

DD IEC/PAS 62543:2008



BSI British Standards

DC transmission using voltage sourced converters

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PRE-STANDARD

DC transmission using voltage sourced converters

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

DC TRANSMISSION USING VOLTAGE SOURCED CONVERTERS

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DC TRANSMISSION USING VOLTAGE SOURCED CONVERTERS

INTRODUCTION

HVDC transmission was first put into commercial service in 1954 and has since been used extensively for the interconnection of asynchronous a.c. networks and for the transmission of power over long distances. The switching elements used for the conversion between a.c. and d.c. were able to switch on as commanded, but depended on a naturally occurring current zero for the turn-off process. Thus the technology relies on the presence of an a.c. voltage in the network for the commutation process, and is known as line commutated converter (LCC) HVDC technology. In this PAS, it will be referred to as LCC HVDC. This technology is still used extensively for HVDC transmission. LCC HVDC schemes installed by the end of 2004 have a total rating in excess of 60 GW, with more being added each year.

The use of voltage sourced converters for d.c. power transmission (VSC transmission) was introduced with the commissioning in 1997 of the 3MW, ± 10 kVd.c. technology demonstrator at Hellsjön, Sweden. VSC transmission enables reliable and controllable power transfer between networks. In principle, the operation of its converters (rectifier and inverter) at the two ends of the VSC transmission does not rely on the strength of the connected a.c. systems. Furthermore, it provides independent control of the reactive power at the two ends and independently of the active power transfer over the d.c. transmission.

The object of this PAS is to describe the VSC transmission technology, with a particular view to the issues to be considered when it is applied at voltages above 100 kVdc, and power in excess of 100 MW. It provides information about the equipment included in a VSC transmission scheme, as well as the characteristics and performance that can be expected.

The information presented here is aimed at several groups of people:

- transmission network owners/operators planning to build a VSC transmission scheme;
- those involved in the specification of a VSC transmission scheme, for example transmission or distribution network owners/operators;
- investors considering inter-connectors and other merchant transmission links;
- anyone wanting to know more about the VSC transmission technology.

Some readers may have technical interests and some may have non-technical interests. Therefore, this PAS has been structured in such a way that different needs can be met by reading selected sections.

For readers without particular interest in the detailed technical issues, the chapters of greatest interest are:

Chapter 2 VSC Transmission Applications

Chapter 10 Environmental Impact

Chapter 13 Life Cycle Cost

Chapter 14 Comparison of Line Commutated Converter and VSC

For readers wanting a deeper insight into the VSC transmission technology, but without knowledge of LCC HVDC technology, it may be advantageous to read Appendix C before reading the rest of the PAS.

OVERVIEW OF VSC TRANSMISSION TECHNOLOGY

Since its introduction in the early 1950s, LCC HVDC technology has undergone continuous development, particularly in the areas of converter switches and controls. Today LCC HVDC schemes provide reliable, efficient and cost-effective solutions for many applications. The use of modern techniques have made it possible to obtain stable operation for LCC HVDC schemes connected to much weaker a.c. networks than previously.

Other fields of power electronics, such as industrial drives, have contributed to the development of new semiconductor devices, because the quantity of devices produced each year for these applications can be many times the number required for HVDC schemes. Motor drives have, over the years, moved on from using line-commutated converters to the use of voltage sourced converters (VSC) with pulse width modulation (PWM) control, which results in compact and more controllable drives. Usually such drives operate at relatively low a.c. and d.c. voltage and do not use series-connected semiconductors.

The 3-MW Hellsjön VSC transmission installation put into service in Sweden in 1997 was an extension of modern motor drive technology. To reach a transmission voltage of 10 kVdc, however, series-connected semiconductors were required. The trial installation proved the feasibility of the technology and demonstrated its superior technical capability when compared to LCC HVDC. Subsequently, more schemes have been installed, with the largest in service at the end of 2004 having a rating of 330 MW and ± 150 kVdc. CIGRÉ has given this new type of d.c. transmission the name VSC transmission.

VSC transmission has a number of technical features that are superior to those of LCC HVDC schemes and make it especially attractive for the following applications:

- feeding into passive networks;
- transmission to/from weak a.c. systems;
- enhancement of an a.c. system;
- land cable systems;
- supply of offshore loads;
- connection to wind farms (on-shore or off-shore) or wave power generation;
- in-feeds to city centres;
- multi-terminal systems.

Continuing developments in semiconductors and VSC transmission technology are likely to make VSC transmission attractive in an increasing number of applications as research and development efforts continue to bring down the capital cost and power losses of the converters.

OVERVIEW OF THIS PAS

This PAS consists of 16 chapters and three appendices.

Chapter 1 provides a list of definitions of symbols and terms introduced in the PAS. Where possible, the terminology for high-voltage direct current (HVDC) transmission, as defined in IEC 60633, has been used. The definitions included in Chapter 1 have been limited to those which are new, as far as HVDC transmission is concerned.

Chapter 2 describes a VSC transmission scheme as a black box and outlines the main characteristics of a VSC transmission scheme, in particular the principles of active and reactive power control, and its operational characteristics. The chapter also outlines potential applications and the present status of VSC transmission technology.

Chapter 3 presents the operational characteristics of a VSC transmission scheme in greater detail, starting from the operation of a 2-level converter. The basic characteristics of 3-level and multi-level converters are described, as well as the use of pulse width modulation (PWM).

Chapter 4 describes different converter topologies which may be used for VSC transmission. Simplified circuit diagrams are given for each of these topologies, along with their waveforms.

Chapter 5 gives an overview of the switches, called VSC valves, which are used to convert between a.c. and d.c. The chapter includes a description of the various semiconductors that could be used for a VSC valve, and outlines the design considerations for a high-voltage VSC valve.

Chapter 6 presents a typical power circuit diagram for a VSC substation and outlines the characteristics of the other major power equipment that may be used.

Chapter 7 discusses the different modes of control that can be used for a VSC transmission scheme, as well as the information needs and performance required. A possible hierarchy of controls is described, followed by a discussion of the controls for a number of different applications.

Chapter 8 discusses the fault performance and protection requirements for a VSC transmission scheme. It outlines the mechanisms leading to different faults and their consequences. Faults (and transients) within the converter on the a.c. and the d.c. side are discussed.

Chapter 9 describes the harmonics generated by a VSC substation and various methods that can be adopted to minimise the need for filtering, including the use of multi-level or multi-pulse converters and PWM switching. The consequences of harmonics in power networks are outlined, and the design of a.c. and d.c. harmonic filters is presented.

Chapter 10 covers the environmental impact of a VSC substation. The topics include audible noise, electric and magnetic fields (EMF), and radio-frequency interference (RFI).

Chapter 11 discusses the studies that may be performed as part of the planning and implementation of a VSC transmission scheme. The studies include those needed as background to the investment decision, those required for the tender exercise, and those for the simulation of critical system tests.

Chapter 12 gives a brief overview of the testing and commissioning associated with a VSC transmission scheme. The process to be followed is very similar to that used for HVDC or FACTS.

Chapter 13 outlines the life-cycle cost of a VSC transmission scheme, including capital cost, power losses, maintenance, disposal costs, refurbishment and cost of unavailability.

Chapter 14 provides a brief comparison of LCC HVDC and VSC transmission.

Chapter 15 looks ahead to the next generation of semiconductors and outlines developments that could further improve the characteristics of the VSC transmission technology and lead to an increase in the number of installed VSC schemes.

Chapter 16 is a brief conclusion.

Appendix A gives a list of VSC transmission schemes in operation at the end of 2004.

Appendix B provides a guideline for a functional specification of a VSC transmission scheme.

Appendix C presents a brief overview of LCC HVDC transmission and is primarily intended for readers who have little or no knowledge of this technology. A list of all LCC HVDC schemes in service at the end of 2004 is included.

DC TRANSMISSION USING VOLTAGE SOURCED CONVERTERS

1. SCOPE

The object of this PAS is to describe the VSC transmission technology, with a particular view to the issues to be considered when it is applied at voltages above 100 kVdc, and power in excess of 100 MW. It provides information about the equipment included in a VSC transmission scheme, as well as the characteristics and performance that can be expected.

1.1 Introduction

This PAS uses the terminology established by IEC 60633 [1-1]. However, due to the differences in converter technology and operating characteristics of voltage sourced converters (VSC) compared to line-commutated converters (LCC), it was felt to be appropriate to define some new terms used in this PAS. Those terms that are either identical to, or obvious extensions, of the IEC 60633 terminology have not been defined.

To support the explanations, Figure 1.1 presents the basic diagram of a VSC substation.

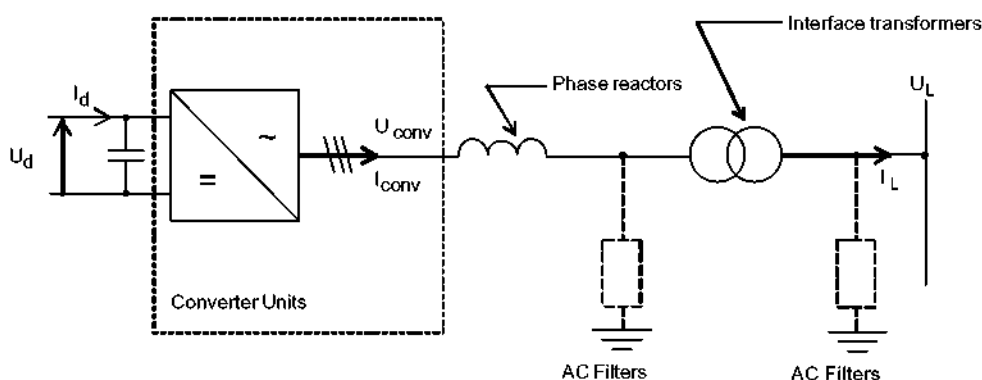


Figure 1.1- Basic diagram of a VSC substation

For the purpose of this PAS, the symbol for a VSC valve is shown in Figure 1.2.

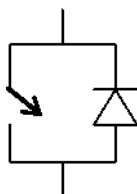


Figure 1.2 - Symbol of a VSC valve as used in this PAS

1.2 LIST OF LETTER SYMBOLS

- U_{conv} Line-to-line a.c. voltage of the converter unit(s), r.m.s value, including harmonics
- I_{conv} Alternating current of the converter unit(s), r.m.s value, including harmonics

1.3 GENERAL TERMS AND DEFINITIONS RELATED TO CONVERTER CIRCUITS AND POLE TOPOLOGIES FOR VSC CIRCUITS

1.3.1 VSC Transmission

A high-voltage d.c. transmission system in which the conversion between a.c. and dc and vice versa is performed by means of voltage sourced converters.

1.3.2 VSC Phase Unit

The equipment used to connect the two d.c. busbars to one a.c. terminal.

Note: In the simplest implementation, the VSC phase unit consists of two VSC valves. It may also include control and protection equipment and other components.

1.3.3 VSC Unit

System consisting of three VSC phase units, together with VSC unit control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion.

1.3.4 VSC Substation

Part of a VSC transmission scheme, consisting of one or more VSC unit(s) installed in a single location together with buildings, VSC d.c. capacitors, reactors, transformers, filters, control, monitoring, protective, measuring and auxiliary equipment, as applicable.

1.3.5 Two-Level Converter

A converter in which the voltage at the a.c. terminals of the VSC unit is switched between two discrete d.c. voltage levels.

1.3.6 Three-Level Converter

A converter in which the voltage at the a.c. terminals of the VSC unit is switched between three discrete d.c. voltage levels.

1.3.7 Multi-Level Converter

A converter in which the voltage at the a.c. terminals of the VSC unit is switched between more than three discrete d.c. voltage levels.

1.3.8 VSC Pulse Number p

Characteristic of a VSC unit connection expressed as the number of non-simultaneous symmetrical commutations occurring during one cycle of the a.c. line voltage, assuming the valves in each VSC unit are controlled to achieve full wave rectification/inversion.

1.4 VSC Unit Equipment

1.4.1 VSC Valve

Complete operative controllable valve device assembly, including its free wheeling diode, which can function as part of a VSC phase unit.

1.4.2 Diode Valve

Complete operative valve device assembly, including its diodes, which may be used in some VSC units.

1.4.3 VSC Valve Level

Part of a VSC valve comprised of a controllable switch and a diode, or controllable switches and diodes connected in parallel, together with the immediate auxiliaries and reactor, if any.

1.5 VSC Substation Equipment

1.5.1 Interface Transformer

Transformer through which power is transmitted between the a.c. system connection point and one or more VSC units.

1.5.2 Phase Reactor

A reactor series-connected directly to the a.c. terminal of the VSC phase unit.

1.5.3 VSC DC Capacitor

Capacitor bank(s) which sustain(s) the direct voltage for the operation of the voltage-sourced converter. The capacitors may be connected between the d.c. terminals of a VSC unit or within the VSC unit.

1.6 References

[1-1] IEC 60633, *Terminology for high-voltage direct current (HVDC) transmission*, 1998.

2. VSC TRANSMISSION APPLICATIONS

2.1 Introduction

The advantage of HVDC transmission has been proven since 1954, when the first commercial link from the mainland of Sweden to the island of Gotland was commissioned. The early HVDC schemes used mercury arc valve technology, but this has now been replaced by thyristor valves because of the superiority of the thyristor technology. With these types of converter switches, the conversion from a.c. to d.c. and vice versa depends on an a.c. voltage for the commutation process. For satisfactory operation, a relatively strong a.c. network with a sufficiently high short-circuit power is necessary. These converters are called line commutated converters (LCC), and HVDC transmission using this technology is referred to in this PAS as LCC HVDC.

Voltage sourced converters (VSCs) have been used for many years in motor drives. The application of VSCs to HVDC transmission, however, is new and has only been a reality since 1997, when the concept of VSC transmission was announced for medium power d.c. transmission. Several schemes are now in operation. At the end of 2004 the largest VSC transmission installation was the Cross Sound Cable between Connecticut and Long Island, New York. Commissioned in 2002, it has a capacity of 330 MW using a transmission voltage of ± 150 kVdc. Appendix A gives a list of VSC transmission schemes in service or under construction at the end of 2004.

The thyristor valve used for the conversion in LCC HVDC can only switch off when the current through it passes zero and, hence, relies on the line voltage for commutation (line commutated converter). In contrast, the voltage sourced converter is based on controllable semiconductor switches, meaning that the valves can be switched on and off by external low-voltage control signals independently of the main current passing through the valve. This difference in operation gives VSC transmission significant advantages over LCC HVDC, since the VSC can function when it is connected to a network with a very low short-circuit ratio, or even to a passive network without any generation or short-circuit power.

In addition, a significant distortion in the a.c. voltage waveshape can lead to a commutation failure for an LCC HVDC scheme, causing a short and temporary interruption in power flow. As the VSC is self-commutating, it does not suffer from such commutation failures.

However, the VSC has diodes connected in anti-parallel to the IGBTs, and in the event of a fault on an overhead d.c. line, the VSC at both ends must be disconnected by opening the a.c. circuit breakers and enabling the arc to extinguish. In such a circumstance, an LCC HVDC converter would suffer a shorter interruption, since the valves can automatically block to stop the direct current flow and extinguish the arc without opening the breakers. This ensures the fast recovery of the LCC HVDC scheme in case of transient faults in the d.c. grid.

As modern semiconductors, such as IGBTs, can be switched on and off several times on each power frequency cycle, it is possible with switching techniques to produce an output waveshape that will eliminate low-order harmonics. The drawback is that these switching operations cause power losses that increase with the switching frequency. However, the better waveshape means that harmonic filtering is easier for VSC transmission than for LCC HVDC, rendering large switchable harmonic filters unnecessary. As a consequence, the footprint of a VSC scheme is much smaller than that of an LCC HVDC scheme of the same rating.

LCC HVDC and VSC transmission are compared in Chapter 14.

2.2 Examples of Possible VSC transmission Applications

The excellent characteristics of VSC transmission are very promising for a wide range of possible applications, such as the following.

- Point-to-point schemes—overhead lines
- Point-to-point schemes—cables
- In-feeds to city centres
- Transmission to/from weak a.c. systems
- Back-to-back schemes
- In parallel with an existing LCC HVDC link, for increase of transfer capability
- Enhancement of an a.c. system
- As a parallel link to a.c. transmission lines, to reduce bottlenecks in transmission networks
- DC land cable systems
- DC transmission cables in areas where it is impossible to obtain permission to build overhead lines
- Multi-terminal systems
- Interconnections of asynchronous power systems
- Supply of loads in isolated areas
- Connection to wind far.m.s (onshore or offshore) or wave power generation
- Supply to and from offshore loads/platforms

In instances where a VSC transmission scheme supplies a local grid with low generation and inertia, and the VSC transmission supply is dominant compared with local generation, the sending and receiving end a.c. grids should be checked for stability.

2.3 The Voltage Sourced Converter as a Black Box

The operation of a voltage sourced converter is described in greater detail in Chapter 3. In this chapter the converter is treated as a black box that can convert from a.c. to d.c. and vice versa, and only steady-state operation is considered.

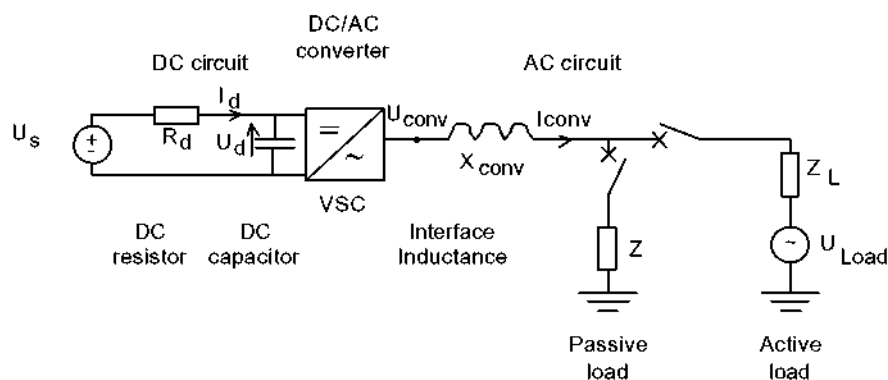


Figure 2.1- Diagram of a generic voltage sourced converter

Figure 2.1 represents a schematic diagram of a generic voltage sourced converter connected to a d.c. circuit on one side and to an a.c. circuit on the other.

The VSC can be operated as either an inverter, injecting real power into the a.c. network ($I_d \times U_d > 0$), or as a rectifier absorbing power from the a.c. network ($I_d \times U_d < 0$). Similarly, the VSC can be operated either capacitively, injecting reactive power into the a.c. network ($j I_{conv} \times U_{conv} > 0$), or inductively, absorbing reactive power from the a.c. network ($j I_{conv} \times U_{conv} < 0$). The VSC can be operated capacitively or inductively in both the inverter and the rectifier mode.

The designation voltage sourced converter is used because the function of the VSC is predicated on the connection of a voltage source on the d.c. side.

To the left in Figure 2.1, a d.c. voltage source U_s is shown with a d.c. resistor R_d representing the d.c. circuit resistance, and a d.c. capacitor connected across the d.c. terminal of the VSC. The d.c. shunt capacitor serves the purpose of stabilising the d.c. voltage U_d . The conversion from d.c. to a.c. takes place in the VSC as explained in Chapter 4. On the a.c. side, an interface inductance is provided which serves two purposes: First, it stabilises the a.c. current, and secondly, it enables the control of active and reactive output power from the VSC, as explained in 2.4. The interface inductance can be implemented as phase reactors, as leakage inductances in transformers, or as a combination thereof. The d.c. capacitor on the input side and the a.c. interface inductance on the output side are important components for the proper functioning of a VSC.

A passive or active a.c. network can be connected to the a.c. side of the VSC. If the VSC is connected to a passive network to its a.c. side, the power flow can be only from the d.c. input side towards the passive load on the a.c. side. However, if the a.c. side is connected to an active a.c. network, the power flow can be in both directions by controlling the a.c. voltage output U_{conv} of the VSC.

By controlling the phase angle of U_{conv} , the active power through the VSC can be controlled as explained in 2.4.1. By controlling the voltage amplitude of U_{conv} , the reactive power through the VSC can be controlled, as explained in 2.4.2.

2.4 The Principles of Active and Reactive Power Control

The VSC can be considered as an equivalent of a synchronous generator without inertia, which has the capability of individually controlling active and reactive power.

The exchange of active and reactive power between a VSC and the a.c. grid is controlled by the phase angle and amplitude of the VSC output voltage in relation to the voltage of the a.c. grid.

The active and reactive power can be controlled simultaneously and independently of each other. If U_{conv} is in phase with the line voltage U_L and its amplitude is equal to U_L , there is no a.c. current I_{conv} from the VSC. Under these conditions, the d.c. current I_d becomes zero and the d.c. capacitor voltage U_d becomes equal to the d.c. source voltage U_s .

2.4.1 The Principle of Active Power Control

The principle of active power control is represented in Figure 2.2, where the active power through the interface inductance is controlled by regulating the VSC voltage angle.

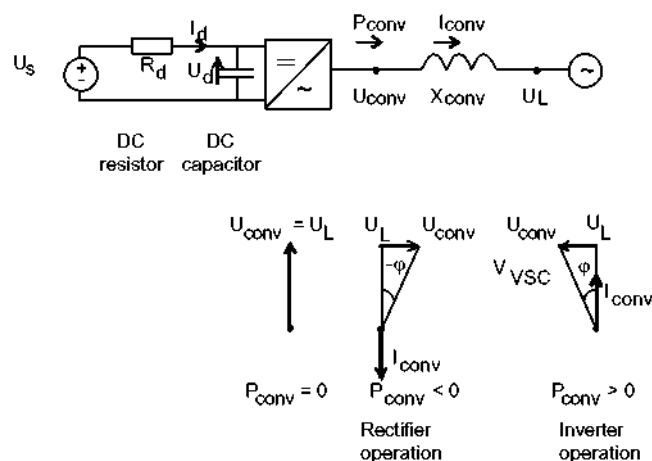


Figure 2.2 - Principle of active power control

If the angle of the VSC output voltage leads the a.c. grid voltage, the VSC will inject active power to the a.c. grid, i.e., it operates as an inverter. On the d.c. side, an equivalent current will be drawn from the d.c. source and the voltage U_d will decrease in accordance with Ohm's law ($U_d = U_s - R_d \cdot I_d$).

If, on the other hand, the VSC output voltage lags the voltage of the a.c. grid, the VSC will absorb active power from the a.c. grid, i.e., it operates as a rectifier. On the d.c. side, an equivalent current will be injected in the d.c. source and the voltage U_d will increase in accordance with Ohm's law ($U_d = U_s + R_d \cdot I_d$).

If the VSC is connected to a passive load, an a.c. output current will be drawn from the VSC determined by Ohm's law $I_{conv} = U_{conv}/Z$. Again, an equivalent d.c. current will be drawn from the source and the voltage U_d on the d.c. capacitor will drop to a value determined by Ohm's law. No active power can be drawn from the a.c. side, because it is a passive a.c. circuit.

2.4.2 Principle of Reactive Power Control

The principle of reactive power control is represented in Figure 2.3, where the reactive power through the interface inductance is controlled by regulating the amplitude of the VSC output a.c. voltage.

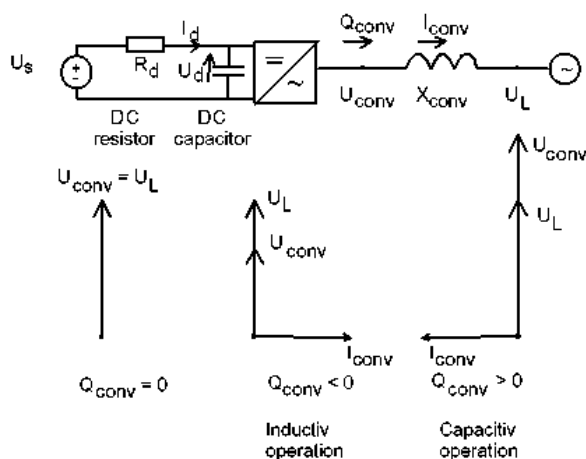


Figure 2.3 - Principle of reactive power control

If the amplitude of the VSC output voltage U_{conv} is higher than the a.c. grid voltage U_L , the VSC will inject reactive power in the a.c. grid, i.e., will operate in the capacitive mode. If the amplitude of the VSC output voltage is lower than the a.c. grid voltage, the VSC absorbs reactive power from the a.c. grid, i.e., the inductive operating mode.

2.4.3 Basic PQ Diagram for a VSC Station

The PQ capability diagram of a VSC shows its possible operating regime. The diagram normally gives the capability at the a.c. interface point. When active output power P is positive, the VSC is operated as an inverter, either in capacitive mode, when Q is positive, or in inductive mode when Q is negative. When P is negative, the VSC is operated as a rectifier, either in capacitive or inductive mode. A simplified PQ diagram at minimum (U_{min}) and maximum (U_{max}) a.c. grid voltage, in which filters are not considered, is shown in Figure 2.4. The VSC can be operated within all four quadrants of the PQ plan.

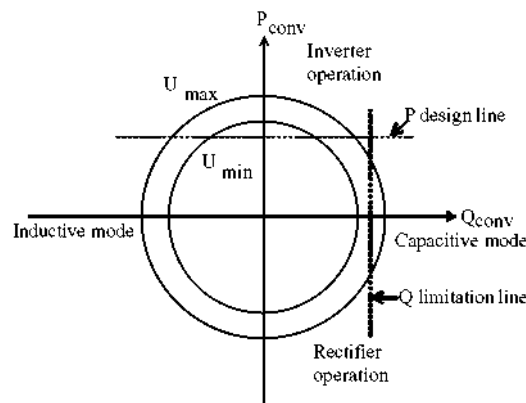


Figure 2.4 - Basic simplified PQ diagram

The PQ diagram shows that the capability of the VSC depends on the a.c. grid voltage. At low a.c. voltage, a higher current is necessary to produce a given output power, and the output capability is limited by the current capability of the converter. At low a.c. grid voltage (U_{min}), full reactive power can be produced within the PQ circle corresponding to U_{min} . However, at high grid voltage (U_{max}), the reactive power is limited because the maximum a.c. voltage U_{conv} is limited due to the d.c. voltage limitation and the current limitation of the valves. It should be noted that the centre of the circles is dependent on the design of the converter and may not be at the origin of the diagram.

The diagram also indicates an active power design line (P design) and a reactive power line (Q limitation). The P design line is the maximum power rating of the VSC and is mainly determined by the maximum current for which the valve is designed. The Q limitation line indicates the maximum reactive power rating of the VSC and is determined by the maximum allowable d.c. voltage on the storage capacitor. The maximum d.c. voltage is determined for the maximum a.c. output voltage U_{conv} , which, in relation to the a.c. line voltage U_L , determines the Q limitation.

The active power design line in the PQ diagram indicates the desired rated power of the VSC. In the example shown, the required power capability in inverter operation is less than the potential capability of the VSC.

The PQ characteristics depend on the a.c. voltage U_{conv} . Therefore, if an interface transformer is provided, the transformer ratio can be used to optimise the PQ characteristics. With an on-load tap changer, the transformer ratio can be continuously optimised to maximise the steady-state power capability of the converter.

An additional benefit of a tap changer is that it can minimise the power losses of the VSC transmission system.

2.5 Operating Principles of a VSC transmission Scheme

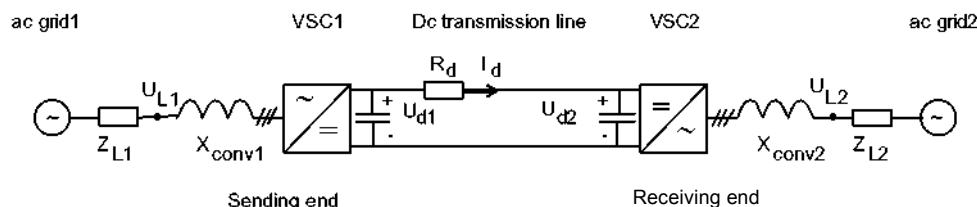


Figure 2.5 - Point-to-point VSC transmission scheme

The point-to-point VSC transmission scheme shown in Figure 2.5 consists of two VSCs interconnected on the d.c. side via a d.c. transmission line and connected to two different a.c. grids on the a.c. side. The basic characteristics of a VSC have already been described. One of these characteristics is that the d.c. voltage polarity is always the same. Therefore, the direction of the power flow on the d.c. line is determined by the direction of the d.c. current. In Figure 2.5 the current flow and the power flow are from VSC1 (the sending or rectifier end) to VSC2 (the inverter or receiving end) of the d.c. line.

The direction of a d.c. current is always from a higher d.c. voltage level to a lower d.c. voltage level. The d.c. voltage at the sending end of the d.c. line must therefore be higher than the d.c. voltage at the receiving end. The value of the current is determined by Ohm's law, as the voltage difference between sending and receiving ends divided by the resistance in the d.c. line is $I_d = (U_{d1} - U_{d2})/R_d$.

In LCC HVDC, the d.c. line power flow can be controlled by holding the d.c. voltage at the receiving end converter (the inverter) at a constant value, and by letting the sending end converter (the rectifier) control the d.c. current. The same approach can be used in VSC transmission. However, one main difference is that in LCC HVDC the current direction is always the same; therefore, the power direction is modified by changing the d.c. voltage polarity.

2.6 Losses

VSC transmission has higher losses than LCC HVDC. This is obviously an economic disadvantage for VSC transmission in bulk power transmission, since its capitalised losses are comparatively high.

However, the technical advantages of VSC transmission can offer other system benefits, such as ancillary services like a.c. voltage support or black network start. VSC transmission is also well suited for use in a liberalised market where rapid and frequent power transmission changes in both directions can be expected. For such applications, it is important to assess accurately transmission losses under realistic operating conditions when comparing LCC HVDC and VSC transmission.

In general, losses can be divided into no-load losses and load losses. The no-load losses are those that arise when the VSC transmission is energised without any power being transmitted, and when no reactive power is exchanged between the VSC stations and the grid.

No-load losses primarily arise in interface transformers, phase reactors and filters as iron or dielectric losses. In addition, various auxiliary systems, such as cooling, heating and power supply to the control system, also contribute to these losses when the VSC stations are energized.

The load losses occur when power is being transmitted and the VSC stations are exchanging reactive power with their a.c. grids. Load losses increase with the loading of the d.c. transmission line and the VSC stations. The load losses arise from ohmic conduction losses in the d.c. lines and in the VSC stations. Load losses in the VSC station come from ohmic conduction losses, and from switching losses in the semiconductor switches and their anti-parallel diodes, and in snubber circuits, if any.

For an accurate capitalisation of the losses, as described in Chapter 13, it is crucial to know the no-load and load losses as a function of power transmission and reactive power exchange with the a.c. grid. Based on this information, as well as on the expected use and loading of the VSC transmission scheme (for example, as a load duration curve over a year), it is possible to capitalise losses.

2.7 Summary of the Basic Characteristics of VSC transmission

Although VSC transmission possesses several inherent technical advantages over LCC HVDC, it should be emphasised that some functionalities similar to those of VSC may be obtained with an LCC if special measures and design are implemented in the scheme. For instance, it is possible to design an LCC HVDC scheme for operation at extreme low short-circuit ratio (SCR), particularly if the installation is supplemented by synchronous condensers for voltage control and additional inertia in the a.c. grids. This would, however, add losses and costs to an LCC HVDC solution.

The advantages and disadvantages of VSC transmission compared with LCC HVDC are summarised as follows.

VSC Advantages Compared with LCC

- The VSC valves are self-commutating.
- Commutation failures due to grid fault or a.c. voltage dips do not occur.
- The VSC may be operated at a very small short-circuit ratio. The least SCR which has been practically experienced by the end of 2004 is 1.3.
- The VSC can energise a passive or dead grid.
- VSC transmission has no minimum d.c. current limits.
- The reactive power, either capacitive or inductive, can be controlled independently of the active power within the rating of the equipment.
- Reactive shunt compensation is not required.
- Only harmonic filters are needed and they need not be switchable.
- Depending on the converter topology, if transformers are needed they do not have to be specially designed HVDC converter transformers, but conventional a.c. transformers may be used.
- The voltage polarity on the d.c. side is always the same. DC cables are always exposed to the same voltage polarity.
- The VSC control can be designed in such a way that the VSC stations can eliminate flicker and selected harmonics in the a.c. grid.
- The VSC stations can be operated as STATCOMs, even if the VSC is not connected to the d.c. line.
- The footprint of a VSC station is considerably smaller than an LCC HVDC station.

- Inherently, VSC transmission can operate without telecommunication between the VSC substations.

VSC Disadvantages Compared with LCC

- At the end of 2004, practical experience with VSC transmission was not as extensive as with LCC.
- The maximum VSC transmission ratings are ± 150 kV and 350 MW (receiving end). For higher transmission capacities, additional parallel VSC transmission schemes would be required, which would add costs and losses to a VSC solution.
- DC line faults require opening of the VSC a.c. circuit-breakers at both ends of a scheme in order to clear the d.c. fault, unless appropriate d.c. breakers are provided in the scheme.
- The switching losses in the VSC valves are higher compared with similar LCC valves, primarily due to higher switching frequency, and because a VSC valve has many more semiconductor switches than an LCC valve of the same rating.

Today, the main obstacles to VSC transmission are its high losses and limited capacity for bulk power transmission.

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3. BASIC OPERATING PRINCIPLES OF VSC TRANSMISSION

3.1 Introduction

The VSC transmission technology described in this PAS uses self-commutated voltage-sourced converters (VSC), in which commutation does not rely on the voltage of the a.c. network. The VSC valves use solid-state devices, like insulated gate bipolar transistors (IGBT) or other devices with controlled turn-on and turn-off capability. VSC transmission has a number of technical features that are superior to those of an LCC HVDC scheme.

A simplified one-line diagram of one of the VSC terminals in a VSC transmission scheme is shown in Figure 3.1. In a point-to-point transmission scheme, the other half of the scheme would be a mirror image about the mid-point of the d.c. link. The d.c. link may be a cable or overhead line. In contrast to line-commutated d.c. transmission, the polarity of the d.c. voltage remains the same at all times, with the d.c. current being reversed to change the direction of the power flow. The different VSC transmission applications are described in Chapter 2.

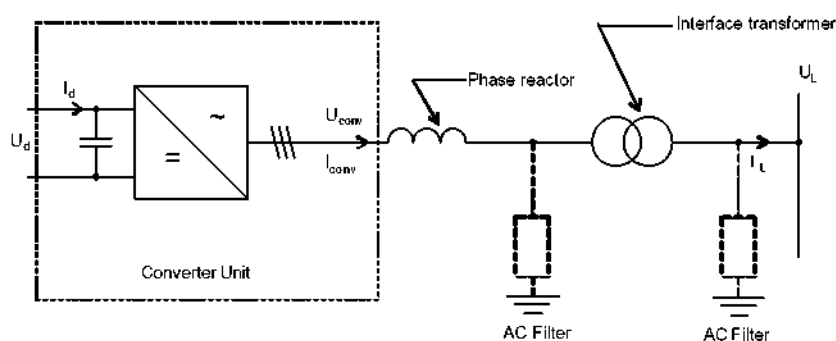


Figure 3.1- One VSC terminal of a VSC transmission scheme

The VSC approximates a voltage source. The term “voltage source” derives from mathematical circuit analysis and can be defined as “a voltage source which maintains a prescribed voltage across its terminal, irrespective of the magnitude or polarity of the current flowing through the source. The voltage may be constant d.c., sinusoidal a.c., a series of pulses, etc. For a prescribed voltage source, the output current depends only on the impedance connected across its terminals.” [3-1].

A VSC has a capacitor connected direct across the d.c. terminals, with no intervening impedance apart from snubbers and wiring. For short-time transients, a capacitor can be regarded as a voltage source, hence this capacitor represents an approximate d.c. voltage source. The switching devices are controlled to interconnect the d.c. and a.c. terminals in a time sequence in such a way that an a.c. source of the same type as the d.c. source is produced. Thus, a VSC produces a quasi-square wave a.c. voltage.

The basic operating mechanism of an ideal VSC is covered in this chapter. The description is initially limited to a 2-level VSC in square wave operation. The 2-level VSC is the simplest structure needed to convert a d.c. voltage into a.c. voltage. Although other types of multi-level VSCs are more complex, their basic operating principle does not differ from that of the 2-level VSC. The different multi-level converter topologies are discussed further in Chapter 4.

For the purpose of illustration, the VSC valves are described as ideal switches without any switching losses. A VSC valve in a real application consists of a large number of series-connected semiconductor devices, and is described in greater detail in Chapter 5. The stray inductances are neglected here, and the d.c. capacitors have been assumed to have infinite capacitance, i.e., no d.c. voltage ripple is shown.

The output of the VSC should be connected in series with a phase reactor, as shown in Figure 3.1. The phase reactor enables the VSC to control power flow in addition to smooth the output current. VSC components are further explained in Chapter 6.

3.2 Basic Operational Principle of Two-Level Converters

The basic a.c. output waveform of a VSC is determined by the topology of the converter. The operating principle of a 2-level VSC is described in the following paragraphs.

A schematic of one-phase of a 2-level converter is presented in Figure 3.2. As shown, it is capable of generating the two voltage levels. In order to improve the quality of the output voltage, pulse width modulation (PWM) (see 9.3) can be used to produce an output waveform with dominant fundamental component, but also high-order harmonics, as described among others in [3-2] and [3-3].

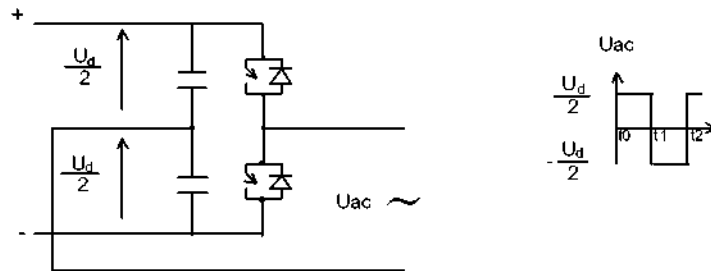


Figure 3.2 - Basic operational characteristic of a 2-level VSC

In a real VSC, the switches are implemented as solid-state switches and the voltage source input characteristic is obtained by connecting two d.c. capacitors in series, as shown in Figure 3.2.

The solid-state switches are unidirectional only, therefore free-wheeling diodes are connected across the solid-state switches, which are shown in the diagram as ideal unidirectional switches. The midpoint of the capacitors can be considered as the reference point for the a.c. output voltage of the phase unit $U_{a.c.} = U_{conv.}$. The output terminals can only be connected at two voltage levels: the positive d.c. voltage $+U_d/2$, or the negative d.c. voltage $-U_d/2$ (two-level converters).

Thus the direct voltage in Figure 3.2 can only have one polarity due to the free-wheeling diodes, whereas the current can flow in both directions.

The four possible current paths in a single-phase, 2-level VSC are shown in Figure 3.3. The output current can either be negative or positive. Positive current direction in the VSC is defined as current flowing from the d.c. side to the a.c. side (see Figure 3.2 and Figure 3.3b and 3.3d).

If the upper VSC valve is on, the output voltage is $+U_d/2$. If the current is negative (Figure 3.3a), the current path is through the upper free-wheeling diode, because the controllable switch can only conduct current in the downward direction. If the current is positive (Figure 3.3b), the current path is through the upper controllable switch.

If the lower VSC valve is on, the output voltage is $-U_d/2$. If the output current is negative, the current path is through the controllable switch (Figure 3.3c), and if the current is positive, its path is through the lower free-wheeling diode (Figure 3.3d).

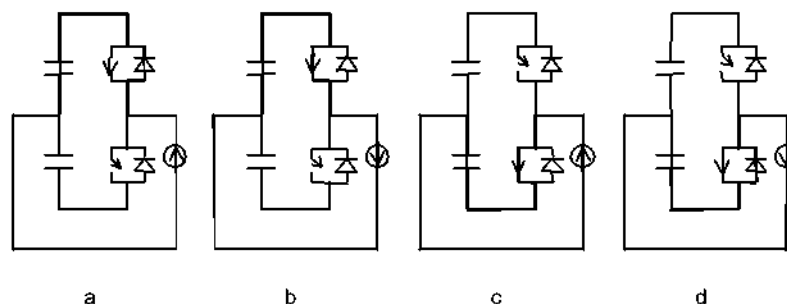


Figure 3.3 - Four possible current paths in a single-phase, 2-level VSC

The following paragraphs describe in more detail the basic operation of the 2-level VSC shown in Figure 3.2.

Assuming both switches are blocked, i.e., with open switches, the free-wheeling diodes form an uncontrolled rectifier. An external a.c. voltage source applied as $U_{a.c.}$ would charge the two d.c. capacitors via this rectifier to the peak value of the a.c. voltage $U_{dc}/2 = \sqrt{2}U_{a.c.}$ across the upper and lower d.c. capacitor, with polarities as shown in the figure. With the d.c. capacitors charged and the external source connected, the VSC is ready for operation.

The controllable switches can be switched on and off in a desired pattern via the gate signals. During operation, one switch is turned on while the other is turned off. Turning on both controllable switches at the same time would create a short circuit of the d.c. capacitors, and must be prevented. In order to avoid such a short-circuit, the controllable switch in the off-state is turned on shortly after the controllable switch in the on-state is turned off. This creates a short instant, called the “blanking time,” when none of the controllable switches are on. During a typical blanking time of some 10 μs , a current path is provided by the free-wheeling diodes.

Assuming the upper switch is turned on at $t = 0$, as shown in Figure 3.2, the a.c. terminal would be connected to the plus terminal of the storage capacitor, resulting in a current flow through the upper switch. Depending on the pulse pattern applied, the upper switch will be turned off after a short time span at $t = t_1$. However, the source impedance of the external a.c. circuit, which in most cases will be the impedance of the interface transformer and/or phase reactor (see Figure 3.1), will maintain the present current. Thus, the diode connected in parallel to the lower switch turns on. As a consequence, the voltage $U_{a.c.}$ changes from plus to minus $U_d/2$. The polarity reversal is initiated by turning off the switch actively, i.e., while it carries current.

The lower controllable switch is required to be on whenever the current reverses to maintain the voltage polarity, and therefore it will get a gate signal following a very short blanking time, typically some 10 μs after blocking the upper VSC valve. The lower controllable switch will then take over current as soon as the current reverses its direction, which depends also on the impedance of the interface transformer and the phase reactor, as well as the a.c. system voltage.

It should now be assumed that the current is still flowing in the diode parallel to the lower switch, when at $t = t_2$ it is required to connect the converter a.c. terminal to the positive terminal of the VSC d.c. capacitor again.

The two mechanisms, turning on and off the switches of the VSC phase unit actively in an alternating manner, entirely determine the switching states of the diodes, and, therefore, the voltage level on the a.c. terminal. This basic principle of operation can be found in all types of VSCs, and applies irrespective of any fundamental power flow (in all four quadrants, active power export or import, as well as capacitive or inductive reactive power). Therefore, the VSC can be represented in a simplified manner as a voltage source with the magnitude and the phase angle of the a.c. voltage $U_{a.c.}$ determined by the d.c. voltage and the pulse patterns. This is further described below, where the VSC in a three-phase configuration is presented.

3.3 Two-Level VSC — Three-Phase Configuration

The basic 2-level voltage sourced converter described above is illustrated in a three-phase (phase a,b,c) configuration in Figure 3.4. Each of the six VSC valves consists of one switching unit with a current turn-on and off capability and a free-wheeling diode.

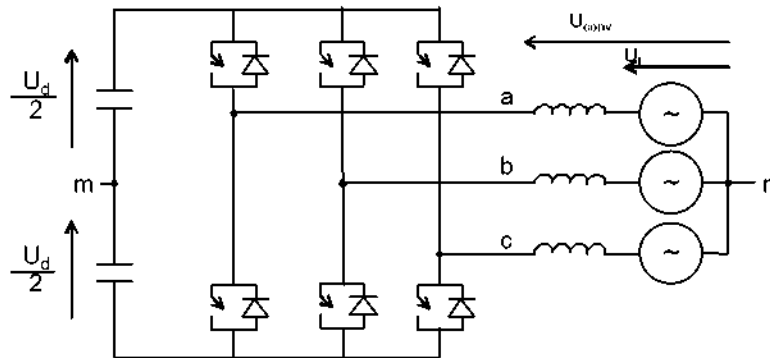


Figure 3.4 - Basic 2-level, 6-pulse VSC—three-phase configuration

3.3.1 Terminal Voltages

The simplest operational mode for the 2-level VSC is the square wave operation. Figure 3.5 presents the terminal voltages on the valve side of the station transformer winding for a VSC in square wave operation. The first three sets of curves are the voltages between phase terminals and the midpoint “m” of the d.c. capacitors. The next three are the line-to-line voltages between the terminals. The last curve is the phase voltage in phase a.

As shown in Figure 3.5, each valve switches on and off once each cycle of the a.c. voltage, thus giving rise to six pulses per fundamental frequency period.

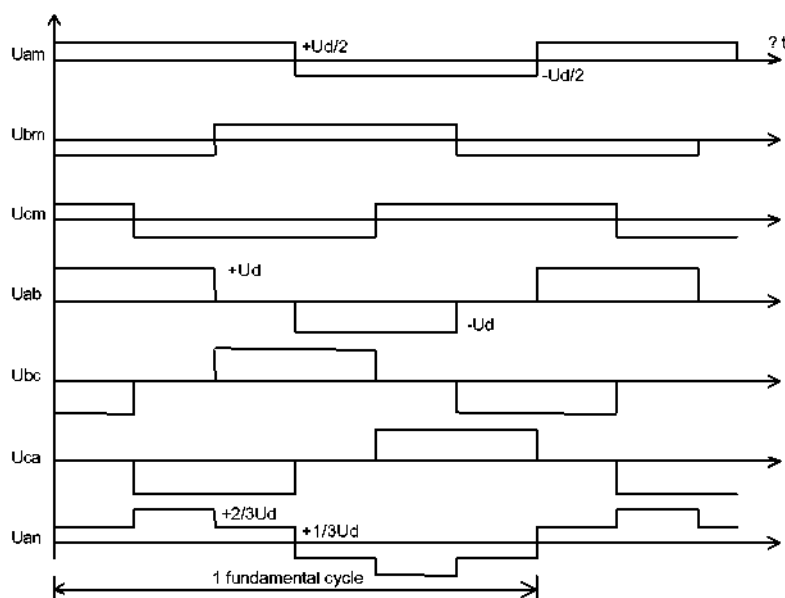
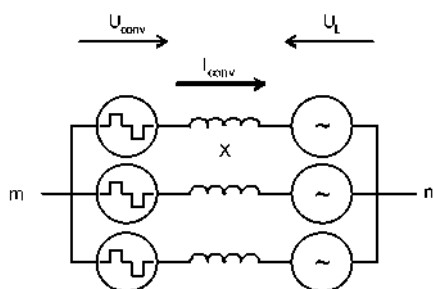


Figure 3.5 - VSC voltages converter side — square wave operation

Curve 1,2,3: Phase-terminals (a,b,c) to midpoint m
Curve 4,5,6: Terminal line-to-line voltage (a-b,b-c,c-a)
Curve 7: Phase-voltage terminal a to neutral

3.3.2 Fundamental Frequency Equations — Square Wave Operation

The VSC square wave operation can be represented with an equivalent circuit [3-3], as shown in Figure 3.6. In this equivalent, the converter voltage U_{conv} in Figure 3.6 is equivalent to U_{an} in Figure 3.5. The filters shown in Figure 3.1 are neglected for simplicity, hence I_{conv} in Figure 3.6 equals I_L in Figure 3.1. The reactance X represents both the interface transformer and phase reactor reactance. The resistance is neglected for simplicity. The a.c. voltage U_L is used as the phase angle reference.



The r.m.s. value of the fundamental frequency component of the phase voltage $U_{Conv-ph}$ on the valve side of the interface reactance for the VSC in square wave operation can then be defined as [3-3]:

$$U_{\text{conv.ph(1)}} = \frac{\sqrt{2}}{\pi} k_{\lambda} U_d e^{-j\delta} \quad 3.1$$

The relationship between the r.m.s. value of the fundamental frequency component of the line-to-line voltage on the valve side of the interface reactance and the d.c. voltage can be expressed as [3-3]:

$$U_{\text{conv(1)}} = \frac{\sqrt{6}}{\pi} k_{\lambda} U_d e^{-j\delta} \quad 3.2$$

where

δ is the phase angle between the converter voltage U_{conv} and the a.c. voltage U_L ;
 k_{λ} is the voltage ratio factor [0..1].

Equation 3.1 includes the voltage ratio factor k_{λ} as shown. For square wave operation k_{λ} equals 1. For a PWM converter k_{λ} equals any value between zero and 1.

By neglecting the resistance in Equation 3.1, the corresponding phase current in phase a can be expressed as:

$$I_{\text{conv.a(1)}} = \frac{U_{\text{conv.ph(1)}} - U_{L(1)}}{Z} = \frac{\frac{\sqrt{2}}{\pi} k_{\lambda} U_d e^{-j\delta} - U_{L(1)} e^{-j0}}{jX} \quad 3.3$$

Corresponding current expressions are obtained for the other phases.

3.4 Active and Reactive Power VSC

Electrical engineering textbooks give the equation for transmission across a system with known series impedance and known sending end and receiving end voltages. By neglecting the resistance and expressing the voltages by line-to-line voltages, the following expressions for P and Q can be derived [3-3]:

$$P = \frac{U_{\text{conv(1)}} U_{L(1)}}{X} \sin \delta \quad 3.4$$

$$Q = \frac{U_{L(1)} (U_{L(1)} - U_{\text{conv(1)}} \cos \delta)}{X} \quad 3.5$$

$$I_d = \frac{\sqrt{6}}{\pi} \frac{U_{L(1)}}{X} \sin \delta \quad 3.6$$

As shown in Equation 3.4, the active power is mainly determined by the phase angle between $U_{L(1)}$ and $U_{conv(1)}$. The reactive power for the VSC (as shown in Equation 3.5) is mainly determined by the magnitude of the converter side a.c. voltage $U_{conv(1)}$ relative to $U_{L(1)}$. This is indeed similar to the way the reactive power is controlled in a synchronous machine, where the “internal voltage” E is equivalent to the VSC voltage $U_{conv(1)}$ in Equation 3.5.

As described in Chapter 2, one of the great advantages of VSC transmission is that it can operate in all four quadrants in the P-Q diagram. This implies that the VSC can generate and absorb reactive power independently of d.c. link power magnitude and direction.

The reactive power from the VSC is determined mainly by the voltage difference between the VSC U_{conv} and the a.c. voltage U_L . At any given operating point, an increase of $U_{conv(1)}$ would result in a relative increase in the reactive power delivered to the grid. Similarly, at any given operating point, a decrease of $U_{conv(1)}$ would result in a relative decrease in the reactive power delivered to the grid.

The active power from the VSC is determined mainly by the angle between the VSC U_{conv} and the a.c. voltage U_L . At any given operating point, an increase of the phase delay of $U_{conv(1)}$ would result in a relative decrease in the active power delivered to the grid. Similarly, at any given operating point, a decrease of the phase angle delay of $U_{conv(1)}$ would result in a relative increase in the active power delivered to the grid.

In normal operation, the d.c. voltage will be approximately constant, whereas the d.c. current will vary in both magnitude and direction. The output active power of the VSC link will, therefore, be proportional to the average input d.c. current both in magnitude and direction.

A change of active power direction for a VSC is achieved by changing the direct current direction.

3.5 VSC Control and Harmonics

There are limitations in terms of the performance for a 2-level fundamental frequency-switched converter. As a consequence, such control is not widely used in practice.

The most commonly used methods to control P and Q in steady state and during dynamics are:

- high frequency switching PWM;
- multi-level;
- combination of the above.

By using PWM, it is possible to achieve fast control of the converter a.c. voltage and, at the same time, keep the d.c. voltage constant. PWM is further described in Chapter 7. The multi-level converter is described in Chapter 4.

By increasing the switching frequency, the harmonic distortion at the a.c. system connection is moved to higher orders, which is easier to filter. However, increasing the switching frequency also increases losses, as further described in Chapter 5. Therefore, an optimisation has to take place in order to balance the harmonic level, on the one hand, and the capital cost, power losses, footprint, etc., on the other.

The converter output voltage can only vary between a limited number of voltage levels. Therefore, in order to obtain a reasonable sinusoidal voltage at the a.c. system connection, output filters would normally be needed in accordance with specified harmonic requirements. Similarly, to satisfy the respective grid requirements, a.c. harmonic filters may be needed to limit the harmonic currents that can flow into the a.c. system.

Typically, low-order harmonics require filters with a higher fundamental frequency rating than those used for filtering higher-order harmonics. The low-order harmonic content in the voltage output of a VSC can be reduced in different ways. Harmonics are covered in greater detail in Chapter 9.

3.6 References

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4. VSC TRANSMISSION TOPOLOGIES

4.1 Introduction

For a high-power VSC transmission system, the key issue that determines the power-circuit structure, and thereby the cost and operating losses of the overall system, is the method used to construct the output voltage waveform. The output voltage waveform should approximate a sine-wave in order to eliminate or minimise the need for harmonic filtering. The switching converter considered for practical implementation is a voltage sourced converter operated with a fixed d.c. voltage. The converter is an array, or matrix, of controlled solid-state switches which connect the d.c. input voltage periodically, for pre-determined intervals, to the output to produce the a.c. output voltage. The converters at each end of a VSC transmission system can be arranged in a number of different ways, with the configuration of the converter normally being referred to as its topology.

It is a fundamental criterion for any viable topology that it enables the functional requirements to be met. Different topologies have different technical characteristics, and therefore allow the overall scheme to be optimised in different ways. Manufacturers may have different preferred topologies and be able to best optimise their proposals around this preferred topology. It is recommended that customers do not stipulate the topology to be used for a VSC transmission system, unless there are compelling reasons for doing so.

It is possible to arrange the converters to have a single-, three- or multi-phase a.c. output/input. For the purpose of this PAS only the three-phase arrangement will be discussed.

The switch-matrix may be of different complexity depending on the number of “dc” voltage levels to be produced at the a.c. output of each converter phase unit. As the number of attainable voltage levels increases, the approximation of an a.c. sinusoidal output is approached at the expense of increasing circuit complexity.

This chapter begins with a description of a number of different arrangements of the commutating switches (VSC valves), referred to as the converter phase unit topology, which may be 2-level, 3-level or multilevel. The chapter then describes how different combinations of the converter phase unit topology can be used to create a converter topology for each terminal of the VSC scheme. The chapter concludes with a brief summary and a comparison of the relative merits of each topology.

A major difference between the application of voltage sourced converters for STATCOM and VSC transmission is that, for VSC transmission, it is necessary to control the two d.c. bus voltages in such a way that the desired real power flows between the two terminals. In practice it means that the d.c. bus voltage is kept almost constant in a VSC transmission system, i.e., there is one less degree of freedom compared to a STATCOM application. In particular, to control the fundamental frequency component of the a.c. voltage, and thus the power factor of operation, it is necessary to allocate one switching edge per half cycle.

4.2 Converter Phase Unit Topologies

The basic objective of the converter is to enable energy to be transferred from an a.c. busbar to a d.c. busbar and vice versa. Under normal operating conditions the d.c. bus voltage in a VSC transmission scheme can be considered to be stiff, due to the d.c. capacitor, i.e., the voltage between the two terminals does not change substantially during a power frequency cycle. The peak-to-peak amplitude of the steady-state d.c. capacitor voltage change within a power frequency cycle is known as the voltage ripple. Voltage ripple is normally expressed as a percentage of the d.c. voltage.

The converter switches (normally called VSC valves) perform the function of connecting the a.c. bus to the d.c. terminals. If the connection is direct through two alternately operating switches, the a.c. bus voltage will change between the voltage levels at the two d.c. terminals. Such a converter is known as a 2-level converter. In the 2-level converter, each of the VSC valves has to withstand the voltage between the two d.c. terminals.

If the d.c. capacitor is subdivided, or additional d.c. capacitors are added, it is possible to arrange for the a.c. voltage to move not only to the voltage at the two d.c. terminals but also to intermediate levels. The number of voltage levels to which the a.c. bus voltage can be switched will depend on the number of valves and the number of d.c. capacitor subdivisions or additional d.c. capacitors. These arrangements are known as 3-level or multi-level converters, depending on the number of voltage levels that can be achieved. The term multilevel refers to a converter phase unit topology where the a.c. bus can be switched to attain more than three different voltage levels.

In 3-level or multi-level phase unit topologies, the VSC valves do not normally have to be designed for the full d.c. terminal-to-terminal voltage. For example, in normal operation each valve in a 3-level converter phase unit topology experiences only 50 % of the terminal-to-terminal d.c. voltage. Similarly, in normal operation, each VSC valve in an n-level phase unit topology experiences only the terminal-to-terminal d.c. voltage of the phase unit divided by (n-1).

In the following paragraphs, converter phase unit topologies suitable for VSC transmission systems will be described in more detail. It should be noted that a considerable research and development effort is being invested in voltage sourced converter technology, so additional suitable topologies will likely become available subsequent to the issue of this PAS.

4.2.1 Converter Phase Unit Topologies—General Aspects

For each converter phase unit topology a number of issues need to be considered. While the relative importance of each issue may vary with different topologies, a brief discussion of the primary ones will be given here, to avoid having to repeat them later.

VSC valves can be turned on and off more than once per power frequency cycle to reduce the harmonics on both the a.c. and the d.c. side. An additional way to reduce the harmonics is to combine the output from several phase units in an appropriate manner. An additional benefit of switching the valves more frequently is that the size of the d.c. capacitor(s) can be reduced. This is because the d.c. capacitor is normally sized to lessen the voltage ripple during operation to about 2 % to 10 %, and when the valves are switched, the current direction in the d.c. capacitor changes direction, reducing the effective ripple.

The rapid switching of the a.c. bus voltage between different levels will result in repetitive, high-frequency transient stresses. These stresses must be taken into account in the design of the components for the VSC transmission system. For a given d.c. voltage, the transient stresses will vary with the number of switchings per power-frequency cycle and the number of intermediate steps (if any) between the two d.c. terminal voltages. The stresses are normally lower the higher the number of levels in the converter phase unit topology. Wound components are particularly vulnerable to repetitive, high-frequency transient stresses. However, other components must also be examined carefully. For example, high losses in the dielectrics of insulation systems may cause premature ageing, unless the particular stresses are recognised and taken into account at the design stage. The interface transformer may be protected against the stresses by providing a high-frequency blocking filter between the valves and the transformer. Naturally, all of the components of such a filter must be designed with special attention to the high-frequency stresses imposed on them.

The manufacturer will normally determine the number of valve switching operations performed during each power frequency cycle through an economic optimisation process. Effectively, more switching operations will result in the following advantages and disadvantages.

Advantages of increased switching operations:

- simpler and smaller a.c. (and d.c.) harmonic filters;
- smaller d.c. ripple;
- smaller footprint for the VSC substation.

Disadvantages of increased switching operations:

- higher power losses in the converter;
- reduced power capability for each device;
- stresses on wound components increase due to the more frequent application of high dv/dt from the converter.

In the following illustrations, in order to keep the figures simple, the waveform for each topology is shown for the case of fundamental frequency switching. However, this operating mode is unlikely to be used for a VSC transmission scheme. An example of a pulse width modulation (PWM) waveform will be given for the 2-level and the 3-level converter.

4.2.2 Two-Level Converters

A 2-level phase unit is the simplest switching arrangement capable of producing a.c. output from a d.c. source in the form of a simple square-wave. A three-phase converter using three 2-level phase units is illustrated in Figure 4.1.

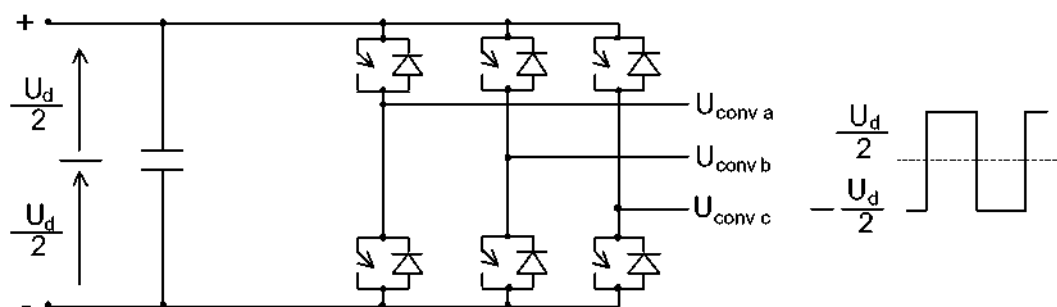


Figure 4.1- Diagram of a three-phase 2-level converter and associated a.c. waveform for one phase

The a.c. waveform shown in Figure 4.1 is the phase-to-neutral voltage, assuming fundamental frequency switching of the phase units. The neutral voltage is the voltage at the midpoint of the d.c. capacitor.

Due to the square-wave output voltage waveform, the 2-level phase unit is unable to facilitate direct control of the amplitude of its fundamental output voltage without the application of PWM.

A typical PWM-switched waveform, using a carrier-based control method with a switching frequency of 21 times the fundamental, is given in Figure 4.2. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).

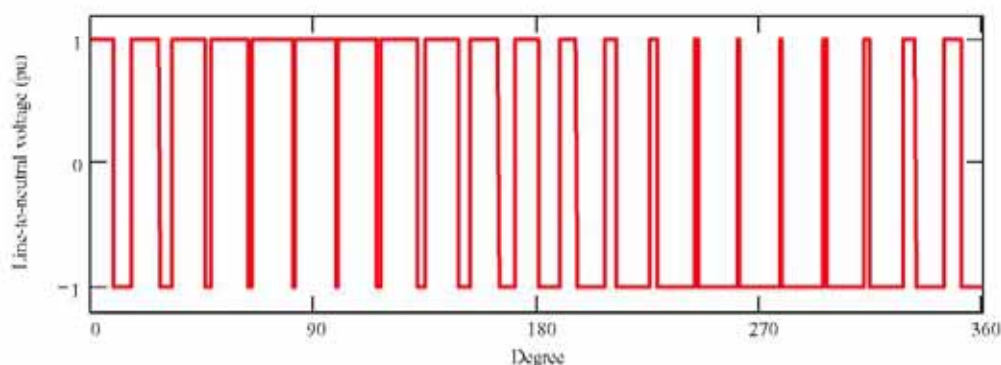


Figure 4.2- Single-phase a.c. output for 2-level converter with PWM switching at 21 times fundamental frequency

4.2.3 Three-Level Neutral Point Clamped Converter

A three phase converter consisting of three 3-level phase units is illustrated in Figure 4.3. The single-phase output voltage waveform, assuming fundamental frequency switching, is also shown in Figure 4.3. The converter has three d.c. terminals to connect to a split or centre-tapped d.c. source. As seen, there are twice as many valves used as in the 2-level phase unit, and additional diodes are required to connect to the d.c. supply centre-tap, which is the reference zero potential. However, with identical valve terminal-to-terminal voltage rating, the total d.c. supply voltage can be doubled so that the output voltage per valve remains the same.

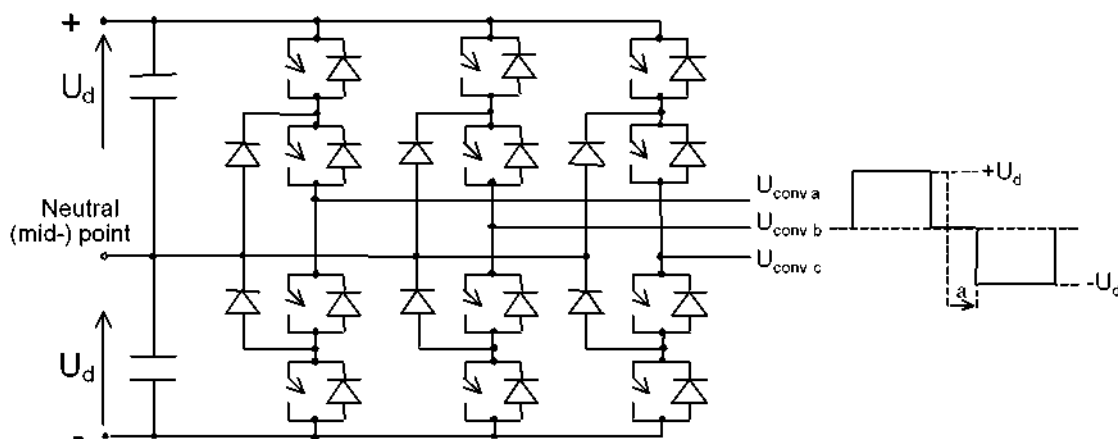


Figure 4.3 - Diagram of a three-phase 3-level NPC converter and associated a.c. waveform for one phase

The a.c. waveform shown in Figure 4.3 is the phase-to-neutral voltage, assuming fundamental frequency switching of the valves. The neutral voltage is the voltage at the midpoint of the d.c. capacitor. As illustrated in Figure 4.3, the output voltage of the 3-level phase unit can be positive, negative or zero. Positive output is produced by gating on both upper valves in the phase unit, while negative output is produced by gating on both lower valves. Zero output is produced when the upper and lower middle valves, connecting the centre tap of the d.c. supply via the two diodes to the output, are gated on. At zero output, positive current is conducted by the upper-middle controllable device and the upper centre-tap diode, and negative current by the lower-middle controllable and the lower centre-tap diode.

As indicated in Figure 4.3, the relative duration of the positive (and negative) output voltage with respect to the duration of the zero output is a function of control parameter α , which defines the conduction interval of the top upper, and the bottom lower valves. The magnitude of the fundamental frequency component of the output voltage produced by the phase unit is a function of parameter α . When α equals 0° it is maximum, while at α equals 90° it is zero. Thus, one advantage of the 3-level phase unit is that it has an internal capability to control the magnitude of the output voltage without changing the number of valve switchings per cycle.

The operating advantages of the 3-level phase unit can only be fully realised with some increase in circuit complexity, as well as more rigorous requirements for managing the proper operation of the converter circuit. These requirements are related to executing the current transfers (commutation) between the four (physically large) valves, with well-constrained voltage overshoot, while maintaining the required di/dt and dv/dt for the semiconductors without excessive losses.

An additional requirement is to accommodate the increased a.c. ripple current with a generally high triplen harmonic content flowing through the mid-point of the d.c. supply. This may necessitate the use of a larger d.c. storage capacitor or the employment of other means to minimise the fluctuation of the mid-point voltage. However, once these problems are solved, the 3-level phase unit provides a useful building block to structure high-power converters, particularly when rapid a.c. voltage control is needed.

The conduction periods for the inner and the outer valves is different, and therefore it is possible to use two different designs of a VSC valve for the two positions.

By switching the valves more frequently, it is possible to eliminate more harmonics. A typical PWM switched waveform, using a carrier-based control method with a frequency of 21 times fundamental frequency, is given in Figure 4.4. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).

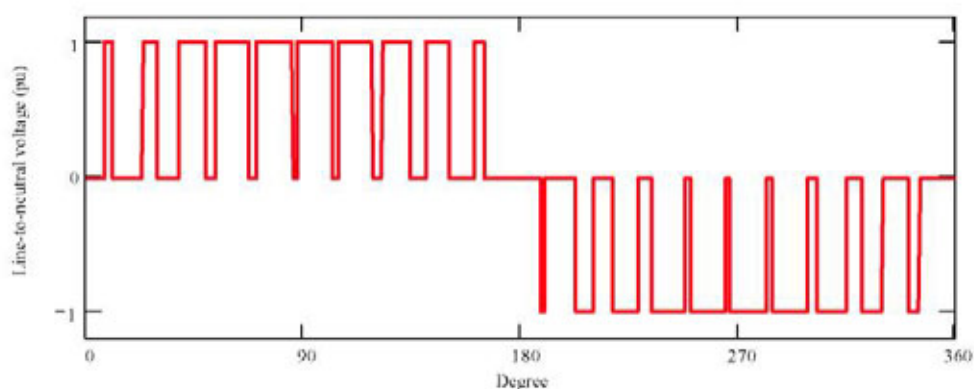


Figure 4.4 - Single-phase a.c. output for 3-level NPC converter with PWM switching at 21 times fundamental frequency

4.2.4 Multi-Level Neutral Point Clamped Converter

In order to further reduce the harmonic content of the a.c. output voltage, the basic 3-level phase unit can be extended to a multi-level, $2n + 1$ phase unit ($n = 1, 2, 3, \dots$) configuration. $2n$ d.c. supplies, provided by $2n$ d.c. storage capacitors (which are common to all three-phase units of a complete three-phase converter) are connected in series, providing $2n + 1$ discrete voltage levels.

Four times n valves are required with $4n - 2$ diodes to selectively connect the $2n + 1$ voltage levels to the output.

A three-phase converter using 5-level converter phase units with the corresponding single-phase output voltage waveform, in which, as an example, the 3rd, 5th, and 7th harmonics are absent, is shown in Figure 4.5. However, it should be remembered that in practice one degree of freedom would be needed for control of the amplitude of the fundamental frequency. Therefore, in practice, in this example only one of the 5th or the 7th harmonic can be cancelled.

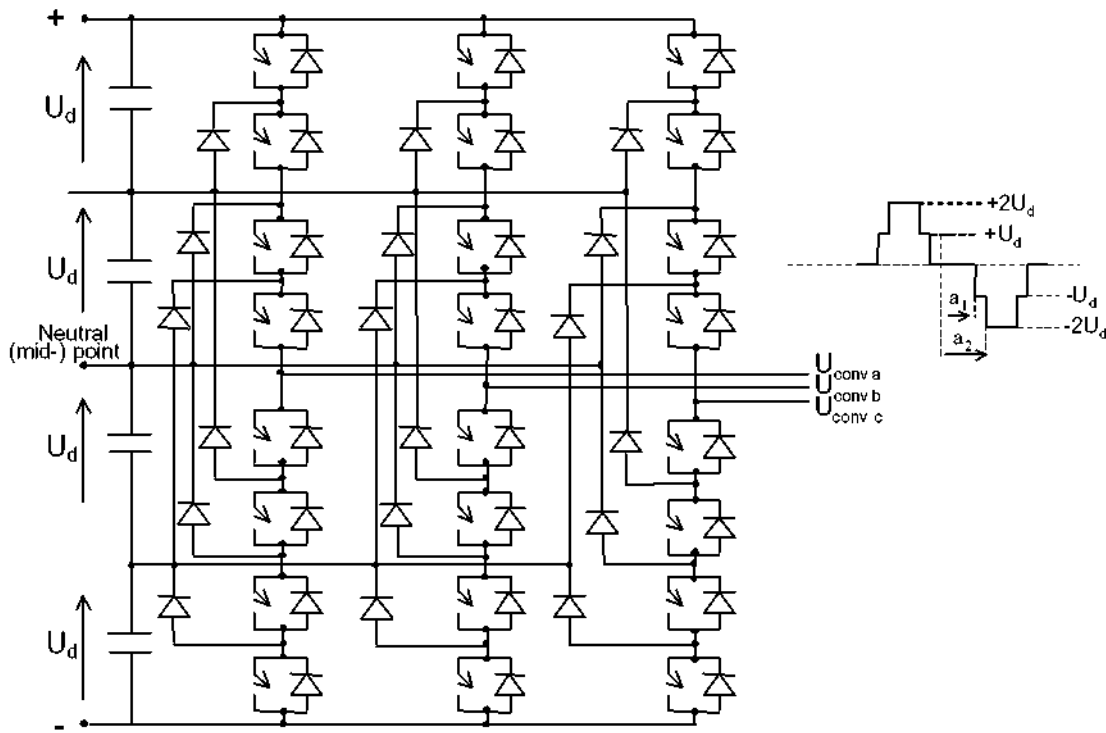


Figure 4.5 - Diagram of a three-phase 5-level NPC converter and associated a.c. waveform for one phase

From Figure 4.5 it is clear that the circuit complexity rapidly increases with the number of voltage levels. However, compared to the 3-level neutral point clamped topology, the individual valves are switched approximately half the number of times in the 5-level topology and the harmonic performance at the output terminals is still superior. The uneven utilisation of the valves and the escalating voltage ratings of tap-diodes may make the economical viability of a pulse number in excess of five questionable.

4.2.5 Three-Level Floating Capacitor Topology

The 3-level floating capacitor topology is an alternative to the 3-level neutral point clamped topology described in 4.2.3. In the floating capacitor topology, the additional voltage step is achieved by the inclusion of a separate d.c. capacitor in each phase. The circuit is controlled in such a way that the d.c. voltage on the additional d.c. capacitor is 50 % of the terminal-to-terminal d.c. voltage. The circuit diagram for a converter using 3-level floating capacitor phase units, along with the associated output voltage waveform, are shown in Figure 4.6.

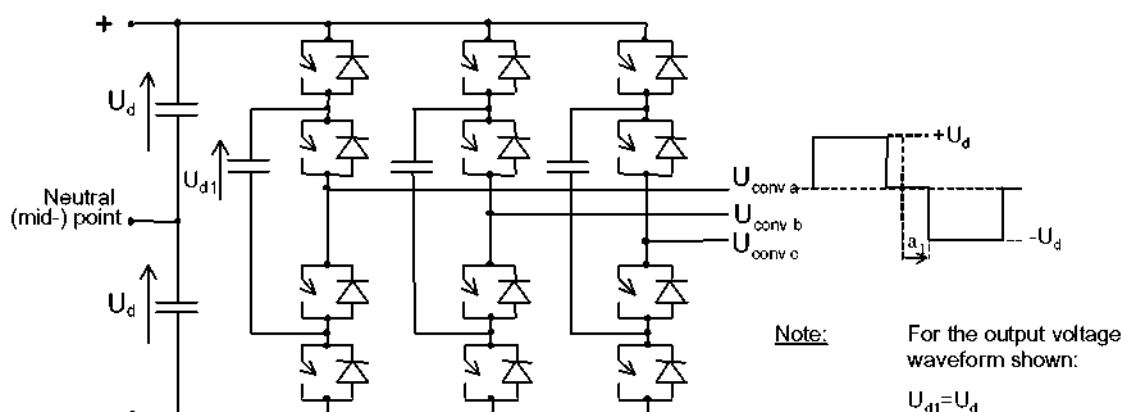


Figure 4.6 - Diagram of a three-phase 3-level floating capacitor converter and the associated a.c. waveform for one phase

The valves switch the a.c. buses between the different voltage levels by directing the current path through (or past) the d.c. capacitors, adding and subtracting the voltage of d.c. capacitors as desired. The intermediary d.c. capacitor may be by-passed for part of the power frequency cycle.

The total d.c. capacitor VA rating may be considerably larger for this topology than for the 2-level or 3-level neutral point clamped topologies. This is partly due to the need for separate capacitors for each phase, but also because the d.c. capacitors carry a significant ripple current.

The output waveform for a converter using PWM switching would be virtually identical to that of the neutral point clamped converter illustrated in Figure 4.4.

4.2.6 Multi-Level Floating Capacitor Topology

The floating capacitor converter circuit described in 4.2.5 can be extended to provide a circuit giving a higher number of levels than three. This is achieved by adding more d.c. capacitors and subdividing the VSC valves. As an example, Figure 4.7 shows the circuit diagram of a 5-level floating capacitor converter and the associated output waveform.

The valves switch the a.c. buses between the different voltage levels by directing the current path through the d.c. capacitors, adding and subtracting the voltage of d.c. capacitors as desired. The intermediary d.c. capacitors may also be by-passed for part of the power frequency cycle.

Typically, the total d.c. capacitor VA rating is considerably larger for this topology than for the 2- or 3-level neutral point clamped topologies. This is partly due to the need for separate capacitors for each phase, but also because the d.c. capacitors carry a significant ripple current.

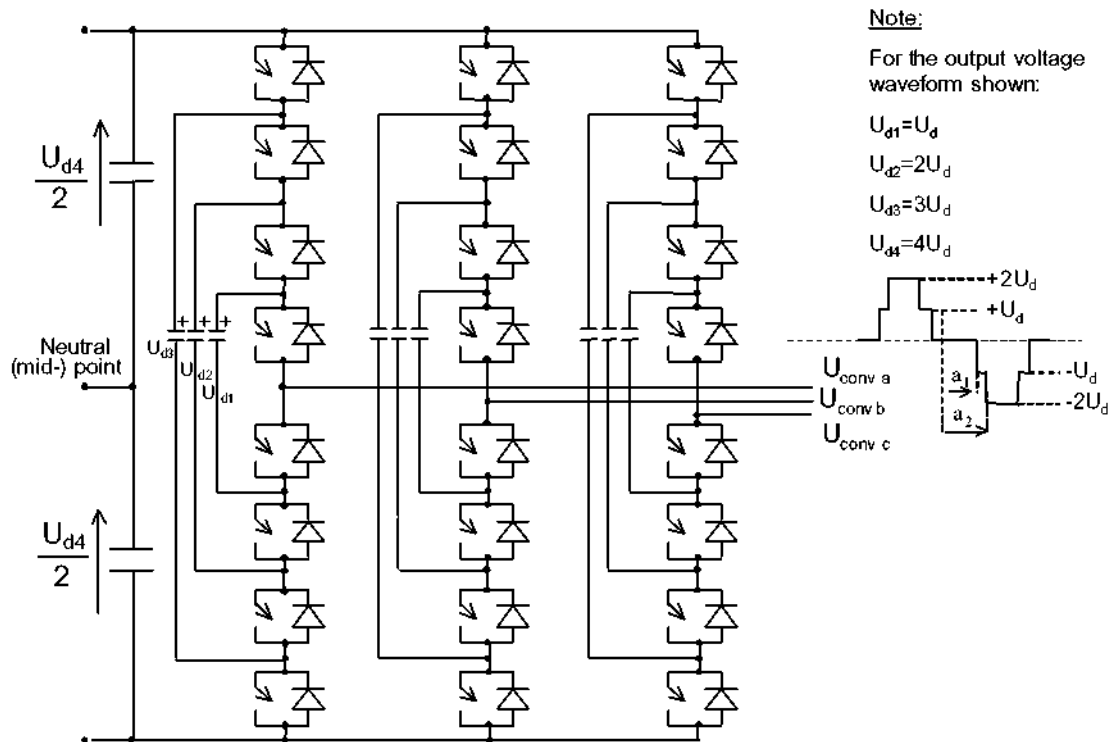


Figure 4.7 - Diagram of a three-phase 5-level floating capacitor converter and associated a.c. waveform for one phase

In principle, any number of floating d.c. capacitors can be used. However, when the number of voltage levels in the output waveform increases, and assuming constant apparent switching frequency for the converter, the volume of the d.c. capacitors also goes up, causing the capital cost and the footprint to get larger. Naturally, the complexity of the control and protection system also increases.

Compared to the 3-level floating capacitor topology, the individual valves are switched approximately half the number of times in the 5-level topology, and the harmonic performance at the output terminals is still superior.

4.3 Combination of Converter Phase Units

4.3.1 General

Each VSC substation may be constructed from a single converter unit of a phase unit topology, as described in 4.2. In this case the converter topology will simply be referred to by the same name as the converter phase unit topology.

In some applications it may be necessary or advantageous to combine several converter units, each constructed using the same converter phase unit topology. For example, it may not be optimal economically to achieve the power, voltage or current rating with a single converter unit. Similarly, several converter units may be combined to achieve good harmonic performance with very few switching operations per power frequency cycle, thus achieving reduced power losses.

The combination of two or more converter units can be accomplished in a number of ways. The d.c. terminals of the converter units can be connected in series or in parallel. Series connection may be an efficient way of achieving high voltage output, as the increase in internal converter clearances can be contained. At very high voltage the required clearance increases much more rapidly than linearly, as the voltage rises. This would result in the stray inductance in the commutating loop also increasing much faster, and the stresses on the VSC valve going up, resulting in either a disproportionate increase in the number of series-connected levels or higher power losses. Where the converter unit consists of a very large number of component converter units, both series and parallel connection of the d.c. terminals can be envisioned.

In principle, the a.c. terminals of the converter units could be connected in series as well as in parallel. This arrangement has been used for some STATCOM and other FACTS devices, and was also used in the VSC transmission demonstration installation in Japan. However, series connection of the a.c. windings is unlikely to be an economic solution for ratings in excess of 100 kVdc. Therefore, this option will not be discussed further.

This section describes different methods that can be used to combine converter units. For all methods it is possible to use 2-level, 3-level or multi-level phase units. For simplicity, a 2-level converter has been used to illustrate the examples. It should be noted that PWM switching will normally be used for the converters. Selective harmonic elimination methods (SHEM) (see Chapter 9 for more detail) may also be used together with transformer phase shifting to eliminate certain harmonics. With fundamental frequency switching of a three-phase, 2-level converter, a six-pulse converter is achieved.

4.3.2 Combination Using Separate Transformer Windings

4.3.2.1 Series Connection of Converters

As with an LCC HVDC scheme, two six-pulse converters can be connected in series on the d.c. side and in parallel on the a.c. side. By phase shifting the transformer windings for the two converters by 30° electrical relative to each other, this layout will operate as a 12-pulse scheme. This strategy may be called a 12-pulse converter arrangement. It can be used to extend the d.c. voltage capabilities of a VSC transmission scheme relative to the capability of the individual converter unit. The harmonic performance of the converter unit can be improved relative to a basic 12-pulse converter by switching the valves more than twice per half power frequency cycle. One switching operation per half-cycle is needed to control the amplitude of the a.c. voltage. Figure 4.8 shows an example of this arrangement.

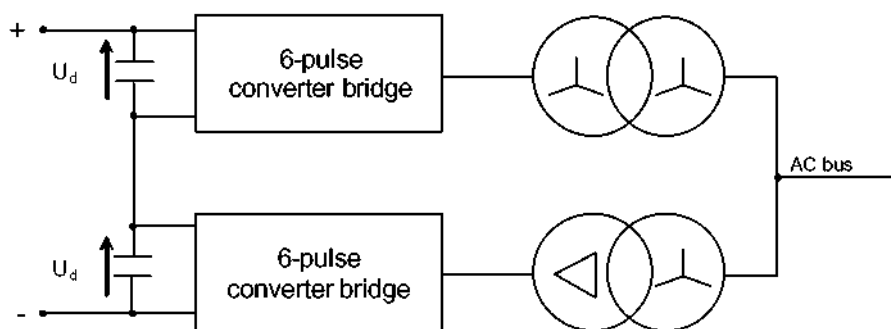


Figure 4.8 - Two six-pulse units connected in series

In the arrangement shown in Figure 4.8, the transformer is similar to that in an LCC HVDC scheme. In particular, the two valve windings have to be capable of operating at an offset d.c. voltage. It should be noted that high levels of harmonic current might flow at those harmonics where cancellation is by transformer action. The circulating currents can be reduced by special modulation techniques, i.e., specially optimised pulse patterns. The transformer will need to be designed to withstand the relevant currents.

In principle, it is also possible to connect more than two converter units in series on the d.c. side, with each converter unit being connected to a separate transformer winding. An example of a system with four converter units in series on the d.c. side is shown in Figure 4.9.

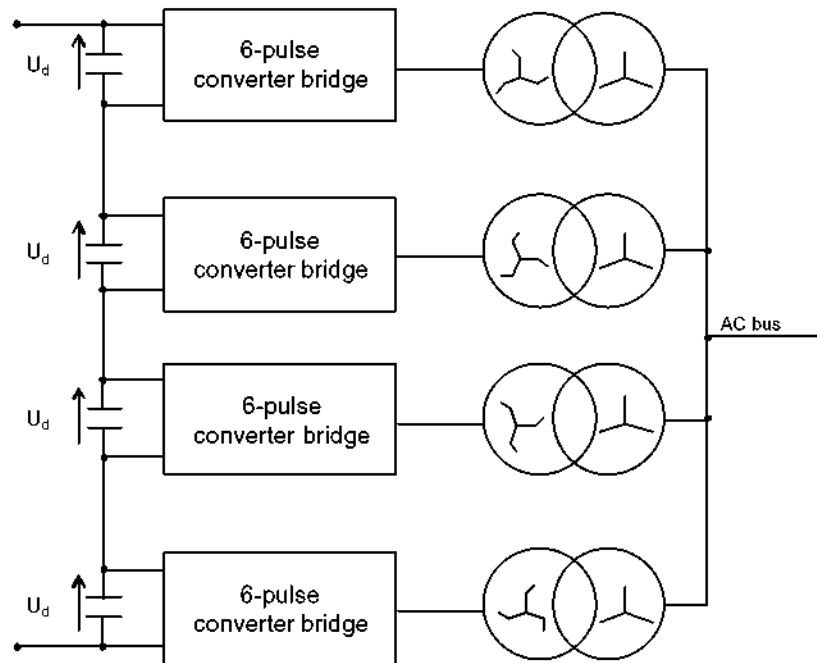


Figure 4.9: Four converter units connected in series on the d.c. side

If, under balanced conditions, the four transformer windings are phase-shifted relative to each other by $-7,5$, $+7,5$, $-22,5$ and $+22,5$ electrical degrees, a 24-pulse scheme is achieved. The comments above relating to switching strategy, power-losses and transformer design also apply to this configuration.

The difficulties in designing a high-voltage and high-power transformer to meet all the technical requirements imposed on it (for example, insulation requirements), and the need for balanced impedance between phases and windings, set practical limits on the number of windings.

4.3.2.2 Parallel Connection of Converters

When the current rating of the VSC transmission scheme is increased beyond the capability of single devices, it may be advantageous to connect two or more converters in parallel.

To prevent undesirable interaction between the two parallel-connected converters, some level of impedance must be provided between the a.c. sides of the two converters. One method for achieving impedance between the converters is to use separate transformer windings for the parallel connection on the d.c. side, as shown in Figure 4.8. Such an arrangement is illustrated in Figure 4.10.

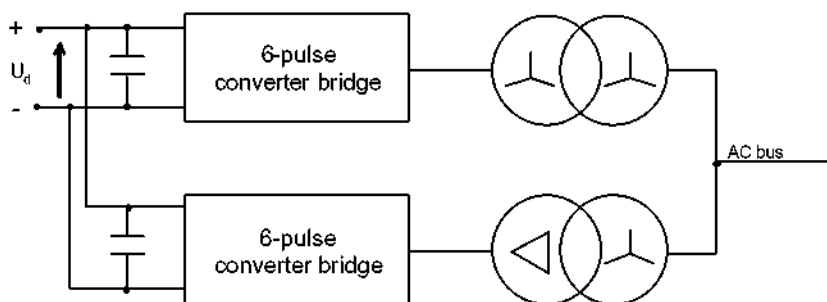


Figure 4.10 - Converter isolation achieved by use of separate transformer windings

Individual transformers for each converter can be used to avoid the large circulating currents between the windings. These transformers should provide appropriate phase shift, and inter-phase transformers between the transformer primaries would provide the actual output.

4.3.2.3 Series and Parallel Connection on the DC Side

In principle it is possible to make an arrangement, as shown in Figure 4.11, where two converters are placed in parallel and then put in series with a set of two other converters.

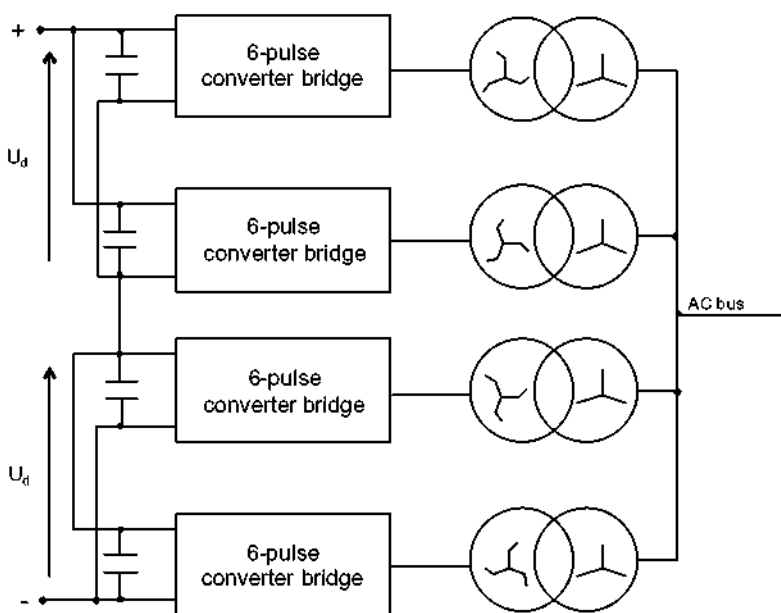


Figure 4.11 - Two converters placed in parallel and then put in series with two other converters

The considerations outlined in 4.3.2.1 and 4.3.2.2, also apply to this configuration. Practical limitations prevent this configuration from being extended to a significantly larger number of series- or parallel-connected converters. Because the technique is best suited to relatively low d.c. voltage, it is more applicable to back-to-back than to long distance VSC transmission schemes.

4.4 Concluding Discussion

Many arrangements can be used in a VSC transmission system. The configuration of the various converter terminals need not be identical.

4.4.1 Converter Phase Unit Topologies

The different phase unit topologies provide different advantages and carry different challenges. The following observations can be made in comparing the 2-level, 3-level and multi-level phase unit topologies.

The total harmonic voltage distortion at the a.c. terminals of a converter using sinusoidal PWM modulation is typically 60 %, 30 % and 15 % for 2-, 3- and 5-level converters, respectively.

The 2-level converter will normally provide the lowest capital-cost solution. It is also likely to be the most compact. However, when used at high d.c. voltage a large number of series-connected semiconductors are needed in the valves, and careful attention must be paid to the voltage distribution within the valve during turn-on and turn-off. Similarly, repetitive voltage excursions on the converter a.c. terminals between the voltage at the two d.c. terminals will result in high stresses on other equipment, which must be designed to withstand these stresses. To achieve good dynamic and harmonic performance, the VSC valves are typically switched at a frequency of around 1-2 kHz. Consequently, switching losses for the 2-level converter tend to be relatively high.

The 3-level converter will normally cost more than the 2-level solution, since it requires additional hardware. The extra equipment means the footprint and volume occupied by the 3-level solution will likely be greater than that of the 2-level solution. The voltage excursion resulting from valve switching will only be half the voltage of a 2-level solution, and for the same apparent switching frequency, as seen by an external observer, each valve will only be switched half the number of times and at half the voltage. Consequently, the switching losses for a 3-level converter will tend to be about half that of a 2-level converter. It should be noted that the stray inductance in the commutation loop may be relatively larger per switched kV, because of the connections to additional capacitors, and this may increase the power losses in the valves. In addition, some of the advantages of this arrangement might be negated by more complex commutation processes, unequal valve loading (inner, outer or midpoint clamping valves), or more complex control and protection requirements.

Comparing the two different 3-level topologies described above, the additional switches will likely make the capital cost for the neutral point clamped converter slightly higher than for the floating capacitor converter. On the other hand, the 3-level neutral point clamped converter may be more compact, with a smaller footprint, since the floating capacitor circuit uses additional d.c. capacitors.

The multi-level converter will normally cost more than the 3-level solution, due to its additional hardware requirements. The footprint and volume occupied by the multi-level solution is also likely to be greater than that of the 3-level solution. However, the valve design will probably be easier, since the normal operating voltage for each valve in an n-level circuit is only $1/(n-1)$ of the terminal-to-terminal d.c. voltage. Similarly, the voltage excursion resulting from valve switching will only be $1/(n-1)$ of the voltage. For the same apparent switching frequency, as seen by an external observer, each valve is only switched $1/(n-1)$ times and at $1/(n-1)$ times the voltage. Consequently, the switching losses for a multi-level converter will tend to be lower than for a 3-level converter. However, some of these advantages might be offset by more complex commutation processes, unequal valve loading (inner, outer or midpoint clamping valves), or more complex control and protection requirements.

Additionally, since each VSC valve will normally incorporate redundancy, the cost of providing redundancy increases as the number of levels increase.

In practice, the number of levels in a multi-level converter would be limited for several reasons. For example, it becomes undesirable to reduce the switching frequency for each valve beyond a certain value because of dynamic considerations and capacitor balancing, even though harmonic performance may not dictate a higher switching frequency. Similarly, the valve stresses will depend to a certain extent on the stray inductance in the commutating loop, and on a per semiconductor level this will tend to increase as the number of levels in the topology is increased. To avoid higher valve stresses due to stray inductance, it may be necessary to add or increase the value of snubber capacitance per semiconductor when using many levels in the multi-level topology. This would increase switching losses and reduce some of the benefit of the multi-level topology.

4.4.2 Combination of Converter Units

Converter phase units may be combined to form a converter terminal of greater rating. This may be done for one or more of the following reasons.

- The desired d.c. voltage cannot be achieved economically with available converter phase units.
- The desired direct current cannot be achieved economically with available converter phase units.
- To lower the switching frequency of the valves in each converter unit without affecting overall dynamic and harmonic performance.

The use of complex winding arrangements may result in high costs for the magnetics used in the combination of converter units. Similarly, power losses will be incurred in the magnetics, reducing some of the benefits gained from less valve switching made possible by the use of a higher pulse number in the overall output waveform. The manufacturer will have to consider these factors in optimising the overall scheme.

To some extent, the use of magnetics to achieve higher pulse number and thereby to allow each valve to be switched fewer times during each power-frequency cycle is similar to the objective of using multi-level topologies. One spin-off benefit of switching each valve less frequently is that it enables a wider choice of semiconductor devices to be used in the valve.

4.5. References

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5. VSC TRANSMISSION VALVES

5.1 Introduction

The switching operations needed to achieve the conversion between a.c. and d.c. are performed by the valves. In a VSC transmission scheme, the valves must be capable of turning on and off in response to control signals, irrespective of the state of the power circuit. Therefore, the valves used in a VSC transmission scheme are fundamentally different from those in an LCC HVDC scheme.

Semiconductors are a crucial part of the VSC valve. The advances in semiconductor devices have been rapid and are the key to the future growth of VSC transmission. Therefore, it is appropriate that this chapter begins with a discussion of semiconductors before moving on to discuss the complete valve.

5.2 Semiconductors for VSC Transmission

An essential function of the semiconductor used in a voltage sourced converter is that it can be turned off and on by means of a control signal. Many different devices with this capability have emerged in recent years, and acronyms tend to be used for each of them. The devices and acronyms discussed in this chapter are as follows.

FWD	Free wheeling diode
GCT	Gate commutated turn-off thyristor
GTO	Gate turn-off thyristor
IEGT	Injection enhanced gate transistor
IGBT	Insulated gate bipolar transistor
IGCT	Integrated gate commutated thyristor
MOS	Metal oxide semiconductor

Acronyms are also associated with device characteristics. The acronyms used in this PAS are the following.

FIT	Failure in time
SCFM	Short-circuit failure mode
SSOA	Switching safe operating area

5.2.1 Overview of High Power Semiconductors

The section presents a brief description of the various semiconductor components available for high power applications [5-1].

5.2.2 Thyristors

Traditionally, electronic conversion of electrical power in the high-power region has been made using the principle of line-commutated frequency conversion, using thyristors for control of the current flow. The thyristor is the equivalent of a “binary current valve” with two discrete states, either conducting or blocking the current. Turn-on is accomplished by injection of a gate current, while turn-off occurs naturally when the 50/60 Hz line current passes through zero. The thyristor cannot be turned off with the gate terminal, which significantly limits the range of applications for this device. Thyristors have been used to handle high power for more than 40 years, and are now available with impressive power handling capabilities (for example, 12 kV / 1,5 kA, 8,5kV / 4kA) and are used in LCC HVDC.

5.2.3 GTO and IGCT (GCT)

Based on the thyristor concept, gate-controlled turn-off was introduced in the late 1970s with the gate turn-off thyristor (GTO), making it possible to build converters for control of the output frequency. The GTO opened the way to high-power voltage sourced converters, which were used, for example, in variable speed a.c. motor drives (with induction motor), STATCOM, and similar applications. However, the power losses for a GTO are higher than those for classical thyristors. The gate current required to turn off the device is also relatively high, and elaborate units are needed to supply these high gate currents. Usually, additional external circuits must be used to limit commutation overvoltages and di/dt to mitigate the stresses on the device. Snubber circuits are often used to control the voltage across the device.

A performance improvement in gate turn-off thyristors was achieved when a new device technology, the integrated gate commutated thyristor (IGCT) was introduced. This new technology achieves homogenous and well-controlled injection and extraction of gate currents in thyristors by using an integrated gate drive unit. The homogenous switching across the device area significantly reduces power losses as compared to the GTO.

With its proven reliability, the IGCT represents an attractive alternative in many high power applications requiring turn-off devices, and is currently used in large motor drives, STATCOM systems, and traction power supply systems. The device itself is sometimes known as a GCT. A device rating of 6 kV / 6 kA is available, making it the largest rating gate controlled turn-off device available at the end of 2004. However, the high energy required for the gate, combined with additional drawbacks mentioned below, make the IGCT less interesting for high-voltage applications requiring series-connected devices.

5.2.4 IGBT Type Devices

An IGBT type device includes both the IEGT and the IGBT.

The IGBT is a device based on the bipolar transistor concept controlled through an MOS. Bipolar transistors were commonly used before the IGBT was available on the market.

There have been numerous attempts to combine the microelectronic technologies used for very precise control of low-voltage signals in integrated circuits with the high-power handling capabilities needed for power semiconductor devices. The most successful to date has been the insulated gate bipolar transistor (IGBT) concept, which combines a high-impedance, low-power gate input with the power handling capacity of normal bipolar transistors and thyristors.

In the IGBT, control is accomplished by using a pattern of MOS transistors distributed on the surface of the device. The MOS transistors allow a high impedance control of the current flow through the device, requiring extremely small amounts of power supplied to the control gate. The ability to withstand high voltages and currents is provided by the vertical part of the device, comprising a bipolar transistor structure. This vertical transistor is of sufficient thickness to withstand high voltages. In addition, the vertical transistor effects are crucial to enhance the conductivity of the semiconductor material, and hence, to reduce excess voltage drop over the device in the conducting stage.

The bipolar effect of the IGBT gives a self-limiting current through the device in case of short circuit at the phase output. The device itself is protected by turning it off within a few microseconds. This feature is specific to IGBTs; by comparison GTOs do not provide any current limitation. As a consequence, IGBTs are capable of withstanding external fault conditions with self-protection and protection of the environment.

The second attractive feature of the IGBT is the linear control through the gate: di/dt as well as dv/dt can be controlled during commutations. Particularly, a di/dt -limiting reactor is not needed, as opposed to the GTO which always needs one. In addition, active voltage clamping by the gate is commonly used to assist the voltage sharing across series-connected elements.

The performance of IGBTs is related direct to the properties of the surface MOS transistor cells, and their success is largely due to the continuous development of these cell structures. The IGBT takes advantage of technologies that have been developed for microelectronic circuits in significantly larger markets.

The IGBT was invented in 1982. Although substantial progress in the area of IGBTs for lower voltages (600-1 200 V) was made in the 1980s, it was not until the beginning of the 1990s that it was realized that this concept was also feasible for higher voltages (2,5 kV, then 3,3 kV in 1997, and 6,5 kV in 2002). Lately, a new type of IGBT has become available that takes advantage of the effect of electron injection from emitter to achieve a low saturation voltage similar to that of a GTO. This type of IGBT is called IEGT.

At the end of 2004, all VSC valves used IGBT semiconductor switches in forward direction with the capability to both turn on and turn off the current. To obtain the rated current capability, the IGBT is made of a number of chips connected in parallel in the same housing. There may be an anti-parallel free wheeling diode (FWD) integrated in the same semiconductor package to ensure current capability in the opposite (reverse) direction, and to prevent the application of reverse voltage. The FWD normally consists of a number of chips in parallel, in the same way as the IGBT. It is also possible to have the FWD in a separate package in parallel with the IGBT. The IGBT chip is designed only to have forward blocking capability, since in the reverse direction there is always the anti-parallel diode for protection. The IGBT and the diode must have the same voltage capabilities.

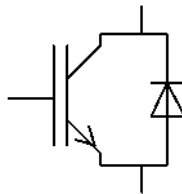


Figure 5.1 - IGBT and antiparallel FWD

The IGBT, seen from a functional point of view, and its antiparallel FWD are normally referred to as an IGBT component.

5.2.5 Comparison of Devices

The IGBT is the most common choice for high-power and high-voltage VSC transmission systems in use today because of its following characteristic features.

- It allows active voltage sharing control.
- Low-power control, since it is an MOS-controlled device. This is advantageous when operating at very high voltage levels.
- Transistor action, which enables precise control of the device in a manner that is not possible with latching alternatives. For instance, the converter can be turned off even in short-circuit conditions.
- High-switching speed, thus making high-switching frequency feasible.

5.3 VSC Valve Design Considerations

In the sections below, only IGBTs are discussed.

5.3.1 Reliability (IGBT)

In addition to the number of series-connected IGBTs that are needed to sustain the converter voltage rating, each single valve in a VSC transmission scheme must include a few redundant devices to enable continued operation in case of failure of an individual component [5-1]. Therefore, a faulty IGBT cannot be allowed to create an open circuit, since the valve must continue operating with the remaining healthy IGBTs. Instead, a faulty device must enter into a short-circuit mode and be capable of conducting current until it can be changed out, for example, during a scheduled maintenance period. This capability of short-circuit failure mode (SCFM) operation is very critical for series-connected IGBTs, and must be verified by appropriate tests under conditions that are relevant for a particular application. Specially-developed packaging is used for IGBTs for VSC transmission and other high-voltage applications. These are press pack designs rather than the module design used for industrial, low-voltage applications. Standard IGBT modules do not have the required SCFM behaviour, as they normally use bond wires that open the circuit upon failure.

Each individual semiconductor device in a VSC transmission scheme will be subjected to normal voltage for a substantial part of its operation time, that is, about half its rated voltage at 50 % duty cycle. The probability that an incident cosmic particle will initiate a destructive current avalanche in blocking mode will therefore be substantially increased. This effect must be counteracted by proper design of the IGBT in order to keep the failure rate (FIT) below specified limits. This is a common issue for voltage sourced converters using GTO or IGBT for applications such as drives.

The LCC HVDC converters operate normally in relatively stable conditions, and the power flow changes at moderate rates. In contrast, the unique controllability of voltage sourced converters makes them attractive for applications that benefit from rather rapid changes in power flow (active or reactive power), for example, for flicker mitigation. As an example, deregulation of the electrical power market has altered the exchange of power between separate networks. This, in turn, makes new and heavy demands upon the power cycling capability of semiconductor devices, which, again, must be verified by appropriate test methods.

5.3.2 IGBT Current Rating

One of the important design bases of the semiconductor in the VSC valve is rated current. In addition, the valve should also be able to handle peak current, including ripple and transients, as well as margins for control and protection actions. The rated phase current gives the nominal stress on the component and shall be considered regarding power losses and junction temperature on the IGBT.

5.3.3 Transient Current Requirements

An important aspect of IGBTs is their capability to turn off current and voltage. This capability is defined in the switching safe operating area (SSOA) shown in Figure 5.2.

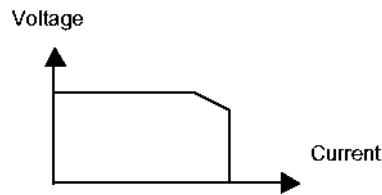


Figure 5.2 - Typical SSOA for the IGBT

During switching the IGBT must be able to turn off the peak current, including ripple. Additionally, a margin is added to handle current control regulation and protection actions during transient conditions. The valve must also be capable of turning off the current should a short circuit occur close to the valve. The IGBT short-circuit operation capability is defined by the SCSOA (short-circuit safe operating area), which is slightly different from the SSOA under normal operation.

5.3.4 Diode Requirements

The FWD in a VSC bridge act as an uncontrolled rectifier bridge. Thus they are exposed to special stresses, in particular during fault scenarios. Because the IGBTs can be switched off within microseconds during transients, they will not be exposed to some of the disturbances. The diodes, however, cannot be switched off, so they have to be designed to withstand the special stresses.

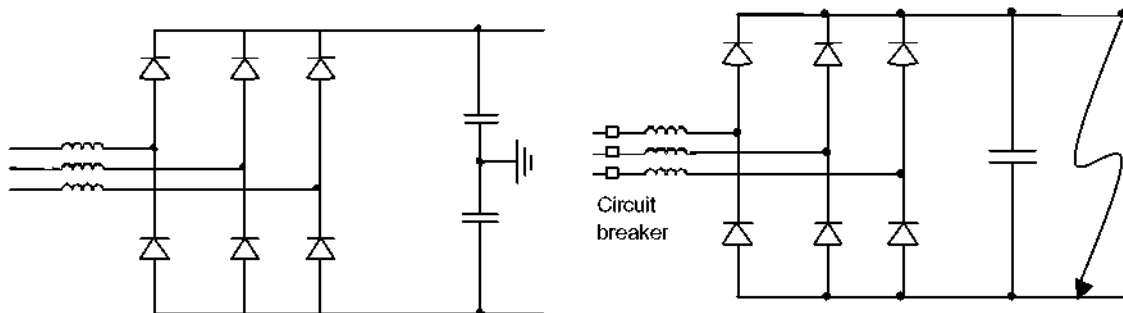


Figure 5.3 - A 2-level VSC bridge with the IGBTs turned off

In case of a d.c. side fault, as shown in Figure 5.3, a short-circuit between the two d.c. terminals creates a fault current path through the diodes. The current in the a.c. phases in the VSC bridge is limited only by the short-circuit impedance of the a.c. network and the reactance in the converter, for example, the phase reactors and/or transformers. The fault current is detected by the protection system, which will open the breaker on the a.c. side and thereby eliminate the fault current. A normal protection and breaker scheme takes a time equivalent of three 50/60 Hz fundamental frequency cycles before the fault current is extinguished. If the d.c. system only consists of cables, a fault will be very unlikely. However, the consequences may not be acceptable if the system is not designed to handle the fault. The valve should be designed to handle the fault current with an asymmetrical offset as a worst case. Here, no reapplied voltage occurs since the breaker has disconnected the a.c. system.

Another transient that the diode may experience occurs if the VSC is energized through the a.c. breaker when there is either no voltage, or a low voltage, on the d.c. side. In this case, the converter experiences a surge inrush current and an overvoltage will occur on the d.c. bus. The valve must be designed to handle the inrush current, or the current will have to be limited.