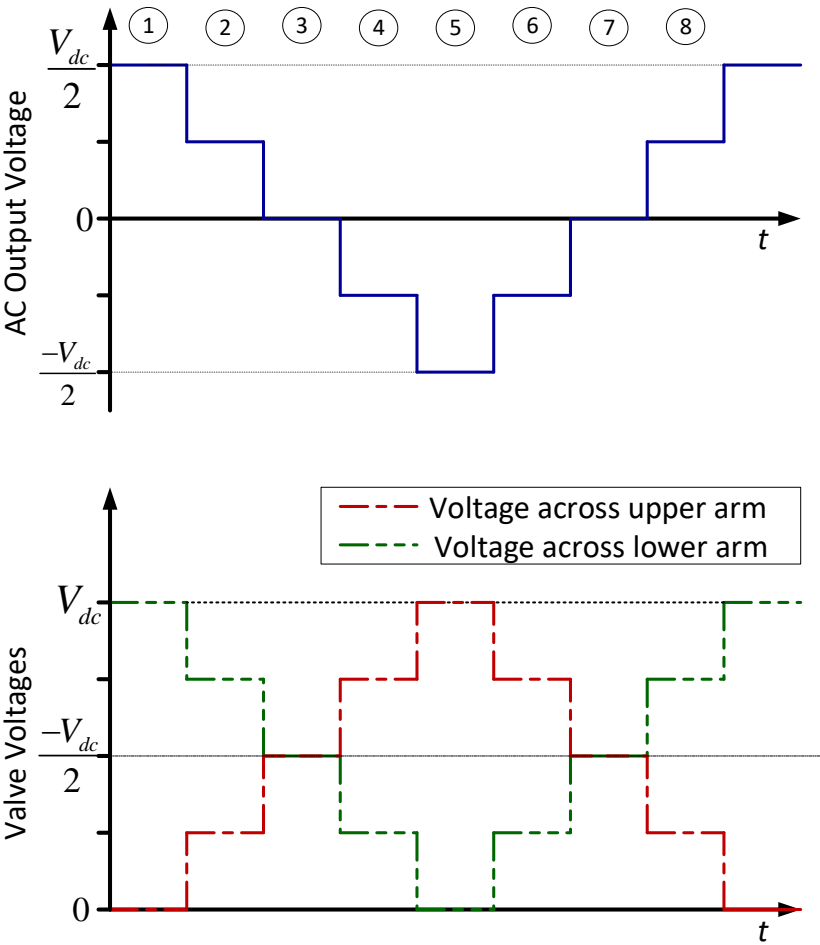


Figure 24. Output voltage (fundamental frequency switching).

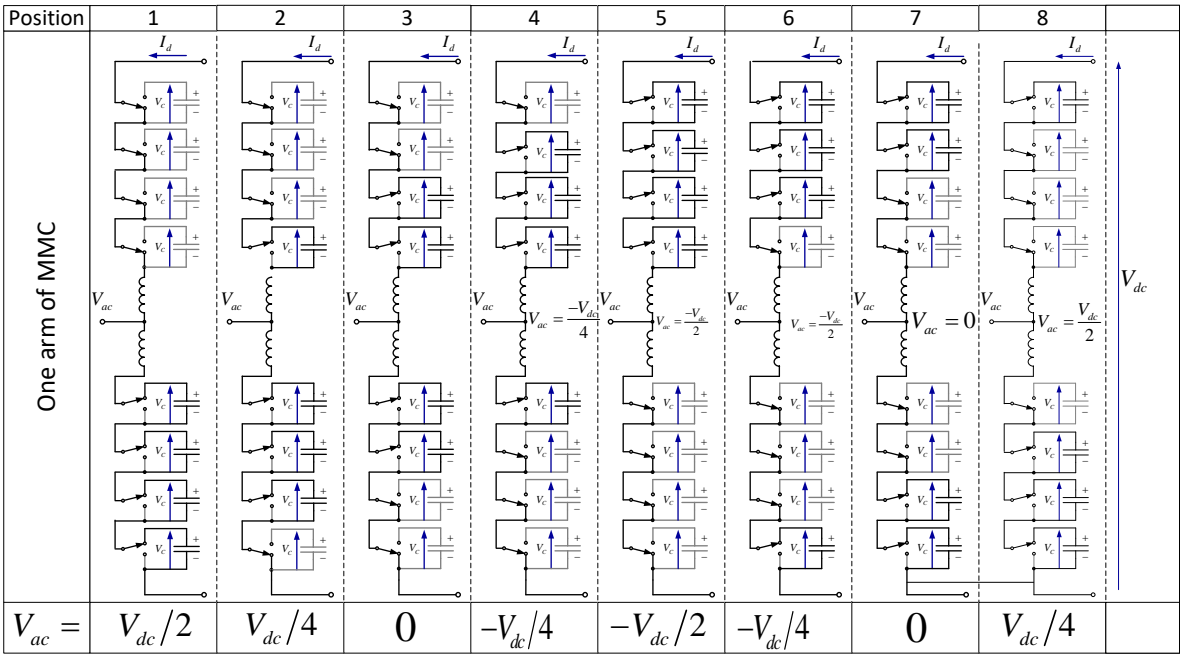


Figure 23. Arm switching pattern for a given Output voltage.

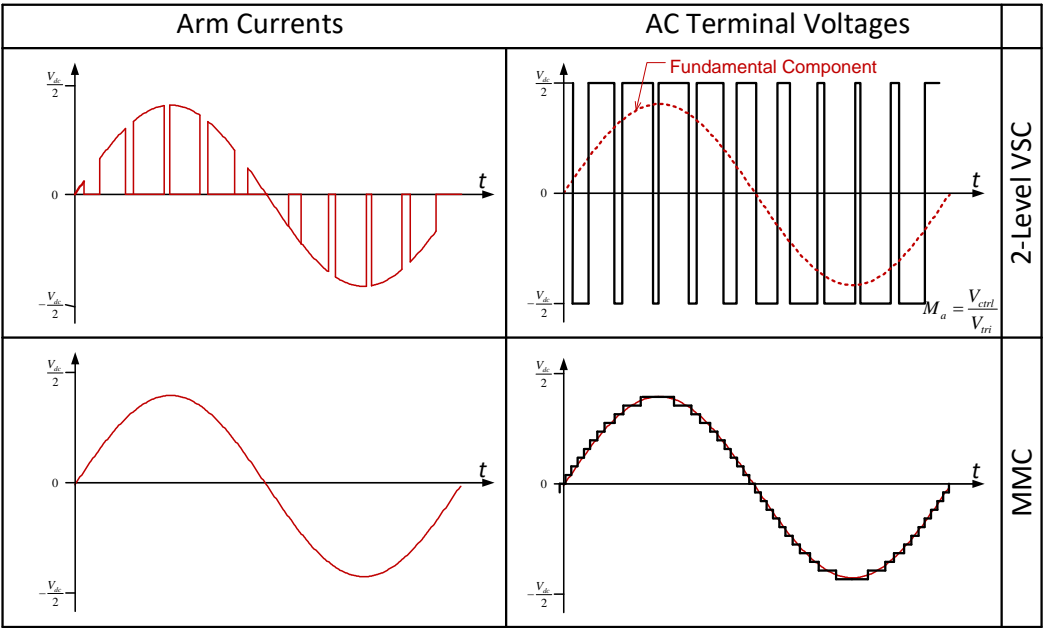


Figure 24. Output voltage (fundamental frequency switching)

Figure 25 displays a generic converter station for a VSC based HVDC link. The details will vary and depending on the local requirements and conditions, not all the components may be needed. In particular the filtering on the AC and DC side will be custom designed to meet the limits imposed, the converter's emission characteristics (influenced by switching frequency and modulation technique) and the characteristics of the AC and DC systems it is connected to. These also influence the design of the converter controller. As an example, Fig. 26 shows the converter station for the MurrayLink.

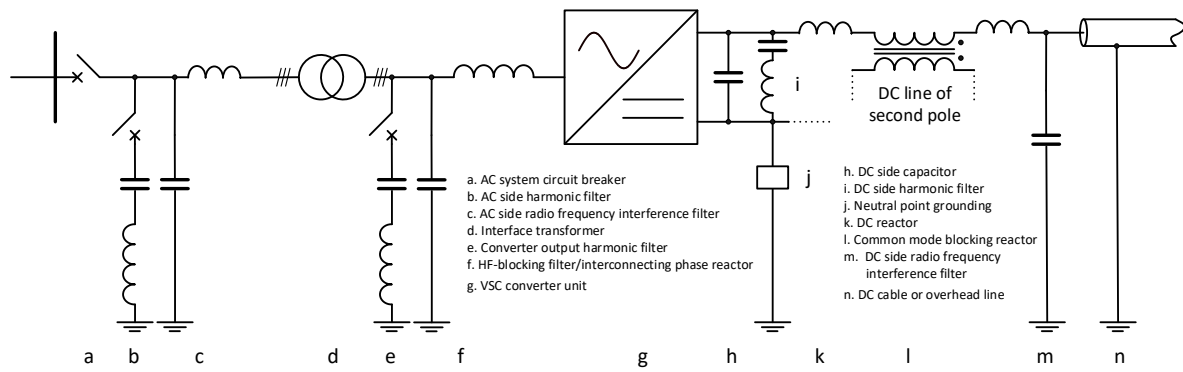


Figure 25. Generic VSC HVDC Converter Station

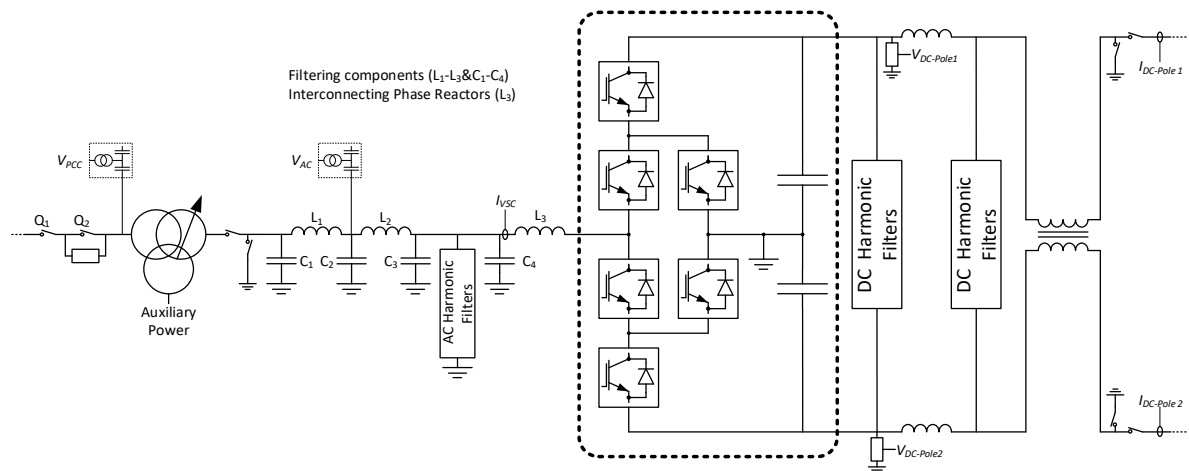


Figure 26. Murray Link VSC HVDC Converter Station

3. Historical Development

Although there were earlier experimental HVDC systems the first commercial system was the 20 MW Gotland Island scheme commissioned in 1954. This LCC HVDC system used mercury-arc valves. In 1970 the first use of thyristors in a commercial HVDC link (Gotland Island) began. The last and largest mercury-arc based HVDC scheme was the Nelson River scheme commissioned in 1971. The delivery of bulk power over distance through overhead line or cables, and the cable technology made HVDC the best option. To overcome low system strength synchronous condensers were installed to aid commutation.

The improvements in IGBT technology allowed the VSC based HVDC schemes to be commissioned with the first being the 50 MW link to Gotland Island in 1999 [63]. This was quickly followed by DirectLink Interconnector (Australia) in 2000 which interconnected two states (Queensland and New South Wales) [64]. Due to the limitations of the technology at the time this consisted of three 60 MW VSC links in parallel. VSC HVDC was chosen due to its low environmental impact and ability of converter stations to accurately control both real and reactive power. The Tjæreborg (Denmark) VSC based HVDC scheme was also commissioned in 2000. It was demonstration of using VSC HVDC for connecting a windfarm. Its rating was 7.2 MW. The MurrayLink connector between Berri (South Australia) and Red Cliffs (Victoria) was at 180 km the longest underground HVDC transmission system. It was commissioned in 2002 [51]. The Trans Bay Cable HVDC scheme completed in 2010 was the first system to use the MMC technology [65]. HVDC based on VSC was quickly adopted for supplying power to off-shore platforms and delivering power from off-shore windfarms. A HVDC link was commissioned to Troll A Off-shore platform (1st and 2nd lines) in 2005. BorWin1 the first commercial HVDC scheme for importing power from an off-shore wind-farm (using two-level PWM) and was commissioned in 2009. There was a rapid development in wind-farms in this period and 2015 saw the commissioning of BorWin2 in 2015 (MMC), HelWin1

(MMC), HelWin2, DolWin1 (using a Cascaded Two-Level Converter [66]). Besides the need for VSC based HVDC for cable systems, interconnections between countries or states are often at the extremities of their grids and hence electrically weak. The ability to independently control P and Q and feed a weak system does favour VCS systems. INELFE (Electric France-Spain Interconnection) uses an MMC topology. With the increase in variable renewable energy (primarily wind) the interconnection enables more optimal use of energy from renewable sources as well as improve security of supply.

The first Multiterminal HVDC scheme was the three terminal Italy–Corsica–Sardinia scheme (known as SACOI). This started as a two-terminal LCC HVDC scheme between the Italian mainland and the island of Sardinia. A tapping from this was made in 1988 to allow up to 50 MW bidirectional power flow from the island of Corsica possible. Similarly the second multiterminal HVDC scheme, Quebec – New England Transmission, which starts from Radisson Substation (Quebec) to Sandy Pond in Massachusetts (USA). In 1992 a third converter station at Nicolet was commissioned to tap off power to supply the Montreal area. Both of these schemes use LCC HVDC. VSC based HVDC is better suited for multiterminal operation and well suited for cable systems since the polarity of the DC voltage does not change. Zhoushan Islands HVDC five-terminal voltage source converter project 2014 [67]. The four-terminal North-East Agra UHVDC system was commissioned in 2017.

A summary of the salient features of LCC based HVDC is given in Table 2 and those for VSC based HVDC schemes in Table 3.

Table 2. Selected HVDC Schemes using Line-Commutated Converters [68].

Name	Year	Technology	Length	DC Voltage (kV)	Power Rating P (MW)
			Cable/OHL		
Gotland 1	1954	Mercury-arc	98/0	200	20
Cross-Channel	1961	Mercury-arc	64/0	±100	160
NZ Inter-Island 1	1965	Mercury-arc	40/571	±250	600
SACOI ¹	1965	Mercury-arc	365/118	±200	200
Konti-Skan 1	1965	Mercury-arc	87/89	±250	250
Zhoushan	1987	Mercury-arc	54	-100	50
Vancouver Isl. 1	1968	Mercury	42/33	260	312
Pacific DC Intertie	1970	Thyristor	0/1362	±500	3100
Nelson River Bipole 1 ²	1977	Mercury-arc	0/895	±450	1620
Skagerrak 1	1977	Thyristor	130/100	±250	500
Cahora Bassa ³	1979	Thyristor	0/1420	±533	1920
Hokkaido – Honshu	1979	Thyristor	44/149	±250	300
Zhou Shan ⁴	1982	Thyristor	44/149	+100	50
Itaipu 1	1984	Thyristor	0/785	±600	3150
Nelson River Bipole 2	1985	Thyristor	0/940	±500	1800
Itaipu 2	1987	Thyristor	0/805	±600	3150
Fenno-Skan	1989	Thyristor	200/33	±400	500
Rihand-Delhi	1990	Thyristor	0/814	±500	1500
Quebec - New England	1991	Thyristor	5/1100	±450	2250
NZ Inter-Island 2	1992	Merc. & Thyr	40/571	+270/-350	1240
Baltic Cable	1994	Thyristor	250/12	450	600
Garabi HVDC	2002	Merc.	0/0	±70	2200
Three Gorges - Changzhou	2003	Thyristor	0/ 890	±500	3000
Three Gorges – Guangdong 1	2004	Thyristor	0/980	±500	3000
Three Gorges – Guangdong	2004	Thyristor	0/940	±500	3000
BassLink	2006	Thyristor	298/72	±400	500
NorNed	2008	Thyristor	580/0	±450	700
Yunnan–Guangdong	2010	Thyristor	0/1418	±800	5000

Xiangjiaba-Shanghai	2010	Thyristor	0/1907	±800	6400
NZ Inter-Island 3	2013	Thyristor	40/571	±350	1200
Estlink 2	2014	Thyristor	157/14	±450	650
North-East Agra	2017	Thyristor	0/1728	±800	6000
Nelson River Bipole 3	2018	Thyristor	0/1324	±500	2000

¹ Later changed to be the first multiterminal link

² Largest mercury-arc valves ever made. The mercury-arc valves since replaced by Thyristors.

³ First HVDC scheme order with thyristors, although operation was delayed. First to use a DC voltage greater than 500 kV. First HVDC link in Africa.

⁴ First HVDC Link in China

Table 3. Selected HVDC Schemes using Voltage Source Converters [68].

Title 1	Year	Topology	Length (km)	Switching Frequency	DC Voltage	Power Rating	
			Cable/OHL	(Hz)	(kV)	P (MW)	Q (MVar)
Gotland VSC	1999	2-level	70/0	1950	±80	50	-55 to 50
Tjäreborg	2000	2-level	4.3/0	1950	±9	7.2	-3 to 4
Directlink	2000	2-level	59/0	1950	±80	180	-165 to 90
Eagle Pass	2000	3-level BTB Diode NPC	0/0	1500	±15.9	36	±36
MurrayLink	2002	3-level ANPC	176/0	1350	±150	220	-150 to 140
CrossSound	2002	3-level ANPC	40/0	1260	±150	330	±150
Troll A	2005	2-level	70/0		±60	84	-20 to 24
Estlink1	2006	2-level OPWM	105/0	1150	±150	350	±125
BorWin1	2009		200/0		±150	400	
Trans Bay Cable	2010	MMC	85/0	<150	±200	400	±170
Nanao Island ¹	2013	MMC MTDC	10/32		±160	200/100/500	
Zhoushan Islands ²	2014	MMC	134 ?141.5/		±200	400	
INELFE	2015	MMC	64.5/0		±320	2×1000	?
BorWin2	2015	MMC	200/0		±300	800	
HelWin1,	2015	MMC	130/0		±250	576	?
HelWin2,	2015	?	130/0		±320	690	
Dolwin1	2015	Casc. 2-L ³	165/0		±320	800	
Dolwin2	2015	MMC	135/0		±320	900	
Dolwin3	2018	-	162/0		±320	900	
SylWin1	2015		205/0		±300	864	
BorWin3	2019	-	160/0		±320	900	
Zhangbei HVDC	2019				±500	1500/4500	
	1	Stage MMC					

¹ 3-terminal HVDC system in parallel to and AC interconnection. Switching devices IEGT/IGBT.

² 5-terminal HVDC system. Provides voltage support to the existing ±50 kV 60 MW LCC-HVDC system on Sijiao island to prevent commutation failure.

³ Cascaded 2-Level converters

⁴ 4-terminal HVDC system

4. Innovations in HVDC

2.2 Capacitor Commutated Converter

Figure 27 shows a schematic of a LCC HVDC system based on a capacitor commutated converter [69-75]. By putting a capacitor in series with the converter transformer lowers the commutating reactance and provides the following benefits:

1. Reduced reactive power demand hence reduces the amount of shunt compensation
2. Reduced area requirements
3. Simplified AC switchyard
4. Increased immunity to commutation failures
5. Increased stability at low SCR
6. Smaller overvoltages at load rejection
7. no AC side zero sequence currents
8. Improved control properties
9. Reduces shunt bank switching and transformer OLTC operations (reduces O & M costs)

The reasons for placing the capacitor on the converter side of the transformer rather than system side are that it reduces the transformer rating (reduced reactive flow through it) and removes the risk of ferroresonance or SSR. Also lower stress on the capacitor for an ac fault on the load side of the capacitor (transformer limits the fault current).

The back-to-back Garabi HVDC system uses capacitor commutated converters and connects Argentina (500 kV) to Brazil (525 kV) [76,77].

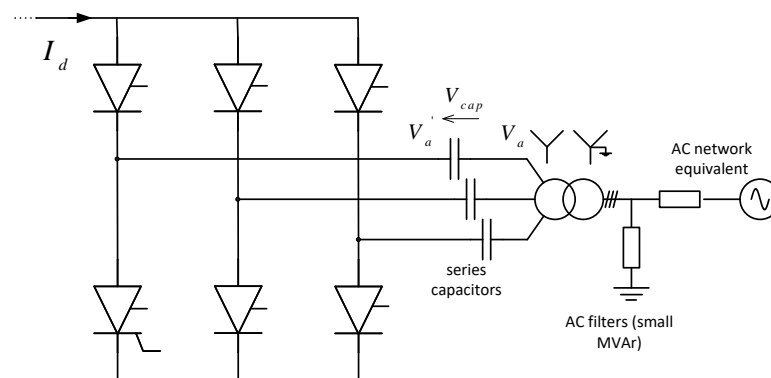


Figure 27. Output voltage (fundamental frequency switching).

2.2 Continuously tuned AC filter

The AC harmonic filtering typically constitutes about 10% of the station losses as well as approximately 9% of the converter station cost [75]. They also have a considerable footprint. The continuously tuned AC filters, depicted in Fig. 28. This passive filter uses a static reactor whose inductance can be controlled so the tuned frequency will follow the frequency and component variations [76]. These have been used in capacitor commutated converter based HVDC systems [77,78]. The greater cost of having an adjustable reactor is balanced by the improved performance.

A continuously tuned AC filter was first tested at Lindome converter station of Konti-Skan 2 HVDC Link and has since been installed on the Pacific Intertie HVDC system (1999) Swe-Pol Link, 600 MW (2000) and Garabi I and II [71].

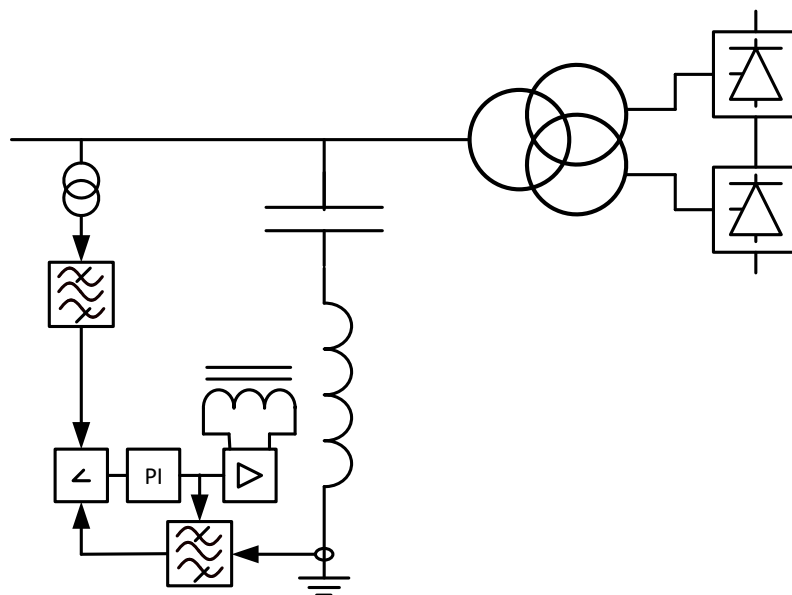


Figure 28. Continuously Tuned AC Filter

2.3 Active DC side filters

The main reason active DC filter are required are to meet stringent limits on DC side harmonics to keep the disturbance levels in nearby telecommunication circuits within acceptable levels [76]. A schematic of an active DC filter is shown in Fig. 29. The first commercial active dc filter was installed at the Tjele converter station in the Skagerrak 3 HVDC Intertie after first trialing the concept in 1991 on the Konti-Skan HVDC link [78]. The active DC filter is a passive doubled tuned 12/24 filter with an active part, located at the Kruseberg station (Sweden). The active filter was commissioned in 1993. This was followed by Baltic cable HVDC in 1994 and Chandrapur-Padghe HVDC transmission project (1998) [79]. This is still an active area of research [80-83].

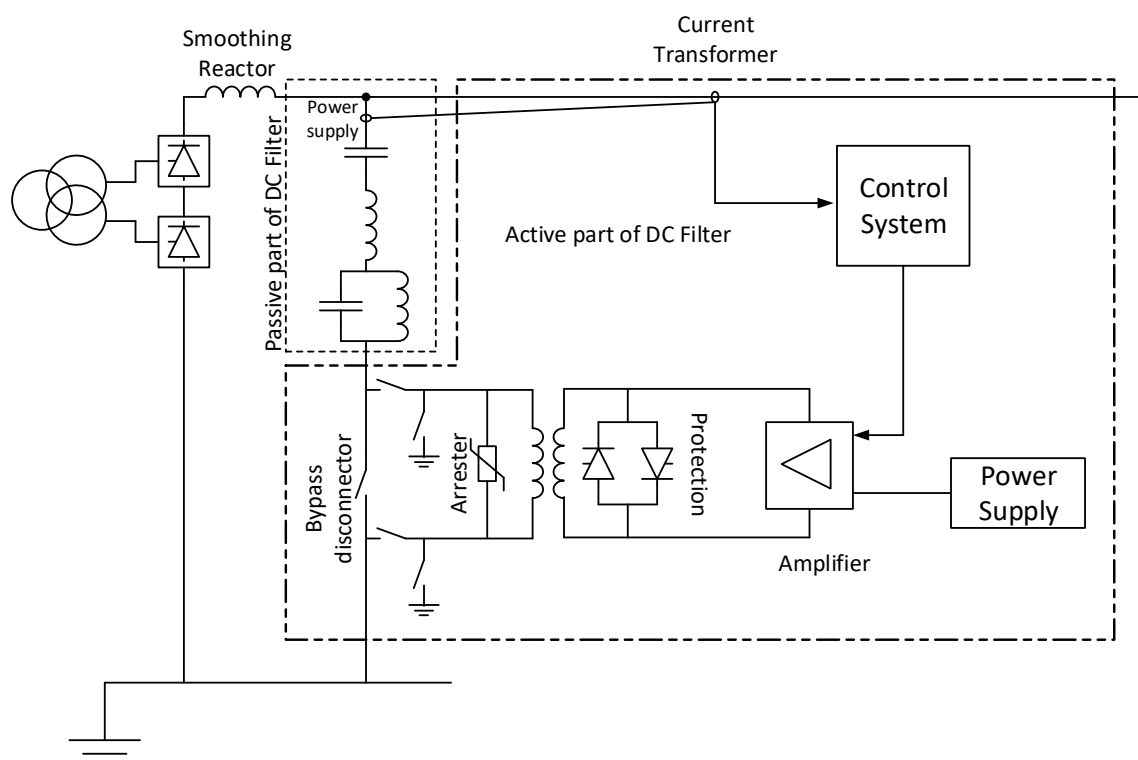


Figure 29. Active DC Filter

2.4 Reinjection concept

The concept of reinjection has developed significantly from the original ripple reinjection concept [84]. The concept is to increase the effective converter pulse number by reinjecting either DC current or DC voltage into the converter. Initially this injection point was the converter transformer secondary, however, later the mid-point between the two bridges has been used. Both multi-level current and voltage reinjection converters have been developed using the reinjection principle. Besides dramatically improving the converter waveforms, features such as independent P and Q control in current source converters has been achieved while maintaining the ability to control DC fault currents. The main impediment is the complexity and cost. An auxiliary reinjection bridge and reinjection transformer are required. In the current reinjection converter, although the main converter bridges still use thyristors the reinjection bridge must use power electronic switches with turn-off capability. As an illustration Fig. 30 shows a multi-level voltage reinjection converter [21,22,85,86].

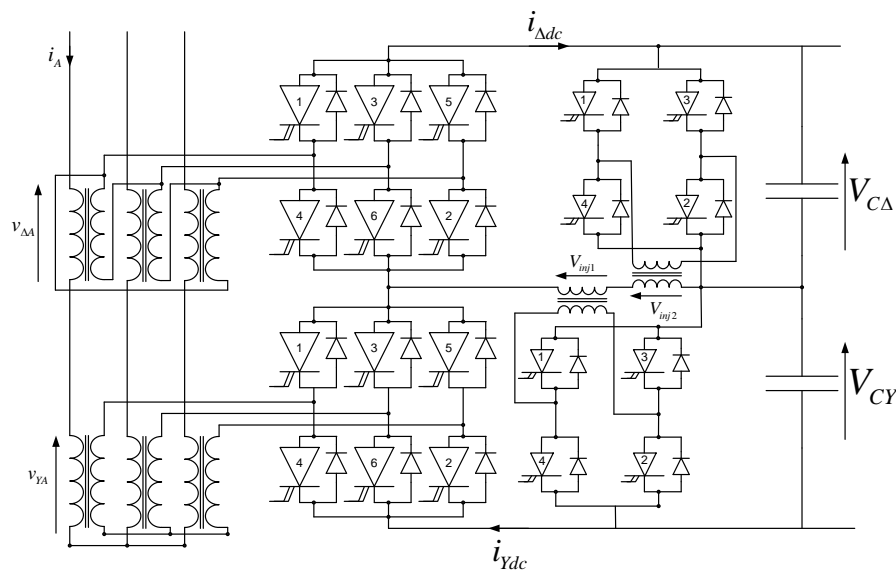


Figure 30. Reinjection Scheme

2.6 DC faults

When a fault occurs on the DC system CSC converters have the ability to de-energise the DC system while VSC converters continue to feed the fault as the antiparallel diodes act as an uncontrolled rectifier. Most VSC based HVDC schemes rely on the AC side protection detecting and de-energising the system. Various techniques have been proposed or used for allowing VSC based systems to cope better with DC side faults. Adding a full converter in the arms of MMC converter, adding parallel bypass thyristors to each semi-module in an MMC converter and the development of DC circuit breakers (see Fig. 31) have all been reported in the literature. The need for DC breakers is heightened with the development of multiterminal HVDC systems. Without DC breakers the multiterminal HVDC grid is what some call regional, in that the system constitutes one protection zone for a DC earth fault. Such a fault will cause temporary loss of the whole HVDC system. An inter-regional HVDC system needs effective and affordable DC breakers so that the system has a number of protection zones and an earth fault will only affect part of the system [87]. This is an active area of research with numerous hybrid and solid-state breaker topologies researched [31, 87-92].

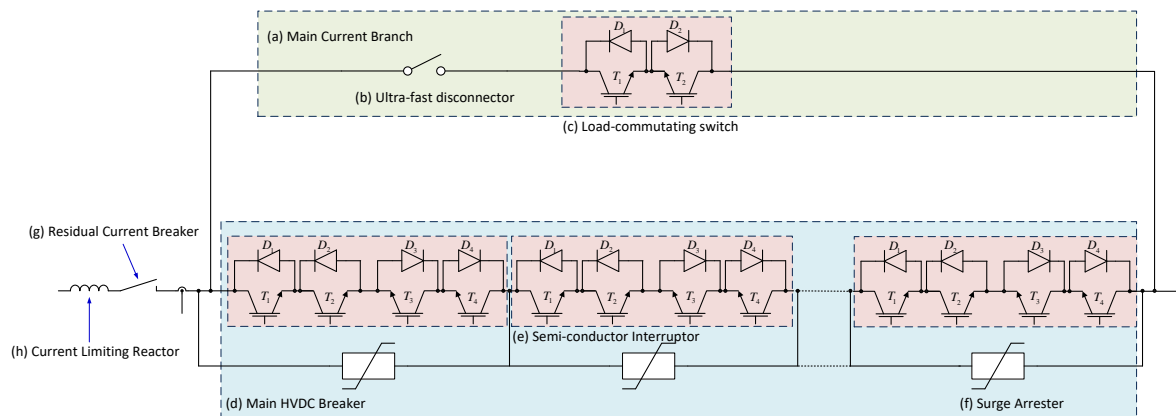


Figure 31. DC Circuit Breaker

5. Discussion

The trend of conveying higher power levels over longer distances will continue resulting in a demand for transmission at higher voltage levels for both LCC and VSC HVDC systems [93–96].

Further development in simulation tools is required for a converter rich system of the future due to the possible complex interactions over different time-scales [97]. Electromagnetic Transient simulation tools are presently available but their detail and complexity make them unsuitable for large system studies. They are computationally expensive as the frequency switching of devices restricts the time-step that can be used [98,99]. Because of the various system time constants co-simulation techniques for mixed time-frame simulation are gaining popularity [100]. A recent publication [101] provides seven HVDC system models that can cover most HVDC grid applications. This provides a starting point in for project feasibility assessments and specifications and enables researchers to customise and benchmark their studies. Moreover, the overview gives a useful review of previous publications and technology.

Hardware-in-the-loop (HIL) testing where actual hardware (control and protection equipment) are interfaced with a real-time digital simulator in a closed-loop arrangement has become a very important facility in identifying problems and mitigating them before the equipment is transported to the site and commissioned.

Power electronic converters are modulators (i.e. they couple the AC side and DC side frequencies) with various sensitivities, based on their control systems and topology. The terms “cross-modulation” and “harmonic interaction” have been used to refer to this phenomena and both CSC and VSC converters act as modulators, transferring and translating the distorting frequencies on one side to the other [102]. The converter can be viewed as a three-port device as the positive and negative sequences on the AC system couple to different frequencies on the DC side. This manifests itself in various ways, such as in composite resonances or core-saturation [102]. For example in LCC HVDC schemes when the AC and DC lines share a common right-of-way the induced fundamental in the DC line can give rise to core-saturation in the converter transformer. Although HVDC converters and their controls can create undesirable interactions, which must be avoided, they also have the ability to dampen oscillations inherent in the AC system by the use of supplementary inputs.

Due to the cost and footprint of filtering equipment, and inherent losses, the trend to low distortion current waveforms will continue. Often these techniques produce distortion at higher frequencies.

The role of telecommunication systems in HVDC systems also needs evaluating carefully. Initially the HVDC converters were controlled based on local variables (DC voltage, DC current, DC Power) and the telecommunication system carried orders for changing the settings. A disturbance in an AC system would naturally result in a new stable operating point without the need for intervention by a telecommunication system. However, if a reliable telecommunication system is available then improvements in coordination, control and protection are possible.

5.1 VSC HVDC systems

The forming of multiterminal VSC-based HVDC to form HVDC Grids is a very active area of research due to the desirability of such systems. This is multifaceted as it involves the control systems and protection of such systems. Under normal operation how are the converters to be coordinated and what role telecommunication systems have in this [46,103,104]? What modulation technique is used and how are the capacitors in multi-level systems balanced. For example in the MMC the voltage balance across the sub-module capacitors must be maintained and the circulating current limited and this has stimulated research into modulation methods for the MMC. In the MMC a fast acting thyristor is placed across the sub-module/cell and triggered to protect the cell diode when a DC fault occurs. Clearance occurs when the AC circuit breaker operates. The diode in the MMC's semi-module (or parallel thyristor) act as an uncontrolled rectifier when a DC fault occurs and using two antiparallel diodes has been proposed to stop the uncontrolled rectification [105]. Hybrid multi-level converter topologies utilising director switches have been proposed [36,106]. Rather than using half-bridges as the sub-module another option is to use a full-bridge and this is the basis for the alternate arm version of the hybrid MMC [27,107-109]. Applying full-bridge cells in series with the "Director" valves enables the multilevel cells to provide a voltage that opposes and limits the flow of current into a DC network short circuit [36]. This enables the converter to remain connected and ready to continue power transmission once the fault is removed. However, this increases the converter losses and the number of semi-conductor devices. More work is required in developing VSC converters that are tolerant to DC faults and low loss. Moreover, a fast and cost-effective DC circuit breaker is needed to limit the impact of DC side faults, particularly in multiterminal systems. The identification and mitigation of DC side faults still needs more research especially for multiterminal systems where isolating only the faulted line without causing power interruption to the whole network is required. Also the role of telecommunication systems needs to be determined. Some have recommended that the primary protection should be based on local quantities and backup protection pilot wire based. In an LCC HVDC system the DC smoothing reactor limits the rise of the fault current and the control action of the thyristor can extinguish the arc. In a VSC system on fault inception the charge in the DC capacitances will discharge to the fault point rapidly and the DC voltage will drop quickly.

VSC converters are susceptible to unbalance in the AC system it is attached to. The negative sequence component in the AC system causes a second harmonic component on the DC side which in turn results in unbalanced waveforms in the AC system the other VSC is connected to [110]. The transmitted power has an oscillatory component and a double-frequency reactive power ripple appears on the AC side.

With the development of renewable generation in remote areas the short-circuit-ratio (SCR) where VSC converters are required to operate is dropping and there are control issues in such scenarios. Unwanted control interactions can occur, either with other VSC converters, or generators that are electrically close or simply with the weak AC system. Grid connected converters use a Phase-Lock-Loop (PLL) for synchronizing to the grid and its performance when the AC is weak or a disturbance occurs can negatively impact the systems performance. Grid synchronization and robust control, particularly in the face of a weak AC system and multiple converters. Overcoming the weaknesses in the PLL is of great importance for the stability of the system. As more converter based generation is integrated into the system and displaces conventional synchronous machine based generation the rotational inertia drops. The frequency regulation becomes more difficult and in the event of a disturbance the system is more likely to be unstable. Another active strand of research is on methods of enabling power electronic converters to provide what is termed synthetic or virtual inertia. That is, provide real power to stabilise the AC system immediately after a disturbance as a synchronous machine does by converting some of its kinetic energy to electrical energy as the frequency drops, or vice versa. Another strand is to design a grid-tie converter without the traditional PLL for connection to weak AC systems [111-113].

Unlike the LCC, VSC does not suffer from commutation failure when an AC system fault occurs, however, the challenge is for the control system to limit any transient overvoltage or overcurrent [50].

Improving the tolerance of HVDC systems to AC and DC faults is a challenging area to research, but is needed to ensure reliable power transmission. VSC-based HVDC systems have a particular challenge with DC faults. Research into topologies, control techniques, and materials & devices are all needed. However, research into converter control systems has the potential to solve many of the problems that have been experienced to date. The coordination of multiterminal HVDC systems, improved steady-state performance in weak AC systems and better dynamic performance and elimination of control interactions are still areas requiring further research.

5.2 CSC-based HVDC systems

CSC HVDC schemes, being line-commutated, are even more dependent on the AC system for commutation to occur and often synchronous condensers have been placed at the inverter end if the SCR is too small to ensure commutation failure does not occur. As with VSC systems, unwanted control interactions can occur with other electrically close equipment [53]. It is usually convenient to subdivide instabilities into several types, distinguished by their frequency. Ref. [96] gives a good overview of the control interactions and instabilities that can occur in LCC HVDC systems, their mechanism and a few examples of where they have occurred. These instabilities can be categorised by their frequency, as follows: (a) Super-synchronous instability (often loosely referred to as “harmonic instability” despite not being an integer multiple of the fundamental) (b) Core-saturation instability (c) Subsynchronous instability (typically 5 – 40 Hz) (d) Power control instability. The response time of the dc controls is short compared to other time constants of the network.

The controllability of HVDC converters also opens the opportunity to provide supplementation controls to help dampen AC system instabilities. When considering an LCC HVDC system, typical considerations are:

1. Load rejection overvoltages
2. Temporary overvoltage after recovering from an AC system fault
3. Voltage change on reactive switching
4. AC network frequency and stabilisation/modulation control
5. Possible subsynchronous torsional interactions with nearby turbine-generators.

These issues still exist and must be considered when planning an LCC HVDC system [114]. Where previously an AC system had only one infeed now an AC system may have multiple HVDC systems interconnecting it and the interaction between converters is of growing importance [53]. Also the interaction between AC and DC systems are becoming more significant as more HVDC systems are deployed.

The control systems for a DC transmission system must be stable with adequate stability margins in the whole range of operation. The role of communication systems in HVDC is changing. Previously with LCC HVDC communication systems were not relied upon. This resulted in a Hierarchical control system (Valve firing (1 ms), Pole (10 to 500 ms) & Master control (up to 10 s)) where the lower levels relied only on terminal conditions and were designed to transition to a new stable operating point if a disturbance occurred without the need for information from the other end. A high level signal would give the coordinating command for steady-state operation. The control speed of a converter is very fast compared to the AC system time constants and hence may have to be limited based on the capacity of the network to support variations in the real and reactive power of the converters. The reliability of modern communication systems is such that many are looking at placing higher reliance upon it for both control and protection roles for both LLC and VSC based HVDC systems. The question is the best way to utilize the communication system while still maintaining a robustness to outages.

5. Conclusions

The technological development in solid-state devices, converter topologies and control techniques will continue to improve the attractiveness of DC transmission systems. Regardless of whether AC or DC there will always be a need to transform the voltage to the optimum level for

transmission and distribution, based on the length and power transmitted. The cost, efficiency and reliability of modern transformers means the grid of the future is most likely to be a hybrid AC/DC system with more DC being deployed and embedded in AC systems. There is already research on DC transmission, not only at the HV and UHV, levels but Medium Voltage (MV) and Low Voltage (LV) levels [115]. This paper has discussed the present state of HVDC technology, deficiencies and where further research and development is required. It is clear that DC transmission will play an increasing role in the grid of the future and control systems design will be more critical to ensure undesirable interactions do not occur, particularly when the AC system is weak.

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