Programme Area: Energy Storage and Distribution

Project: Network Capacity

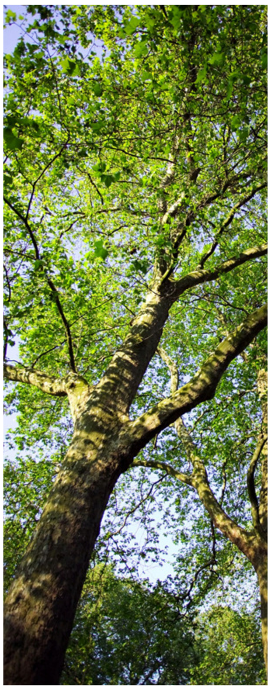
Title: Feasibility Assessment of Onshore Multi-Terminal High Voltage Direct Current (HVDC) Systems in the UK

Abstract:

This document reports the results of an initial review addressing the feasibility of deploying MT-HVDC systems into the UK transmission system, focusing on the practicalities of conversion of existing AC lines to HVDC, harmonic issues, DC cable technology and multi-terminal system control.

Context:

The Network Capacity research project identified and assessed new technology solutions that could enhance transmission and distribution capacity in the UK. It assessed the feasibility and quantified the benefits of using innovative approaches and novel technologies to provide improved management of power flows and increased capacity, enabling the deployment of low carbon energy sources in the UK. The project was undertaken by the management, engineering and development consultancy Mott MacDonald and completed in 2010.


The ETI Energy Storage and Distribution Programme - Network Capacity Project

Work Package 2 Task 1 Final Report
Feasibility of Onshore Multi-terminal HVDC in UK Grid

August 2010
The Energy Technologies Institute (ETI)

Mott MacDonald

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02	8th August 2010	R. Ball	M. Scutariu	R. Ball	ETI comments incorporated.

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Content

1. Summary

1.1 Background

Mott MacDonald has been commissioned by the Energy Technologies Institute (ETI) to carry out the ETI's Network Capacity Project. This project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically the project will assess the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project is focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.
- The second area concentrates on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

The work associated with both areas comprises an assessment of the credible options from these technologies in the context of power flow management including the benefits and also associated impediments to their development and deployment, and will provide guidance in respect of technology development opportunities. The work has been structured into two packages;

- Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work in this package comprises a literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It will also include analysis of environmental and social impacts, and of the barriers to development and deployment.
- Work Package 2 concentrates on the use of multi-terminal HVDC transmission and its integration within the existing UK T&D networks. The work in this package will comprise a feasibility assessment and detailed modelling of multi-terminal HVDC to assess its performance, impact and potential interactions arising from its use. It will also include analysis of the requirements for such integration, the benefits case for conversion of existing AC lines, and of the barriers to development and deployment.

1.2 Work Package 2 Task 1 Final Report

Mott MacDonald commissioned Manitoba HVDC Research Centre (Manitoba) to carry out an assessment of the feasibility of Onshore Multi-terminal HVDC in the UK Transmission Grid as covered by the Work Package 2 Task 1 scope of work. The final report received from Manitoba via their sub-consultants TransGrid Solutions Inc is included as Appendix A. The report incorporates amendments that have been made in response to ETI comments received on the draft reports submitted in April 2010.

The report is provided as a separate stand-alone document at this stage. The final report for the project consolidates and updates the outputs from each of the individual task reports, including that covered by this document, in order to provide a coherent output that represents the integrated output from all of the work carried out.

Appendices

Appendix A. Manitoba HVDC Research Centre. Feasibility of Onshore Multi-terminal HVDC Systems Integrated into the UK AC Grid

Engineering Support Services for:

Feasibility of Onshore HVdc Systems Integrated into the UK AC Grid

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Report R1137.01. 03

Work Package 2 - Task 1 Report

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August 2, 2010

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Revisions

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1. Introduction

The Energy Technologies Institute (ETI) has identified the need for important engineering studies to assess innovative approaches and technology solutions that could lead either:

- to the enhancement of the capacity of the *existing* onshore UK electricity transmission and distribution networks, or
- to the *expansion* of these networks by means other than the construction of new overhead line infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current T&D system can accommodate.

The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically this project will assess the feasibility of two potential areas of development (below) to improve operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project (work package 1) is focused on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.
- The second area (work package 2) concentrates on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

Task 1 of the work package 2 includes a feasibility assessment covering the power quality issues at HVdc terminals, technical issues associated with conversion of ac overhead lines to dc, high level discussion of dc cable technology and multi-terminal HVdc control regimes. This report is prepared to fulfill the requirements of this task.

This report is structured as follows: section 2 will briefly discuss the conversion process and the resulting harmonics generated at HVdc terminals. Then it discusses the filtering requirements and the relevant standards. Section 3 discusses the options, issues and experience with conversion of ac overhead lines to HVdc lines. Section 4 focuses on HVdc cable technology and finally section 5 will discuss multi-terminal HVdc controls.

2. Power Quality Issues at HVdc Terminals

2.1. Introduction

The process of ac to dc conversion and vice versa produces harmonic voltages and currents. This affects the power quality at HVdc terminals. This section discusses only the effects of these harmonics on the power system. Please refer to Section 6 for a discussion on the conversion process for LCC and VSC converters and how the harmonics are actually generated.

2.2. Harmonics

As detailed in Section 6, all technologies used for the conversion of ac to dc produce harmonics to a varying degree. Thus when one discusses harmonics for HVdc, the effects, mitigation and performance indices are the same irrespective of the conversion technology. This section will discuss the effects of harmonics on the power system and the measurement of harmonics.

2.2.1. Effects of Harmonics on the Power System.

Harmonics cause various issues on the power system as well as in neighbouring communication circuits. Some of these issues include:

1. Extra Heating in transformers, machines and other power system components

   In a normal power system, power flow is only possible at the normal power system frequency, therefore no power exchange is possible at different harmonics. As this energy needs to go somewhere, it is dissipated in the various power system resistances as I^2R losses. Synchronous and induction machines are particularly affected by this heating as the damper bars in the machines dissipate power at frequencies different than fundamental, and therefore dissipate more heat.

2. Resonant Over-voltages

   If the ac power system has a high impedance at a specific harmonic and if a harmonic current at the same harmonic is trying to flow, the resultant harmonic frequency over-voltage may cause excessive stress on the system insulation

3. Control Inaccuracies

   An HVdc control system uses various measurements from the ac and dc systems. If these measurements contain harmonics, it may cause a modulation of the firing angle. If this modulation is excessive, the controller may go unstable. This is known as harmonic instability and is usually considered in the design of the controls (i.e. using equi-distance firing), and mitigated using notch filters.

4. Interference with Communication Circuits.

   Harmonics flowing on both the ac and dc overhead lines (if applicable) can potentially couple into nearby communication circuits. This interference can cause quality issues and may even cause dangerous voltage to be present on communication circuits

2.2.2. Harmonic Performance Measurements

In section 2.2.1, it was established that harmonics cause various issues with the power system. In order to measure the effects of the harmonics on the power system, various harmonic performance measurements are available. In the UK, the two relevant standards are:

- G5/4-1 *Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Tranmission and Distribution Networks in the United Kingdom*, Oct. 2005
- PR IEC/TR 6100-3-6:2008 *Electromagnetic Compatibility (EMC) – Part 3-6: Limits – Assessment of Emission Limits for the Connection of Distorting Installations to MV, HV and EHV Power Systems.*

For the most part, these two standards are the same, where they diverge, the G5/4-1 standard has been used.

2.2.2.1. Individual Harmonic Distortion Factor

The Individual Harmonic Distortion Factor (D_n) is defined as:

$$D_n = \frac{V_n}{V_1}$$

Where:

V_n is the measured voltage at harmonic n
V_1 is the nominal fundamental voltage
D_n is the distortion of a particular harmonic in %

2.2.2.2. Total Harmonic Distortion

The total harmonic distortion (THD) is defined as:

$$THD = \frac{\sqrt{\sum_{n=2,N} V_n^2}}{V_1}$$

Where;

n is the harmonic number. N needs to be sufficiently large, and in practice is usually around 50
V is the voltage at a given harmonic

2.2.2.3. Connection Guidelines

G5/4-1 has recommended that any total harmonic distortion (THD) not be above the following limits depending on the voltage to which the HVdc link is connected to (the point of common coupling or PCC) as shown in
Table 1.

Table 1 Summary of THD Planning Levels

System Voltage at the PCC	THD Limit (%)
400 V	5
6.6, 11 and 20 kV	4
22 kV to 400 kV	3

G5/4-1 has recommended that any individual harmonic distortion not be above the following limits depending on the voltage to which the HVdc link is connected to as shown in Table 2 to Table 5.

Table 2 Planning Levels for Harmonic Voltages in 400 V Systems

Odd Harmonics (non-multiple of 3)		Odd Harmonics (multiple of 3)		Even Harmonics	
order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)
5	4	3	4	2	1.6
7	4	9	1.2	4	1
11	3	15	0.3	6	0.5
13	2.5	21	0.2	8	0.4
17	1.6	>21	0.2	10	0.4
19	1.2			12	0.2
23	1.2			>12	0.2
25	0.7				
>25	0.2 + 0.5 (25/h)				
Note the THD Level is 5%					

Table 3 Planning Levels for Harmonic Voltages in 6.6 kV, 11 kV and 20 kV Systems

Odd Harmonics (non-multiple of 3)		Odd Harmonics (multiple of 3)		Even Harmonics	
order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)
5	3	3	3	2	1.5
7	3	9	1.2	4	1
11	2	15	0.3	6	0.5
13	2	21	0.2	8	0.4
17	1.6	>21	0.2	10	0.4
19	1.2			12	0.2
23	1.2			>12	0.2
25	0.7				
>25	0.2 + 0.5 (25/h)				
Note the THD Level is 4%					

Table 4 Planning Levels for Harmonic Voltages in 6.6 kV, 11 kV and 20 kV Systems

Odd Harmonics (non-multiple of 3)		Odd Harmonics (multiple of 3)		Even Harmonics	
order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)
5	2	3	2	2	1.0
7	2	9	1.0	4	0.8
11	1.5	15	0.3	6	0.5
13	1.5	21	0.2	8	0.4
17	1.0	>21	0.2	10	0.4
19	1.0			12	0.2
23	0.7			>12	0.2
25	0.7				
>25	0.2 + 0.5 (25/h)				
Note the THD Level is 3%					

Table 5 Planning Levels for Harmonic Voltages in 275 kV and 400 kV Systems

Odd Harmonics (non-multiple of 3)		Odd Harmonics (multiple of 3)		Even Harmonics	
order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)	order 'h'	Harmonic Voltage (%)
5	2	3	1.5	2	1.0
7	1.5	9	0.5	4	0.8
11	1.0	15	0.3	6	0.5
13	1.0	21	0.2	8	0.4
17	0.5	>21	0.2	10	0.4
19	0.5			12	0.2
23	0.5			>12	0.2
25	0.5				
>25	0.2 + 0.3 (25/h)				
Note the THD Level is 3%					

2.2.2.4. Telephone Influence

Telephone influence refers to the capability of a power circuit to cause interference in a nearby telephone circuit. While these influence factor was not mentioned in G5/4-1 or PR IEC/TR 6100-3-6:2008, it is mentioned in IEEE 519 *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, which is the main North American standard. In order to measure the influence of the harmonics on a telephone circuit, the following measurements have been defined:

1. <u>Telephone Influence Factor (TIF)</u>

   TIF is a frequency weighted measurement which was decided upon by a committee of experts several decades ago to take into consideration the frequency of a particular harmonic and its ability to cause a disturbing noise in a particular telephone receiver set. TIF can be calculated by;

$$TIF = \frac{\sqrt{\Sigma ⟦(T⟧_f \cdot V_f)^2}}{V_1}$$

   Where;

   T_f is the single frequency TIF weighting at frequency f
   V_f is the voltage at frequency f
   V_1 is the nominal fundamental voltage

   The TIF weighting function, Tf, reflects the present C-message weighting and coupling and is described in more detail below

2. <u>I·T Product</u>

   The I·T product is a bit more difficult to calculate, but it gives a better indication of the coupling to nearby circuits as it considers the total interfering effect of the current. The I·T product can be calculated by:

$$IT = \sqrt{\sum_{n=2}^{m} ⟦(T⟧_n \cdot I_n)^2}$$

   Where;

   T_n is the single harmonic TIF weighting at harmonic n (see below)
   I_n is the rms value of the nth harmonic

The human ear hears some frequencies better than others and in order to account for this, weighting curves have been developed to account for the human ear sensitivity and the response of the receiver. These factors are defined as T_f and T_n above, and can be found in the IEEE 519-1992 and is shown below.

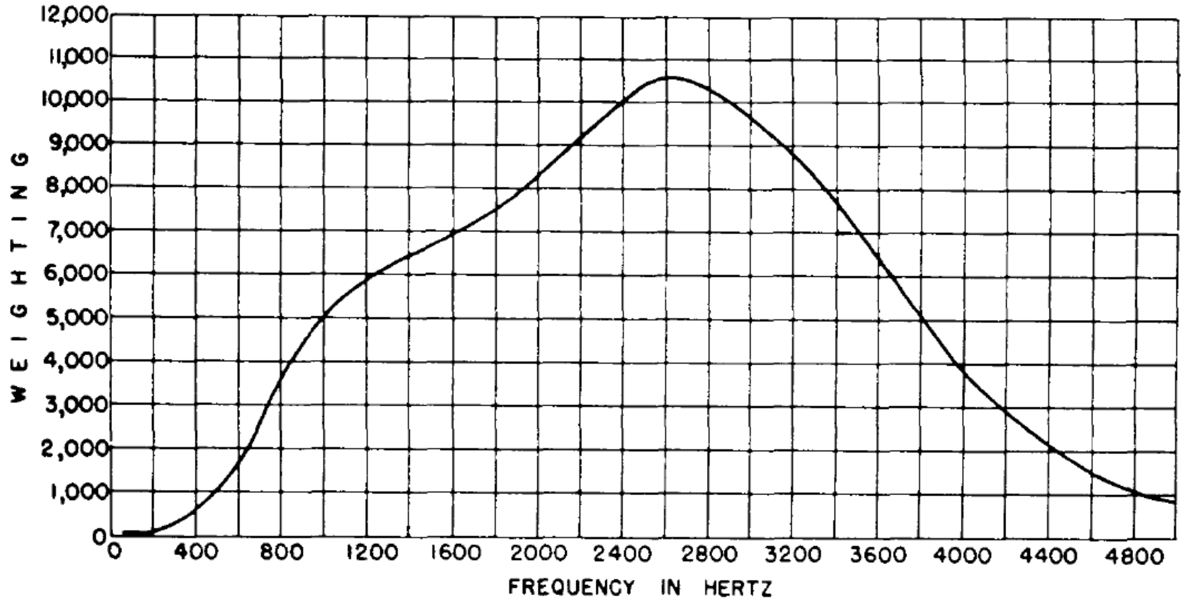


Figure 2-1 TIF weighting values

Some typical values for TIF and I·T are given below.

TIF	IT
40	50,000

Recently, some utilities have been moving away from specifying telephone interference factors as the the impact of harmonics on modern digital communication circuits seems to be less and specifying correct harmonic distortion levels, this should limit any potential interference with communication circuits. While this may work in some cases the owner of the dc link and/or of the transmission network should still specify some cursory calculations and due diligence to ensure that no interference will occur.

2.2.2.5. Radio Interference

The potential for higher frequency emissions is also possible. The systems have to be designed to limit any interference with radio, television, microwave, or other equipment in service. In order to measure this, IEEE 139-1988 defines a measurement method to measure the radio frequency emissions produced.

2.2.2.6. PLC Interference

One also has to be aware of the spectrum used by power line carrier equipment, the high frequency signals that are present on the power lines, generated by HVdc link or any other associated equipment must be sufficiently limited not to interfere with the operation of the power line carrier equipment.

2.3. Harmonic Filtering

In HVdc systems, harmonic filters are used on the ac and dc sides to reduce the harmonics generated by the converter from propagating into the ac or dc system. Figure 2-2 shows the location of ac and dc filters. A filter will create a low impedance path (for shunt filter) or a low admittance path (for a parallel filter) at a specific frequency. If designed properly, this will act as a local "sink" for any generated harmonics and prevents them from entering the associated ac or dc network. These considerations apply equally to multi-terminal HVdc schemes as to two terminal schemes and so no additional power quality issues are expected to arise from multi-terminal schemes.

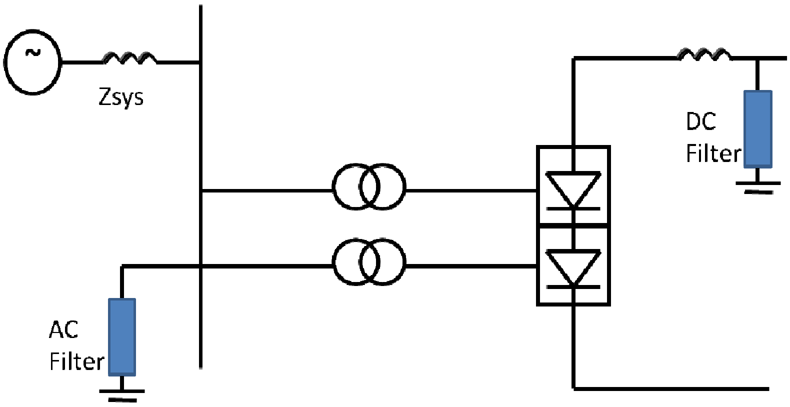
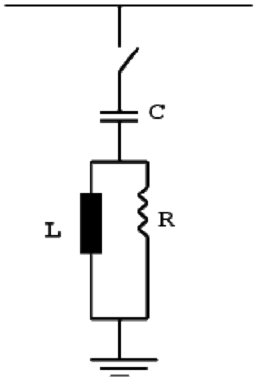


Figure 2-2 AC and DC Filters

In addition to providing harmonic filtering, they are capable of providing reactive power. As was stated earlier, line commutated converter produce more harmonics than a voltage source converter, but the general discussion below can be applied to either type of installation as required. Many different types of filters are possible, ranging from a simple single tuned filter as shown in Figure 2-3 to multi-tuned filters as shown in Figure 2-4. The multi-tuned filters are becoming increasingly popular, as they can be tuned for multiple frequencies (up to three tuned frequencies at the time of writing this report) and only require the circuit (breakers, disconnects, etc) for one single tuned filter.



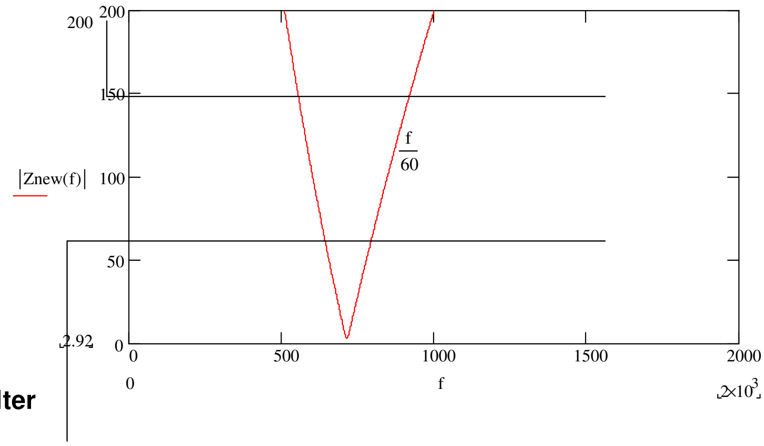


Figure 2-3 Single Tuned filter

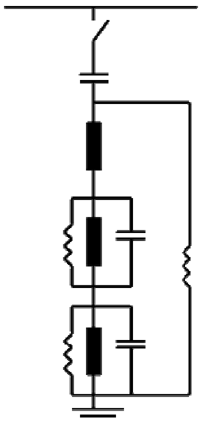


Figure 2-4 Triple Tuned Filter

2.3.1. Filter Design

When designing a filter, the following parameters must be given in order to design a filter (not withstanding the ac and dc requirements which will be discussed later)

- Tuned Frequency(cies)

The frequency ω_o at which the reactive elements of the filter are mutually cancelled and the filter has a local minimum of impedance.

- Passband (or bandwidth)

The frequency band centered around the tuned frequency where the impedance is within 3dB of the minimum impedance

- Quality Factor

This is the ratio of the impedance magnitude of the reactive component (i.e. capacitor) to the resistance.

- Detunning

Detunning can occur due to component tolerances and/or normal variations in component values due to aging, temperature and even system frequency variations. Need to account for this in the design.

2.3.2. Optimal AC Filter Design

The actual performance of the filter will depend largely on the impedance of the ac network. If we consider the ac system, as shown in Figure 2-5;

- Ic are the harmonic currents generated by the converter
- If is the harmonic current in the ac filter
- In is the harmonic current in the network
- Yf is the filter admittance
- Yn is the network admittance
- Vh is the harmonic voltage on the converter bus

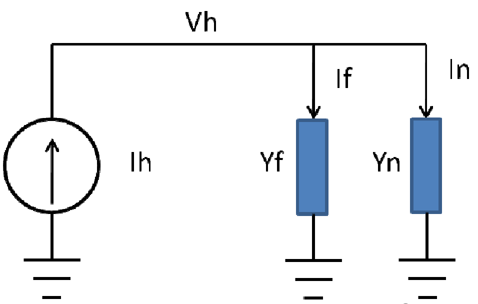


Figure 2-5 Equivalent harmonic Circuit

It is obvious from the above figure that if harmonic currents exist on the network at the frequency for which the filter is tuned for, the filter becomes a low impedance path for these harmonics, and as such needs to be rated for any existing harmonics.
Considering that;

$$Vh = \frac{Ic}{Yf + Yn}$$

In order to design the harmonic filters properly, the system admittance Yn needs to be included when designing the filter. The actual admittance of the network is very hard to determine, and needs to be based on multiple frequency scans considering various system contingencies. Once this is done, Yn can be specified as the minimum and maximum impedance and the minimum and maximum phase angle of the impedance respectively. Once these boundaries are established, the filter can be designed to extents of the power system.
In addition to the power system requirements, one needs to be ensure that the specification states the required distortion limits. As defined earlier, the harmonic distortion is defined based on the harmonic voltages. When designing the filters, the manufacturer will input the allowable distortion limits as a design constraint.

2.4. References

1. C. Adamson and N.G. Hingorani, *High Voltage Direct Current Power Transmission*, Garraway LTD, 1960
2. G. Asplund, “HVDC Grids – Possibilities and Challenges”, Cigre’ SC B4 Bergen Colloquium 2009.

3. Conversion of an Existing AC Line to HVdc

3.1. Introduction

The need for the most efficient use of the right of way (ROW) is being felt keener than ever. The problem is not limited to any particular country, but it is a matter of universal concern. At the same time, social pressure is building up to restrain acceptable values of electric and magnetic fields in the neighborhood of the existing and newly constructed transmission lines. Under these circumstances many electrical utilities are faced with utilizing the existing ROW's by upgrading/uprating or by converting ac lines to HVdc lines. HVdc has proven to be an effective alternative to ac in several applications especially for long distance transmission of bulk power.

It is a well known fact that for a given transmission tower size; significantly more power can be transmitted on a dc circuit than on an ac circuit.

For some OHL, especially old AC interconnections, the transmitted power may decrease over time because of changes to the system including new power plant connections. For such situations, it could be an opportunity to convert an AC line into a DC merchant line, if this doesn't affect the system safety.

HVdc is a mature technology and HVdc systems has been in service since the early 1960s [1], in addition the reliability of HVdc systems has improved dramatically over the years. HVdc systems are currently operating with a forced energy availability of 98% or better and a lot of cases are better than 99% [2].

3.2. AC transmission line conversion alternatives

There are several reasons to consider converting an ac transmission line that need to be looked at and studied in order to determine if there is a need for the conversion 3]. These include:

1. Increase in the power transfer capacity of an ac transmission line right of way particularly when it is considered difficult or impossible to construct new overhead transmission lines.
2. Expanding the power transfer capability of a transmission path taking into account N-1 requirements of the various existing ac transmission lines in the path.
3. Expand the power transfer capability without increasing the short circuit capacity at a terminating busbar.
4. Segmentation of an ac power network by creating asynchronous transmission boundaries can be part of the plan for the network.

There are a number of alternatives for the upgrading/conversion of an ac line [4]:

1. Conversion of an ac single circuit line to a dc line as shown in Figure 3-1.

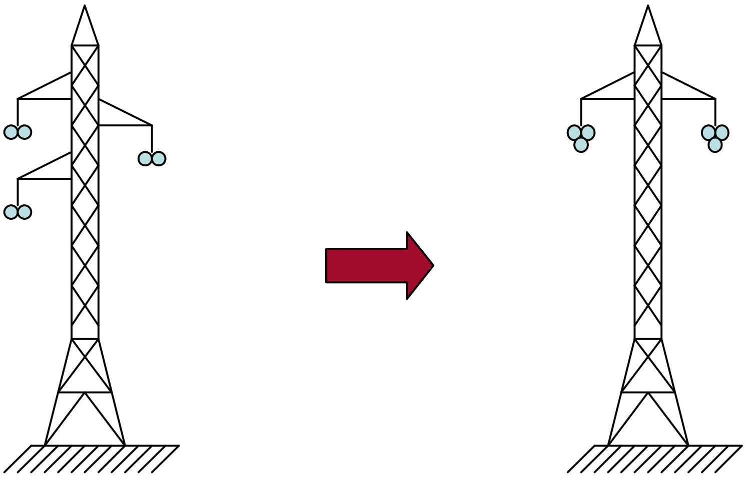


Figure 3-1 Conversion of a single circuit ac line to a bipolar dc line

2. Conversion of an ac double circuit ac line to a dc line as shown in Figure 3-2 and Figure 3-3.

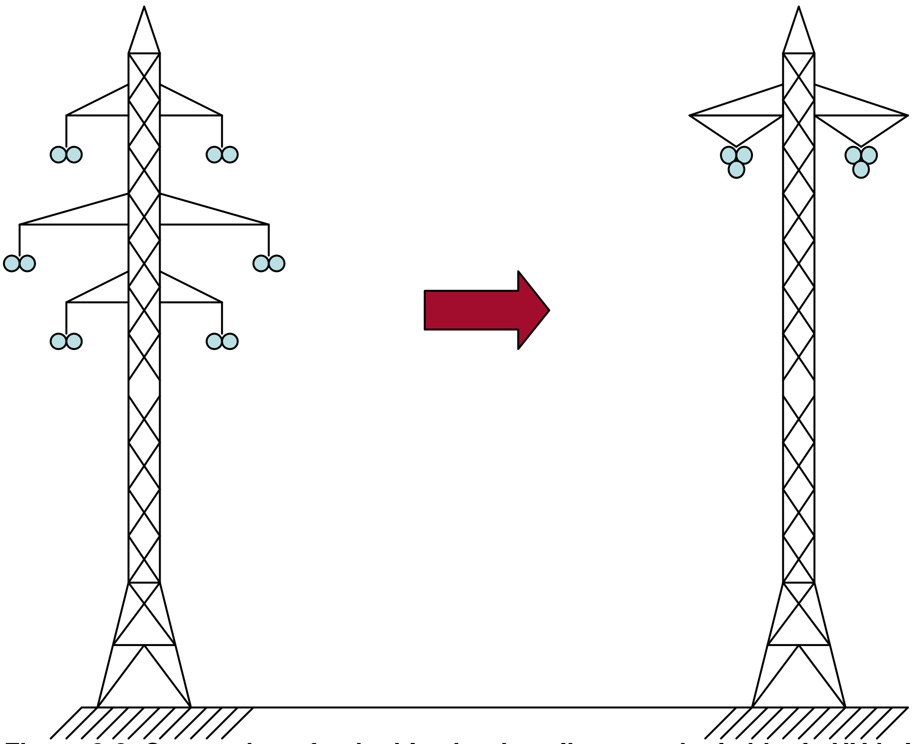


Figure 3-2 Conversion of a double circuit ac line to a single bipole HVdc line

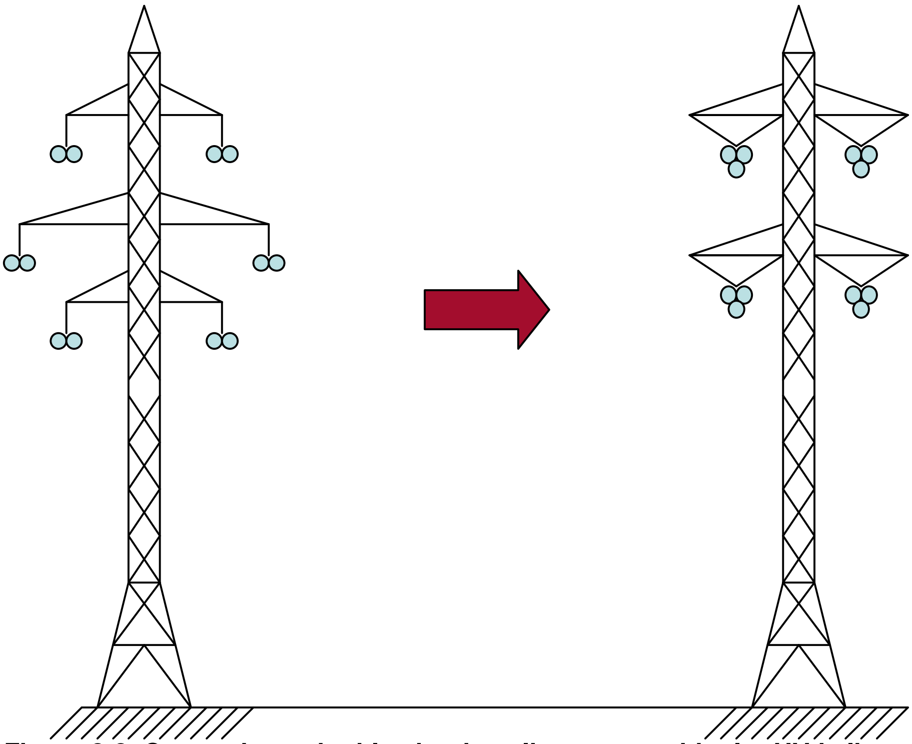


Figure 3-3 Converting a double circuit ac line to a two bipolar HVdc line

3. Conversion of one circuit of an ac double circuit line to an HVdc bipolar line. This would result in both ac and dc lines on the same towers as shown in Figure 3-4.

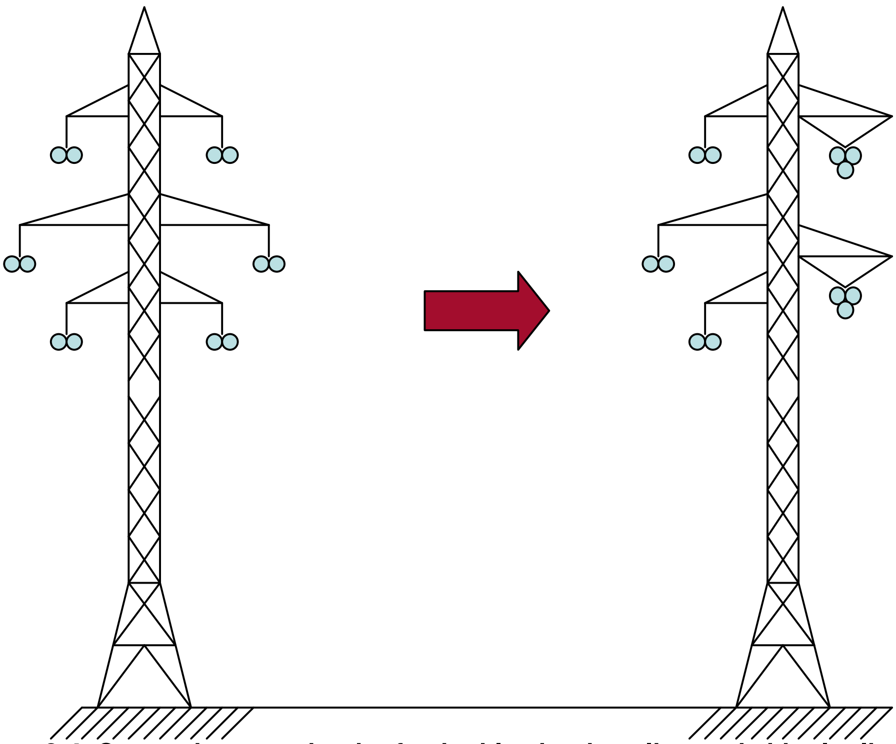


Figure 3-4 Converting one circuit of a double circuit ac line to dc bipolar line.

4. Addition of a dc circuit on an existing ac line. This would result in both ac and dc lines on the same towers as shown in Figure 3-5.

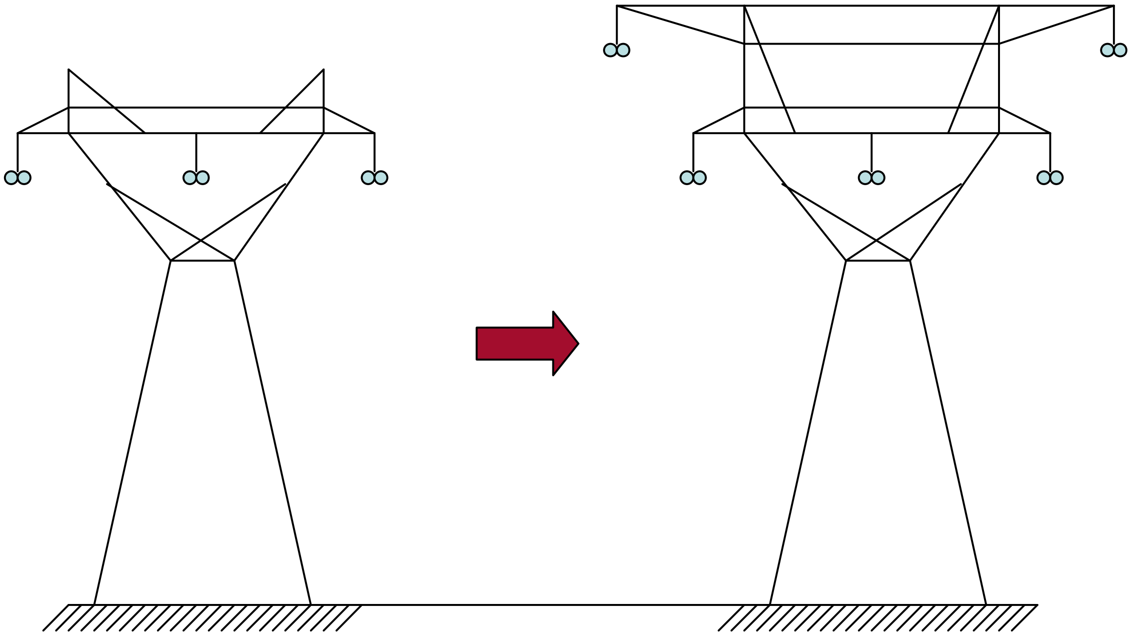


Figure 3-5 Addition of a dc circuit on an existing ac line

Please note the tower conversions shown in Figure 3-1 to Figure 3-5 are only examples of possible ways of converting an ac line to dc. There are of course a number of other possibilities including the use of only two cross arms and giving up the third. For any conversion project the mechanical and electrical design as well as the economics need to be studied in detail for the particular line in consideration.

When approaching the conversion of an ac line to a dc line one has to determine the suitability of the existing transmission line especially with respect to tower cross arms, insulators and the conductor configuration. Studies need to be performed to determine any structural changes and capability of foundations for the different options.

A lot of work has been done in the area of conversion of ac lines and it has been considered for a long time [3,4,5,6,9]. However, there has been only one line that the actual conversion took place [8].

The conversion of the ac line to a dc line obviously involves the selection of the maximum allowable dc voltage. This maximum allowable dc voltage is governed by:

- The conductor gradient for corona, radio interference RI, and audible noise AN.
- The gradient at ground level
- The clearances to the tower and between phases
- The clearance to ground for safety consideration.

3.2.1. AC transmission line conductors

Conductor thermal ratings are calculated using the applicable standards, for example IEEE 738-2006 or IEC/TR 61597 or Cigre WG 22.12 report in 1992. The thermal rating is typically based on the heat balance calculations. The heat escaping from the conductor is due to:

- Convection
- Radiation
- Heat storage

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The heat input to the conductor is due to:

- Solar heating
- Ohmic losses

The balance between the heat escaping and the heat input is what determines the thermal rating. Obviously weather conditions must be taken into consideration. Slight variations in the assumed weather conditions will affect the results and will make a difference in the calculated ratings. Typically in Europe and North America a wind speed in the summer of 0.61 m/s perpendicular to the line, maximum solar heat intensity at noon and ambient air temperature of 30^0C to 45^0C is considered for design purposes. The difficulty here is that conductor ratings are based on statistical analysis of some times measured field data.

The interesting point here is that at one time ac lines were certainly operated at much lower current values compared to their thermal limits. However, the introduction of FACTS devices enabled the utilities to increase the current loading of ac lines closer to their thermal limits. Therefore the next step to increase the transmission capability of a transmission line is:

- To increase the current rating further with the risk of causing damage to the conductor as well as loss of life, especially knowing the statistical nature of the field data.
- Replace the original conductors with High Temperature Low Sag conductors (HTLS).
- Conversion to HVdc.

3.2.2. Characteristics of dc line insulation

It is worth while reviewing the characteristics of dc line insulation to understand the requirements for converting an ac line to a dc line from an insulation standpoint. The string design and insulator selection is an exercise which requires specific considerations given the unique application. The insulators for dc lines are made with specific dielectric materials, additionally the string length and characteristics, such as leakage distance, have to be adjusted for the prevailing contamination conditions.

The unidirectional electric field applied on the insulators of a dc line has a strong impact on the integrity of the dielectric materials that are traditionally used for ac applications [7]. Currently IEC 61325 covers in detail and precisely the minimum requirements for HVdc glass and porcelain insulators. Composite dc insulators have been applied in some HVdc lines; however, composite line insulators in HVdc are not covered by the standards.

Unlike ac applications the voltage distribution in dc is controlled by the resistivity, therefore choosing materials of uniform and high resistivity is very important. There are two parameters in dc insulation that are both linked to the resistivity:

- Ionic migration
- Thermal runaway

In addition the risk of electrochemical corrosion needs to be considered more with dc insulation compared to ac insulation. The effect of airborne particles attracted by the unidirectional electric field will generate a background pollution level. The metal and fittings can be severely degraded from the resulting unidirectional electric activity on the surface of the insulator in the vicinity of the fittings. This will result in the failure of the pins. DC insulators are equipped with sacrificial zinc sleeves at the pin.

The cast iron cap itself can also suffer corrosion and while ac insulators are assembled with normal caps, for dc applications corrosion protection is applied on both the pin and the cap side.

There are some important factors to be taken into consideration when deciding on the HVdc insulator string.

- Maximum voltage level of the line
- Altitude of the line route
- Contamination conditions

A typical dc line voltage rating is about 3-6% above the nominal rating of the HVdc system. For example for a 500 kV system the dc line reference value may be 515 kV. The air gap length required for a string in a dc line is usually not the driver. The string length is determined by contamination consideration rather than switching impulse requirements.

Environmental pollution consists of both soluble and non-soluble contaminants. The soluble component is generally some kind of salt, usually sodium chloride (NaCl) and when dissolved in the surface layer of water, increases the surface conductivity of the insulator. Non-soluble contamination such as dust or kaolin does not affect the surface conductivity of the insulator, but may influence the absorption of moisture on the insulator surface. The contamination severity is generally characterized by equivalent salt deposit density (ESDD), which corresponds to the equivalent amount of sodium chloride on the surface area of the insulator, in mg/cm^2, which has the same conductivity as the actual deposit dissolved in the same amount of water. The non-soluble deposit density (NSDD) is the amount of non-soluble deposits expressed as the weight of these deposits per unit area of the insulator surface in mg/cm^2. The pollution performance of insulators is generally expressed only as a function of ESDD.

Application of statistical design methods for insulator selection is difficult because of the limited availability of experimental data on the influence of various parameters on the performance of insulators. An alternative approach has, therefore, been suggested in which design guidelines are proposed that are based on the results of extensive laboratory and field studies on different types of insulators. The proposed guidelines recommend specific leakage distances (cm/kV) required in areas of different pollution severities and are shown in the following table. The specific leakage distances in the table apply equally to vertical strings, V strings and horizontal strings because no significant effect of string orientation was found.

	Contamination Severity, mg/cm^2			
	Very Light < 0.005	Light 0.005-0.02	Moderate 0.02-0.05	Heavy >0.05
Specific Leakage Distance (cm/kV)	2.0 – 2.5	2.5 – 3.2	3.2 – 4.0	4.0 – 7.0

3.3. Design criteria for HVdc lines

Electrical design of HVdc transmission lines consists mainly of selecting the air insulation clearances between the energized conductors and the various elements at ground potential in the vicinity, the choice of the number and type of insulators required to support the energized conductors and selection of conductor bundle and its height above ground. The main objectives are to obtain a line design with reliable performance over the operating life of the line, acceptable environmental impact and minimum overall cost.

Design of air insulation comprises selecting the conductor-tower, conductor-conductor and conductor-ground air gaps to withstand the maximum operating voltage of the line as well as the switching and lightning overvoltages to which the line may be subjected. The design procedure requires knowledge of two basic sets of information:

1) the maximum operating voltage and the shapes and magnitudes of the switching and lightning overvoltages;
2) the flashover and withstand characteristics of the air gaps associated with HVdc lines under direct, switching and lightning voltages.

The highest levels of switching surges on bipolar dc lines occur on the unfaulted pole due to a pole to ground fault on the other pole due to lightning or polluted insulator flashover. Overvoltages originating in the ac system or in the converter station are generally limited by lightning arresters. The magnitude and shape of the surge voltage on the unfaulted pole due to a ground fault on the other pole depends on the fault location along the line as well as the equipment connected at the line ends such as dc side harmonic filters etc. The shape of surges generated depends to a large extent on the circuit parameters defining the transmission line and the terminal equipment, while the magnitude of the surge depends on the location of the fault. For a given fault location, the magnitude also varies at points along the line. Digital or analog simulation techniques may be used to determine the shapes and magnitudes of switching overvoltages generated on HVdc lines.

For the experimental determination of the dielectric breakdown and withstand characteristics of air gaps, the switching surges on dc lines are represented by a standardized waveform of a 250 μs/2500 μs double-exponential transient superimposed on the direct voltage of the line [10]. The peak amplitude of the switching surge is, therefore, given as $V_p = (V_{dc} + V_t)$, where V_{dc} is the operating direct voltage of the line and V_t is the peak of the superimposed transient voltage. At any given point along the line, the peak amplitude V_p may be considered as a random variable, represented by a probability distribution function $P(V_p)$. Simulator studies of HVdc transmission systems have indicated that the highest values of V_p can range between 1.5 p.u and 2.2 p.u.

There has been a steady evolution in the design procedures used for determining the air gap clearances of HVdc transmission lines. Early line designs used deterministic methods for evaluating the minimum gap clearances necessary, based on the available data on rod-plane flashover characteristics and the prevailing safety regulations. The procedure consists essentially in estimating the highest switching overvoltage V_s (usually 1.7 p.u) and then determine the air gap clearance that can provide 99.9% withstand probability, i.e. $V_s = V_{50\%} .(1\text{-}3\sigma)$, where $V_{50\%}$ is the critical flashover voltage of the selected gap. Additional safety factors may be added in selecting the air gap clearance to take into account other factors. The clearance determined as described above actually corresponds to the maximum expected swing of the conductor towards the tower, which can be determined knowing the insulator length (in the case of an I-string) and maximum wind forces on the conductors. The conductor tower clearance at zero wind conditions may then be determined as the sum of the minimum clearance required to withstand the switching surges plus the conductor swing displacement. Finally, the pole spacing is obtained as (2d + w) where w is the width of the tower structure.

The design procedure described above can be improved as more accurate information on the voltage stresses as well as on the insulator strength of conductor-tower gaps become available through the efforts of research and testing. For example, the data on the flashover and withstand characteristics of actual conductor-tower air gaps rather than rod-plane gaps should be used, particularly for switching surge withstand, to improve the design procedure.

As in the case of ac lines, conductor selection for HVdc transmission lines is based on corona performance considerations, mainly the corona loss (CL), radio interference (RI) and audible noise (AN). The main difference between the impact of corona on the design of ac and dc lines arises because the highest levels of RI and AN occur on ac lines during rain and on dc lines during fair weather. In addition to CL, RI and AN, the design of HVdc transmission lines should also take into account the possible environmental impact of ground-level electric fields and ion currents.

Any procedure for the corona design of HVdc transmission lines requires two sets of information:

1) Methods for predicting the CL, RI, AN and the ground-level electric fields and ion currents as functions of line voltage and parameters such as the number and size of conductors in the bundle, pole spacing and conductor height as well as of prevailing weather conditions;
2) Design criteria for CL, RI, AN and ground-level electric fields and ion currents.

Similar to ac lines, the corona performance of dc lines is a complex function of corona physics, conductor surface conditions and the prevailing weather conditions. Development of prediction methods for the corona performance of HVdc lines requires theoretical as well as experimental studies. Long-term measurements covering the weather conditions occurring in different seasons of the year, made on experimental as well as operating transmission lines are an essential basis for the development of prediction methods.

Corona losses may have an impact mainly on the economic choice of overall conductor cross section. An optimum conductor cross section is generally determined to give the minimum overall annualized cost of the line, which includes the capital cost of the line and the cost of power losses in the conductor comprising the I^2R losses and corona losses. However, as the operating voltage of the line increases, the importance of corona losses compared to the I^2R losses decreases.

For lines above about ± 200 kV, it may be necessary to split the total conductor cross section determined on the basis of economic considerations, into a number of sub-conductors in a bundle, in order to obtain acceptable levels of RI and AN. The height of the conductor bundle determines the acceptable levels of ground-level electric fields and ion currents.

As in the case of ac lines, design criteria for RI from dc transmission lines are based on its impact on radio reception in the AM broadcast band. A number of studies have been carried out to determine acceptable signal-to-noise ratios (SNR) for corona-generated RI from ac transmission lines and the results used to develop standards and guidelines. Comparatively fewer studies have been carried out, however, for RI from dc lines. Based on the results of the most comprehensive of these studies, the following SNRs are obtained for ac and dc corona:

DC fair weather	:	26 dB
DC foul weather	:	21 dB
AC fair & foul weather	:	22.5 dB

At present, there are no standards or regulations that set limits to RI specifically from dc transmission lines. However, the similarities as well as the differences between the characteristics of RI from ac and dc transmission lines may be used to develop guidelines for dc lines. The similarity is that acceptable SNR's for RI from both ac and dc lines are roughly the same. However, while RI from ac lines in foul weather (rain or wet snow) is 10-20 dB higher than in fair weather, foul weather RI from dc lines may be 5-10 dB *lower* than in fair weather.

3.4. Aspects of the conversion process

There are many aspects to the process of converting an ac line to a dc line:

1. Dc voltage selection
2. DC insulation selection
3. Is tower upgrade necessary
4. In the case of multiple circuits on the ac tower, should all be converted or only one should be converted, which means ac and dc lines on the same tower.

The DC voltage must be selected properly to ensure the proposed conversion results in acceptable values of electric and magnetic fields and the ion current densities under the lines.

The following is a case study based on [6]. The studies were performed to analyze the options and the possible enhancements if 220 kV ac lines are converted to HVdc lines in Polish grid.

The conversion concept adopted assumed that the existing conductors should be used and the insulators replaced with appropriate insulators for HVdc transmission. Several existing tower configurations were considered. The two configurations considered at the end were the Delta conductor configuration shown in Figure 3-6 and the horizontal conductor configuration shown in Figure 3-7.

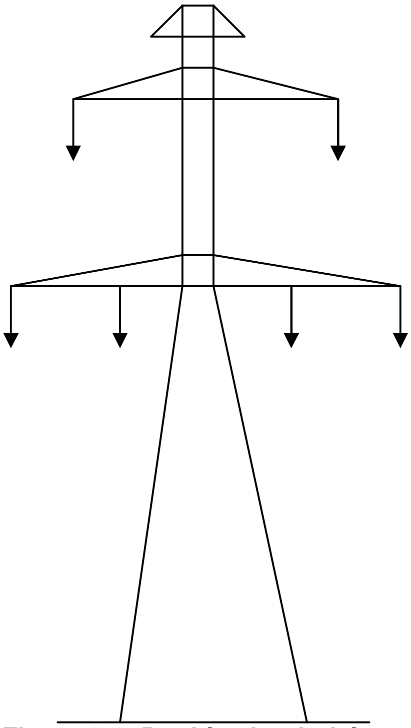

Figure 3-6 Double circuit delta conductor configuration

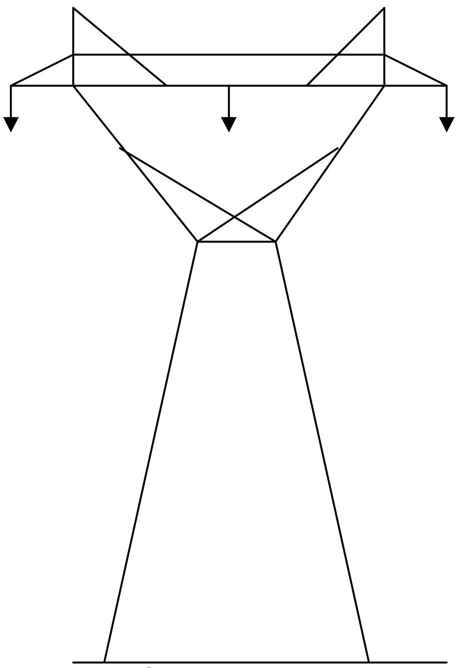

Figure 3-7 Single circuit flat conductor configuration

The approach adopted was based on the distance between the cross arm of the tower and the conductors as defined by the length of the ac insulators. When replacing the ac insulators if they are replaced with HVdc insulators of the same length but with different shape and longer creepage distance, it is possible to determine the dc voltage. The pollution zones were classified to pollution zone I, pollution zone II, and pollution zone III, with I being the lowest ESDD and III the highest. By replacing the insulators with the appropriate HVdc insulators and the appropriate creepage distance 26-34 mm/kV for zone I, 32-44 mm/kV for zone II, and 56mm/kV for zone III, it was found that the dc voltage in zone can be +/- (290-

380)kV for zone I, (225-305) kV for zone II. In the case of zone III the conversion of the line to HVdc line is not suitable because the dc voltage would be too low.

The next check was to ensure that the conversion proposed results in acceptable values of electric and magnetic fields and the ion current densities under the lines.

The proposed conversion of the double circuit delta configuration ac line in zone I pollution resulted in a dc voltage selection of +/- 350 kV and an increase in the transmission capacity of 175% as shown in Figure 3-8.

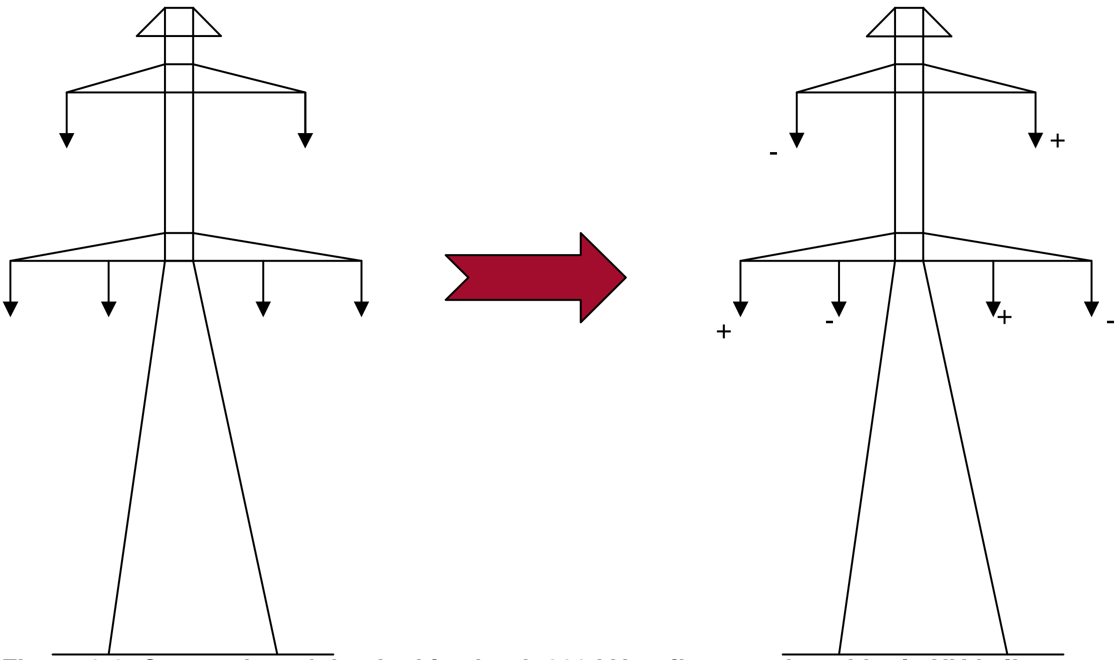

Figure 3-8 Conversion of the double circuit 220 kV ac line to a three bipole HVdc line at +/- 350 kV [6], the capacity increased by 175% and the right of way reduced from 38 meters to 29.5 meters

3.5. Hybrid transmission lines

The interesting point of the conversion of ac lines to HVdc lines is that the only project that actually did the conversion ended up with a hybrid transmission line meaning both the dc line and the ac line are on the same tower [8]. The project referred to here is the HVdc national project in India which involves a 220 kV double circuit ac line of 196 km length and rated 240 MW. One circuit was converted to a ±100 kV dc line which resulted in an increase in the transmission capacity to 400 MW.

Simulator studies were performed to demonstrate that the close coupling of the two parallel circuits presented no major problems.

It is worth while to address first possible impacts of the coupling between ac and dc on the same tower. The steady state induction effect leads to power frequency currents flowing in the dc side of the converter valves [3]. In addition the converter transformers may experience an offset saturation phenomenon, because of the possibility of dc component in their primary windings proportional to the power frequency current on the dc side.

The areas of concern are:

- Greater generation of harmonics on both the ac and dc sides of the converter valves
- Increase in the level of audible noise

- Converter transformer heating, which may affect its life
- Impact on the control and protection
- Impact on recovery from dc line faults because of secondary arc effects [11]
- Faults between the ac and the dc lines

Having now examined the issues surrounding the hybrid lines, the studies performed [8] for the hybrid line in India showed that by careful design of the control and protection, most of the problems can be mitigated. However, special attention must be given to the additional stresses imposed on the ac and dc filters.

3.6. The Tripole concept

The tripole concept has been introduced by L.Barthold in [4,5,12]. The concept of the tripole is based on the fact that in the steps leading to the conversion of an ac line to a dc line there is always three conductors to deal with. Therefore, one can take advantage of the presence of the three conductors and their short term thermal capability. The concept basically calls for having three poles and if we can refer to the three poles as P1, P2, and P3, the third pole P3 can be applied in a manner to complement the operation of poles P1 and P2. If we start with P1 operating at the maximum current I_{max} and P2 at the minimum current I_{min} then the difference I_{max} - I_{min} can be carried by P3 to balance the dc current in the ground. This can basically be repeated on a duty cycle to relieve P1 and P2 from carrying maximum current for extended periods. The concept is best illustrated in Figure 3-9 from [12].

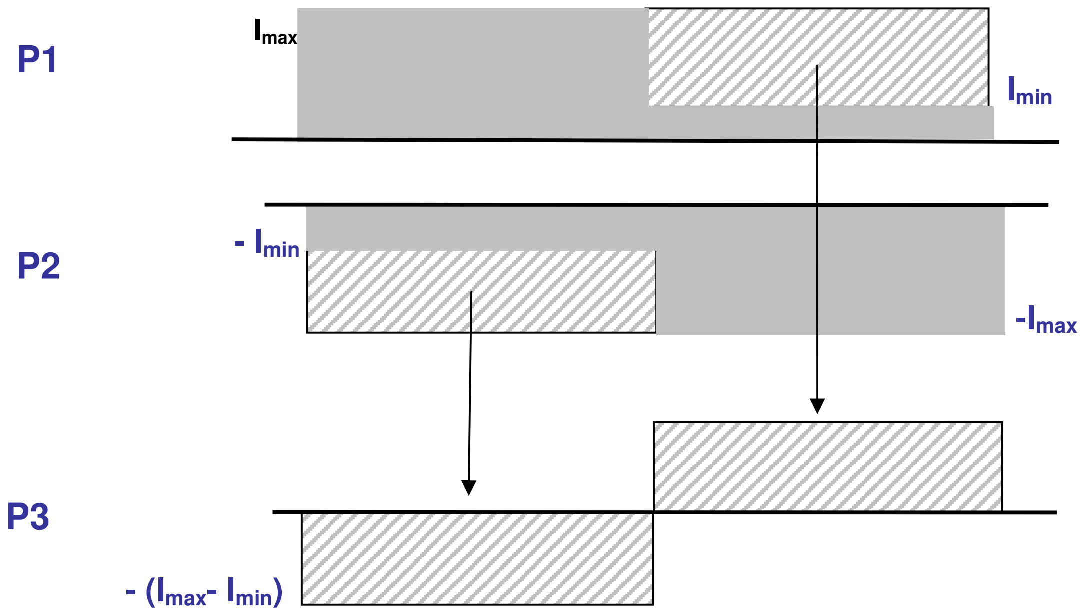

Figure 3-9 The tripole concept

Obviously I_{max} and I_{min} and the duty cycle have to be selected to establish the correct heat generation and thermal rating of the conductor.

The concept is dependant on having valves in P3 that can reverse the direction of flow of current. This means P3 has to be equipped with bidirectional valves as illustrated in 3-10.

Obviously this concept will result in more transfer capability if we are dealing with one circuit because of the idle third conductor is now being utilized. It has not been done yet, but there are projects considering it. The technical risk is limited because it only involves controls and bidirectional valves in one pole.

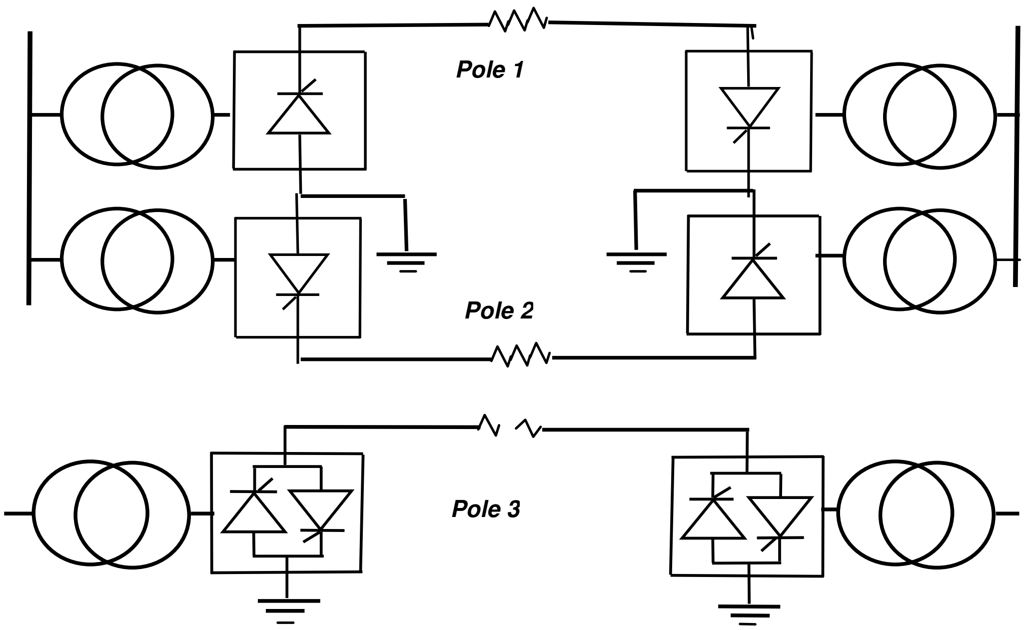

Figure 3-10 Tripole converter concept [12]

3.7. Transformerless HVdc

The possibility of configuring converter at each end of an ac transmission line without converter transformers has been presented in [2713,14] based on line commutated converters. The concept is presented in Figure 3-11. A transformerless HVDC link will be applicable if we can match the dc voltage to the ac voltage. There will result in a cost saving.

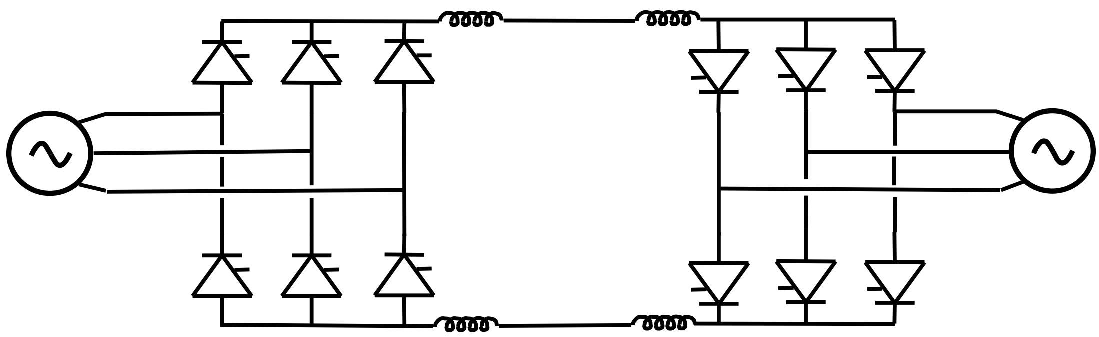

Figure 3-11 Basic configuration of a transformerless HVdc system

With line commutated converters in the transformerless configuration of Figure 3-11, the following points are raised in reference [13]. There is a potential problem of three-pulse ground mode harmonics being injected to the ac systems due to common mode ac and dc system grounding. Air cored phase reactors or autotransformers will be required in place of the converter transformers to limit the harmonics, and contain the di/dt stresses on the valves.

A common mode harmonic blocking reactor may be required if the phase reactors are inadequate to restrain the ground mode triplen harmonics as shown in Figure 3-12. Ground mode triplen harmonics have a far greater potential for interfering in operation and performance than positive and negative sequence harmonics typical of conventional converters.

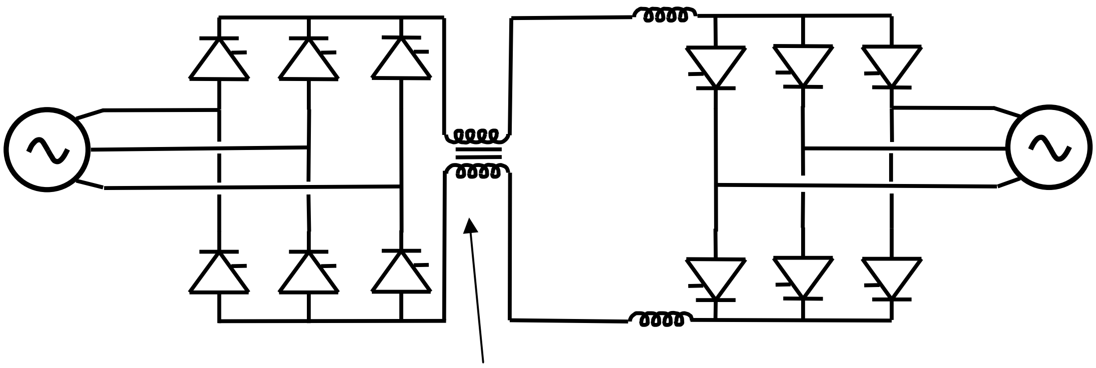

Figure 3-12 Configuration of a transformerless HVdc transmission line with common mode blocking reactor

The six pulse bridge is effectively two three pulse poles, where each pole produces its own dc current. A control system for balancing the direct current in the two poles is dependent on the accuracy in measuring the dc current, where it is challenging to ensure the difference is zero. Any spill-over dc current that enters the ac system can contribute to saturation of transformers located nearby. Series capacitors between the valve group and the ac system will block any dc current. If a common mode blocking reactor is applied, the difference in dc current in each pole is readily detectable in the measurement of dc flux in its core. The dc flux measurement can be achieved with high accuracy and so be applied with the controls to eliminate any difference in dc current in the poles.
The nominal dc voltage achieved with a transformerless configuration is provided by the expression:

$$U_d \approx 1.145 V_{L-L}$$

Where U_d = pole-to-pole dc volts
And

V_{L-L}= ac system nominal line to line rms volts.
This means that for a 230 kV ac transmission line, the pole-to-pole dc volts achieved is 263 kV without the use of a converter transformer. This is considerably less than the dc voltage possible if the line is converted to dc where peak ac volts to ground should at least be possible for each pole. In this case the pole voltage to ground is 230 x √2/√3 which would result in a pole voltage of 188 kV, which realizes 376 kV pole-to-pole volts.

3.8. References

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4. HVdc Cables

4.1. Introduction

The number of HVdc projects using long HVdc cables is on the increase, mostly for sub-marine power transmission. HVdc system utilizing dc cables have been in service since 1954 and the number of systems in the planning stage is increasing. However, one must emphasize that since 1954 the technology and the rating has increased dramatically.

The economic design of dc cables is very important, because the cost of the dc cables is a high proportion of the total cost of the HVdc project. The feasibility and economic viability of HVdc cable projects can improve if HVdc cables can be made at lower costs or the transmission capacity of the HVdc cables is increased.

There are two factors that affect the design of an HVdc cable, the current carrying capacity which is related to the thermal stresses on the cable, and the voltage capability of the cable which is related to the voltage gradient on the insulation. There are technical challenges in improving both these factors and there is an on going research in both fields.

There are currently four types of cable used in HVdc projects:

- Oil filled (OF)
- Gas filled (GF)
- Mass impregnated (MI)
- Solid extruded insulation (XLPE)

The following sections will briefly describe each of these technologies and some of the existing HVdc cable projects in the world.

4.2. HVdc cables in operation

Table 6 below is a summary of some of the HVdc cables in operation.

Table 6 Existing HVdc cable systems in operation

Name	Commissioning year	Voltage (kV)	Power (MW)	Insulation	Length (km) L= land S=Sea	Converter Line commutated (LCC) Voltage source (VSC)
Gotland 1	1954	100	20	MI	100	Decommissioned
Gotland 2&3	1983 and 1987	+/-150	260	MI	92+0.9/ 92+6 (L+S)	LCC
Gotland HVDC Light	1999	+/- 60	50	XLPE	70	VSC
Cross Channel	1986	+/ 270	2000	MI	71	LCC
SACOI	1992	+ 200	300	MI	221	LCC
The Baltic Cable	1994	450	600	MI	261	LCC
Direct Link	2000	+/- 80	3X60	XLPE	59	VSC
Fenno-Skan	1989	400	500	MI	200	LCC
GRITA	2001	400	500	MI	163 +43	LCC

Haenam-Cheju	1996	+/-180	300	MI	101	LCC
Hokaido-Honshu	1993	+/- 125	600	OF	43	LCC
Kontiscan 1	1965	250	250	OF+MI	87	LCC
Kontiscan 1	1988	285	300	OF+MI	87	LCC
Kontek	1995	400	600	MI	171 (L+S)	LCC
Leyte-Luzon	1998	350	440	MI	23	LCC
New Zealand	1965-1992	270/-350	1240	MI	40	LCC
Skagerrak	Bipole 1976 Monopole 1993	Two mono poles @ 250/ and one monopole @ 350	275x2 And 500	MI	127 127	LCC
SwePol	2000	450	600	MI	239+14.8	LCC
Norned	2008	+/-450 Mid point ground	700	MI	580	LCC
Cross Sound	2002	+/- 150	330	XLPE	40	VSC
Murray Link	2002	+/- 150	220	XLPE	180	VSC
Transbay Cable	2010	+/- 200	400	XLPE	80	VSC
Bass link	2006	400	500	MI	295+1.7	LCC
Neptune	2007	500	650	MI	80	LCC
Kai Channel	1998 Currently operating only at 250 kV	500	2800	OF	50.7	LCC

The table shows that the majority of the HVdc projects employing line commutated converters LCC use MI cables, and the voltage source converters (VSC) use XLPE cables. The OF and GF cables are rarely used.

4.3. Mass impregnated cables (MI)

Mass impregnated cables are the most widely used type of cable in HVdc transmission systems. The Sweden-Gotland HVdc link used this type of cable in 1954 for the first time. MI cable ratings have increased over the years in both voltage and current. Presently, cables rated for 600 kV dc voltage have been successfully type tested and are available now. The maximum dc current rating is presently up to bout 1700 A and there are indications that it will climb to 1800 A in the near future. This means a power rating of approximately 1100 MW per cable or 2200 MW per bipolar link.

MI cables are utilized with LCC thyristor converters mainly because of the higher ratings and their capability to withstand dc polarity reversal. The dc polarity reversal is essential in LCC thyristor converters mainly to accommodate the change of power direction and also during HVdc disturbances. MI cables can be also used with VSC converters; however, for most applications the cost will be higher compared to

XLPE alternatives. The use of MI cable with VSC converter is justified in cases where the dc voltage rating is too high for XLPE cable.

The typical MI cable is constructed with a copper conductor of sufficient cross section area to accommodate the dc current. The conductor is surrounded by a conductor screen to allow proper transition between the conductor and the insulation. It is typically a semiconductor paper tape. This is followed by the insulation system which is typically wood pulp paper impregnated with high viscosity fluid. This is followed by the insulation screen which is a paper layers and metalized paper followed by fabric tape which includes copper threads to protect the core. This is followed by the Lead sheath and a polyethylene layer which acts as an anti corrosion protection. The typical MI cable has an outer reinforcement and armour layer for mechanical protection.

MI cables have been laid to a depth of 1600 m [6] and at a span of about 150 km continuous. For longer distances pieces of cable must be connected to each other using a field joint. Figure 4-1 below shows the layers of a typical MI cable.

Figure 4-1 Typical submarine MI cable construction [7]

4.4. Cross linked Polyethylene cables (XLPE)

XLPE cables have been applied in HVdc since 1997. Their voltage rating has increased to 325 kV and their current rating to 1500 A. XLPE cables have been used in HVdc applications with VSC converters that utilize Insulated Gate Bipolar Transistors (IGBT) valves. Both two and three level converters as well as multi-module converters have been used with XLPE cables. There are also reports that a 350 kV cable has been type tested. It should be mentioned however that the highest voltage XLPE cable presently in testing and commissioning is 200kV (Transbay project).

The technology to produce extruded cables is generally less complicated than technology needed to produce mass impregnated or oil filled cables and therefore production costs is considerably lower. In addition to that, extruded insulation can operate at higher temperatures than MI cable. Despite these advantages the use of XLPE cables is somewhat hampered by its sensitivity to polarity reversal.

When an XLPE cable is under DC voltage for a relatively long time (hours) and fully charged, its voltage polarity cannot be changed quickly. This is due to the presence of the space charge trapped within cable insulation due to its high resistivity. As a result this type of cable cannot be used together with conventional thyristor based line commutated HVdc converters as the DC voltage polarity reverses quickly in these converters during a power reversal and some transients. The application of XLPE cables in HVdc is suitable for the Voltage Source Converter (VSC) technology since in this application the change in power direction does not require a voltage polarity reversal, it is its current that reverses.

The conductor in an XLPE cable can be either copper or aluminum. The cross section must be suitable for the current carrying capacity of the cable. This is surrounded by the semiconductor rubber layer, surrounded by a field controlling layer and an insulating layer. Armouring and mechanical protection which is in the form of double steel wire is then provided. A typical XLPE cross section is shown in figure 4-2. The insulation system consists of 3 layers that are simultaneously cured, the first layer is the conductor screen which is of a semi conductive polymer, followed by the insulation polymer, then followed by the insulation screen which is again a semi conductive polymer. Further information regarding the actual detailed design of the screens is protected by confidentiality agreements with the cable manufacturers.

In submarine applications XLPE cables can be laid to a depth of 1500 m [2]. They can also be used in underground applications. By the end of 2005 the number of km years of XLPE cables stands at 4200.

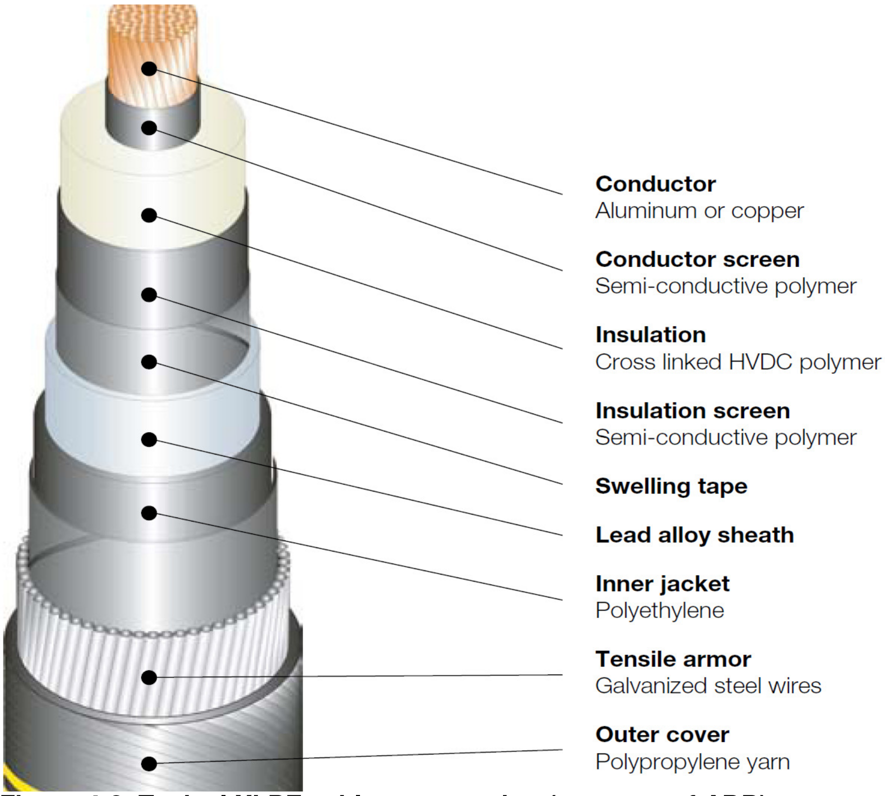

Figure 4-2 Typical XLPE cable construction (courtesy of ABB)

The following **Table 7** gives a comparison between the electrical properties of XLPE insulation and MI insulation.

Table 7 Electrical Properties of MI insulation and XLPE insulation

Insulation	Breakdown strength MV/m	Resistivity Ohm. m	Relative permittivity	Thermal Resistivity K.m/W
MI	170	$5x10^{12}$	3.5-4	5-6
XLPE	700	10^{14}-10^{17}	2.4	3.5

Joints for the connection of two cable sections or repair are very critical. However, this is not unique to XLPE cables it also applies to MI cables. Although, the joints for land design and submarine design are the same, the mechanical design is different due to external forces and water tightness.

A typical joint for an XLPE cable system is shown in Figure 4-3.

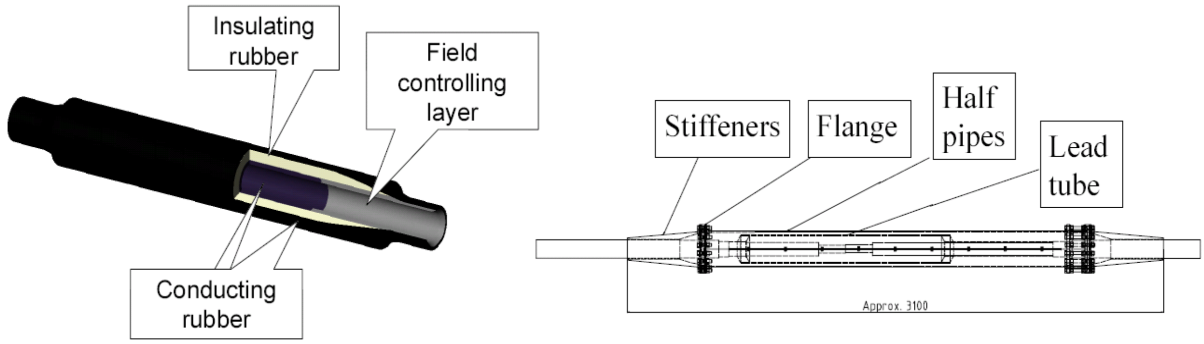

Figure 4-3 Stiff joint system [2]

4.5. Oil filled cables (OF)

OF cables have been manufactured for HVdc applications up to 500 kV and 2800 A. The advantage of an OF cable is the higher permissible conductor temperature compared to the MI cable. Polypropylene Laminated paper (PPLP) insulation has been used in OF cables at 500 kV because of the higher DC and impulse breakdown strength than Kraft paper, which means less insulation thickness (3).

OF cables are not widely used due to environmental concerns.

4.6. Gas filled cables (GF)

The Gas Filled cables are not commonly used in HVdc applications due to the fact that they require gas pressurization at both ends and may experience uncontrolled water propagation in case of cable damage.

4.7. Cable terminations

Cable termination bushings are applied mainly to connect the HVDC cable to an over head line at transition yards, or to connect the HVDC cable to the actual converter station.

Historically porcelain oil filled bushings with oil impregnated condenser core were applied. Porcelain oil filled condenser core type bushings in HVDC systems operating at 400 kV and higher experienced flashovers. The causes of the flashovers were reported to be:

1. Pollution
2. Bad weather conditions
3. Unequal wetting

The trend in the early days based on the experience in the operating HVDC systems is to specify a higher specific creapage up to 60 mm/kV. However, such increase did not improve the flashover performance of the bushings. Utilities and manufacturers of HVDC equipment cooperated and a number of solutions were adopted including:

1. Frequent cleaning. This is costly and is only effective for a short period of time immediately following the cleaning.
2. The application of silicone or petroleum base grease. This is an effective solution that has been shown to reduce the number of flashovers. However, grease application is labour intensive and the grease must be reapplied periodically to avoid the flashover and permanent equipment damage.
3. The application of RTV coating. This is certainly effective to avoid flashovers and has the advantage of being a hydro phobic coating which is effective in preventing the unequal wetting flashovers. However, depending on the site pollution conditions it may have to be removed and a new coating applied.
4. The use of booster sheds, which have been proven in laboratory tests and in the field to be effective in reducing the number of flashovers.
5. Implementing an automatic washing system.

The development of composite bushings certainly improved the flashover performance. Composite bushings are typically of a resin impregnated graded condenser core, housed in a non porcelain housing, with externally applied silicon rubber sheds. In the higher voltage applications of 500 kV and above the bushing is filled with SF6. However in some of the recent designs even at 500 kV solid composite bushings are available.

Composite silicon rubber type bushings have demonstrated good performance for both pollution and unequal wetting type flashovers. Composite bushings are typically lighter in weight compared to an equally rated bushing. They were introduced in HVDC applications up to 500 kV in the mid eighties.

Composite bushings are now commonly used as cable termination bushings or wall bushings.

4.8. Electrical stresses on HVdc cables

Typically lightning overvoltages do not enter a pure cable transmission system. However, faults on the cable side of a smoothing reactor can lead to steep front travelling waves. Although the amplitude of such overvoltages is low, there will be steep voltage changes.

In the case of a mixed overhead/cable transmission, lightning overvoltages are important for the design. Surge arresters are therefore provided at the interface of the cable and overhead line.

Most of the internal overvoltages occurring in a cable transmission system have amplitudes less than 1.5 pu for 100 ms and they do not influence the insulation coordination of the HVdc cable.

On the other hand external faults especially on an overhead line/cable system are important because of:

- Reflections
- Load rejection
- Overvoltages on the ac side resulting in an overvoltage on the dc side
- Persistent commutation failures
- Loss of control pulses at the rectifier
- Inadvertent pulse blocking at the inverter

Generally cables are protected by surge arrestors at both ends (cable transition/termination points). The margin between the protective level and withstand level of the cable insulation is split into:

- The margin between the protective level and the test voltage level (test margin)
- The margin between the test level and the expected withstand (manufacturing margin)

The general consideration for selecting margins:

- Service experience
- Frequency of occurrence of overvoltage
- The shape and characteristics of the overvoltage.
- Uncertainties
- Aging effects.

4.9. Testing

There are two test recommendations for MI HVdc cables:

1. Recommendations for mechanical tests on Sub-marine cables Cigre WG 21-06.
2. Recommendations for tests of power transmission dc cables for a rated voltage up to 600 kV, Cigre WG 21-01.

For XLPE cables below 250 kV dc Cigre Brochure 219 is available and for voltages above 250 kV Cigre' WG B1-32 is in the process of preparing recommendations. The working group's report is expected to be released in 2011.

4.10. Challenges and the future trends

The increasing demand for transmission of massive amounts of power from renewable energy resources, combined with the increased limitations on building new overhead transmission lines are the major development forces for HVdc cables. MI cable technology has been impressively improved to allow transmission of up to 2200 MW through one bipole. MI submarine cables have reached the depth of one mile. Further development in increasing the voltage and current ratings, reducing weight and reducing the number of joints is expected to continue. It is anticipated that a rating of 3000 MW per bipole to be achieved within a few years[7]. Lower cost and better mechanical properties have also increased the interest in the XLPE cables. Development of this type of cables is also anticipated to continue in the future toward higher power ratings.

Currently there is work progressing in the area of super conducting cables, and there is one proposed project [5]. However, presently is only a proposal. A schematic diagram of this project is shown in Figure 4-4.

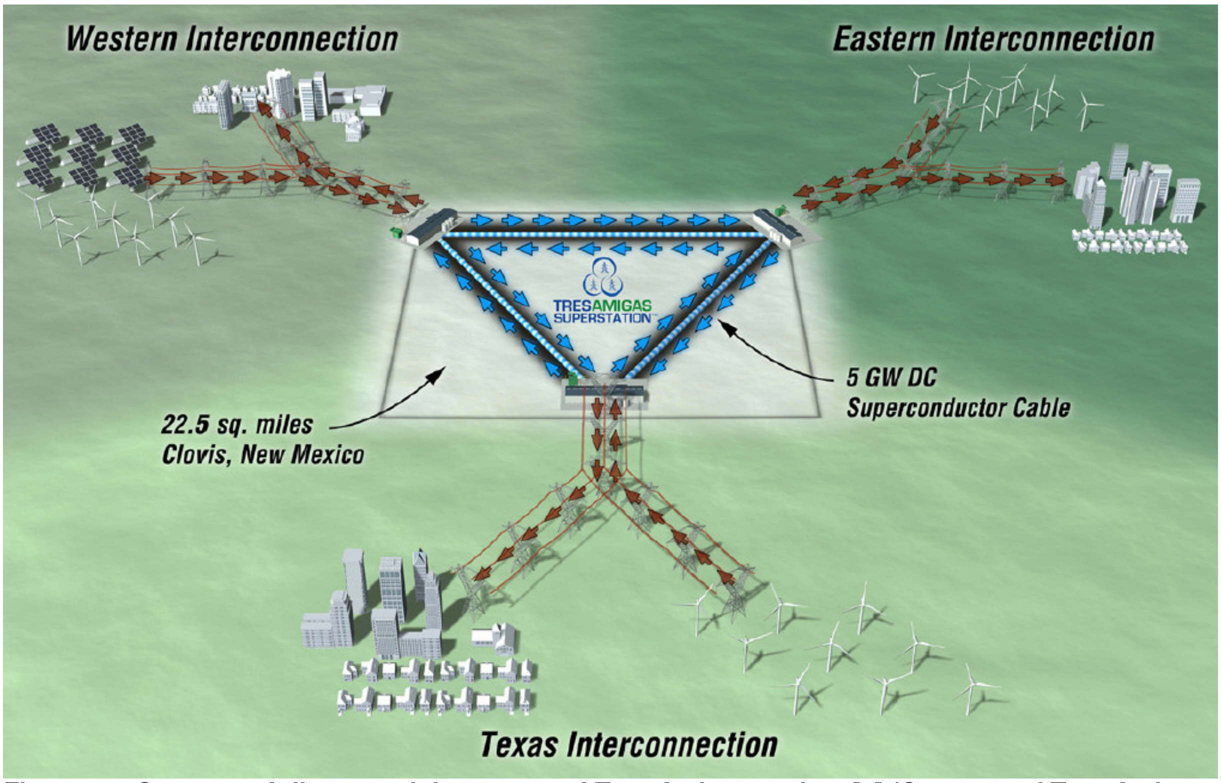

Figure 4-4 Conceptual diagram of the proposed Tres Amigas project [5] (Courtesy of Tres Amigas LLC)

4.11. References

1. The Italy-Greece HVDC Link. Cigre Session 2002 paper 14-116
2. HVDC with voltage source converters and extruded cables for up to +/- 300 kV and 1000 MW. Cigre Session 2006 paper B4-105
3. Development of 500 kV DC PPLP-insulated oil filled submarine cable. Cigre 1996 Paper 21-302
4. Cigre JWG 33/21/14-16 Overvoltages on HVDC cables
5. “Assessment and evaluation of the next generations of HVDC technologies”, EPRI report 1016070
6. “Feasibility of a new long distance submarine HVDC link between Sardinia island and Italian peninsula (SAPEI)”, Cigre’ Session 2004, paper B4-206.
7. “Challenges and achievements for new HVdc cable connections”, Cigre’ SC B4 2009 Bergen Colloquium, paper 502.

5. Multi-Terminal HVdc Systems

HVdc transmission development dates back to 1954 when the first HVdc link between Gotland and the main land of Sweden. The early HVdc links were the point-to-point systems transferring power between only two terminals. The idea of adding 'taps' or more terminals to a HVdc link was discussed from the early days of HVdc, but was never realized until 1989 when the SACOI 1 system between Italy and Sardenia was modified to supply power to the island of Corsica. Shortly after the Quebec-New England five-terminal system went into service in 1992. The operation of this system was proved to be a challenge because of the number of terminals and the large difference in the terminal sizes. Later on two smaller terminals were removed to allow for more reliable operation. There has been no new multi-terminal HVdc schemes built since then, but there are a few at various study or design stages. An example is India's proposed +/-800kV, 6000MW NER-Agra system [3].

5.1. Multi-Terminal HVdc Configurations

A multi-terminal HVdc system can consist of line commuted converters (LCC's) at all terminals as shown in Figure 5-1 below. Note connection details for reversing the power direction in terminals are not shown in this figure and are discussed in section 5.2.Both existing multi-terminal HVdc systems, i.e. SACOI and Quebec New England have a configuration similar to this. This configuration is difficult to use if one or some of the terminals are significantly smaller than the others. As discussed in section 5.3.1 below, small terminals can cause the entire power transfer to be halted for disturbances in ac system connected to them, and they may get damaged if the entire dc current from other terminals flow towards them. A fast bypass switch combined with a fast isolation switch may be required to avoid the risk of damage to a small terminal [5].

Theoretically all or any one of the terminals can be made of a voltage source converter, however if an LCC inverter terminal is present in the system using a VSC terminal is not advised due to poor fault performance as explained in section 5.3.3. Figure 5-2 below shows a multi-terminal system consisting of voltage source converters only while Figure 5-3 shows a system made of two LCC and one VSC terminals. Note that unlike an LCC, the voltage polarity across a VSC cannot change due to the presence of the anti-parallel diodes across the IGBT's.

A three-phase voltage source converter normally consists of three phase arms connected in a bridge configuration as shown in Figure 6-42. In a multi-terminal system for small VSC terminals (or taps) a series connection of three phase arms like Figure 5-4 is also proposed. Although this configuration has the advantage of each phase arm being rated for a third of the full dc voltage, at this point it is only a proposal.

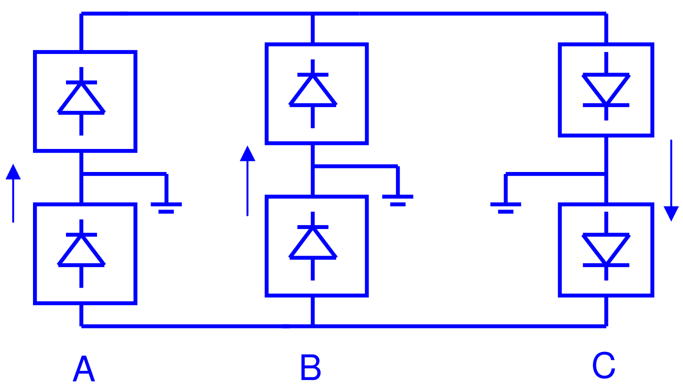

Figure 5-1 A three-terminal HVdc system with LCC converters only

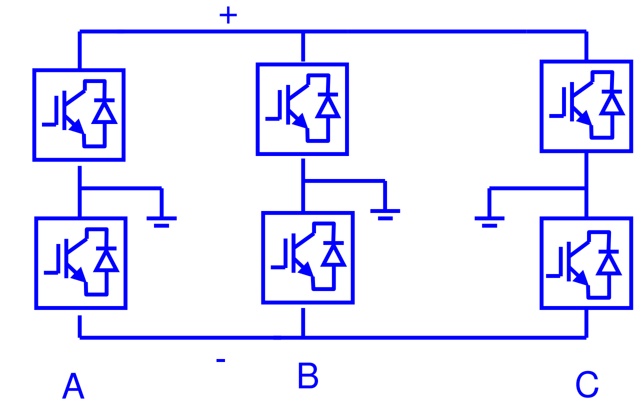

Figure 5-2 A three-terminal HVdc sysem with VSC converters

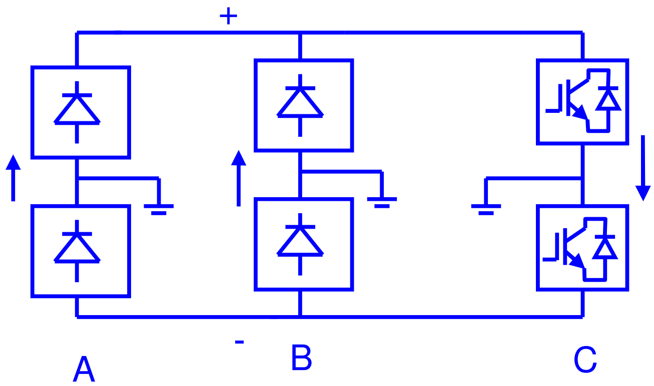

Figure 5-3 A multi-terminal HVdc system made of two LCC and one VSC terminal

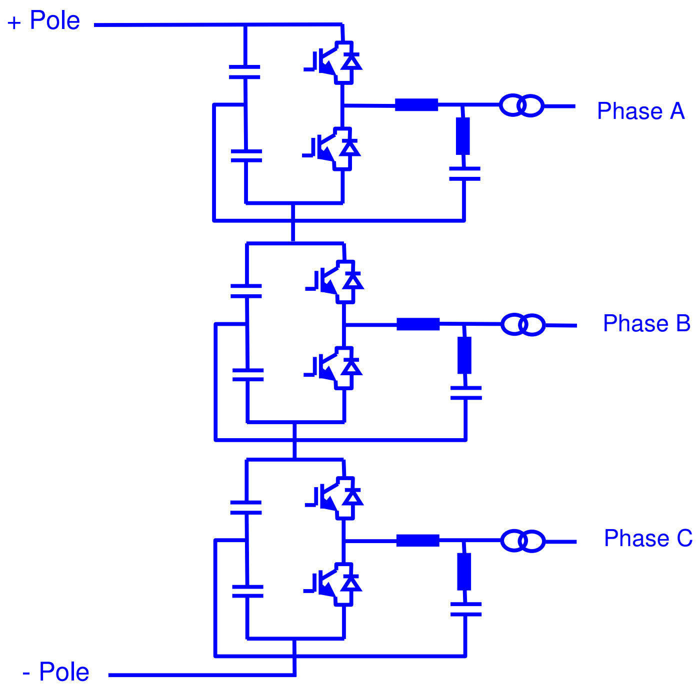

Figure 5-4 Small VSC tap with series connected phase arms

5.2. Power Reversal

There are significant differences between the power reversal in an LCC based HVdc system and a VSC based system. The following paragraphs review methods of changing the active power direction in these two types of systems.

5.2.1. LCC based HVdc Systems

In a two terminal LCC based HVdc system the reversal of power direction is achieved through the reversal of the polarity of the dc voltage. So in a two terminal bipolar HVdc system as shown in Figure 5-5 below, the positive pole becomes negative and the negative pole becomes positive, while the current still flows in the same direction, hence the direction of power is reversed.

The change of power flow direction is done typically under operator control, with a single command from the master station. Once the sequence is initiated it proceeds automatically without further operator intervention.

In principle the sequence shall command:

- Current reference set to zero in the bipole with a ramp function, the ramp rate is determined by ac system requirements, and it can be changed.
- Once the dc current and dc power are zero, the rectifier/inverter signals are changed in the control and protection system automatically, which then changes the modes of operation of the converter stations.
- The current is ramped back up. Again the ramp rate is dependent on the ac system.

In a typical HVdc system the time for power reversal can be as short as 100 milliseconds, if longer times are needed by the ac system, it can be accommodated. One important point in a two terminal HVdc system is that reversing the power direction does not require any switch gear operation.

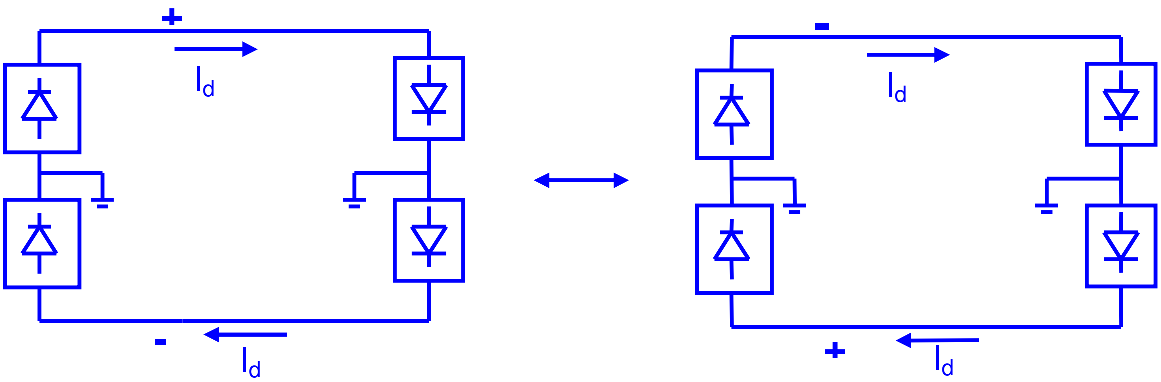

Figure 5-5 Power reversal in an LCC based two-terminal HVdc system

In a multi-terminal system as shown in Figure 5-1, again the dc current direction can not be reversed through the thyristor valves. Therefore a different strategy must be applied for the reversal of power direction. In addition, to make a multi-terminal system as flexible as possible, it should be possible to reverse the power direction in each terminal independently. Obviously, if the reversal of power direction is performed for the complete HVdc link, then the same two terminal strategy can be applied.

In Figure 5-1 station A is a rectifier, station B is a rectifier, and both stations are transmitting power to the inverter in station C. While operating in this mode and configuration, a decision may be made to change station B from a rectifier to an inverter. The change is still is initiated by the operator, and once initiated there is no requirement for further operator intervention. It is clear that because stations A and C continue operating in their present mode of operation, the dc voltage polarity cannot be reversed and since the direction of the dc current cannot be reversed either, then other measures must be applied. For reversal of power flow direction in a multi-terminal system the following is required:

- All converters must be insulated on both sides for full voltage operation
- Reversing switches must be supplied for each converter as shown in Figure 5-6

The reversing switches include the High Speed Switch (HSS) which is essentially a single phase ac circuit breaker. This switch can break current at its zero crossing at the same speed as a normal ac breaker (in a few cycles) but cannot break dc current. Therefore dc current has to be brought to zero before an HSS can be opened. If the speed of power reversal is not an issue a standard dc disconnect can be used instead of an HSS.

If the station B in Figure 5-3 is operating as a rectifier the initial state for both converters in station B shall be that:

- The high speed switches HSS1 and HSS2 are closed together with the disconnect switches 1 and 2.
- Disconnect switches 3 and 4 are open

When the command is issued to reverse the power direction for station B, meaning to change it from a rectifier to an inverter, the following will happen:

- The current reference of station B will be set to zero by a ramp and the voltage reference of rectifier A and the current reference of inverter C will remain the same. The ramp rate is dependent on the capabilities of the ac systems. This current reference coordination is fast and is calculated at the central master power controller and current coordination.
- The command current reference of zero in station B will essentially bring the actual current of station B to zero.
- As soon as the dc current is zero in B, the high speed switch HSS1 followed by HSS2 are commanded to open. The function of these switches is to quickly isolate station B from the dc line and neutral busbar. These switches are even more important if station B is an inverter as discussed later. Once HSS1 and HSS2 are opened the converters in station B are blocked.
- Disconnect switches 1 and 2 are commanded to open and disconnect switches 3 and 4 are commanded to close. This would physically reverse the direction the thyristor valves are connected to the dc busbar.
- The switch HSS2 is commanded to close followed by HSS1.
- The converters are deblocked at maximum firing angle to maintain zero dc current.
- The current reference of the new inverters released by ramp in coordination of the stations A and B through the master power controller and current order coordination.

Obviously because of the operating time of the disconnect switches, this process would take several seconds. If a faster sequence is desired (200-300 milliseconds) then all disconnect switches would be replaced with HSS switches. In fact the system would require only 4 switches.

The above sequence is the same for any rectifier station. If an inverter station is to reverse power flow direction, and assuming it is station B again, then the starting point is:

- The high speed switches HSS1 and HSS2 are closed
- The disconnect switches 3 and 4 are closed
- The disconnect switches 1 and 2 are open

The sequence for reversing the power direction is similar to the above.

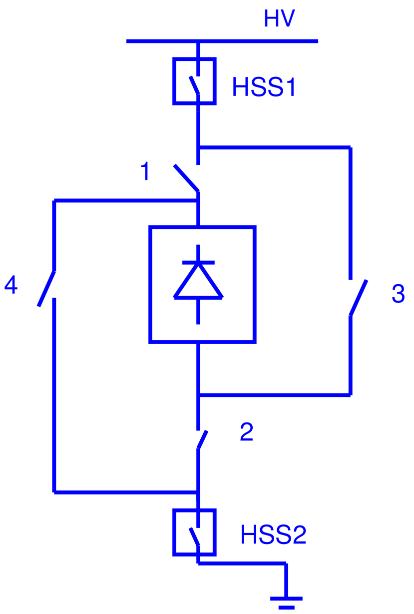

Figure 5-6 Switching arrangement for changing power direction in an LCC terminal

5.2.2. VSC Based Systems

Unlike an LCC, a voltage source converter can change its power direction through changing its dc current direction without a need for changing its voltage polarity. The particular switching arrangement discussed in case of LCC is therefore not required. Power reversal is simply done through a change in the phase angle of the ac voltage produced by the converter with respect to the ac system bus voltage i.e. the sign of the ac load angle is reversed.

5.3. Fault Performance

LCC based HVdc links and VSC based links perform differently for both ac and dc faults. The following paragraphs briefly review the fault performance for the options.

5.3.1. LCC based systems

DC faults
A fault in the dc transmission system causes the dc voltage to drop and power transmission to stop in the faulty pole in all terminals. Power flow in the healthy pole (in a bi-polar system) will continue and may be even increased to compensate for (part of) the lost capacity in the faulty pole. If the fault is temporary it can usually be cleared by forced retarding all rectifiers. Power transmission can be resumed in the faulted pole usually within about 250 ms. In case of a permanent fault however, the faulted portion of the transmission line (or cable) should identified and separated. The remaining portion of the line (or cable) can be returned to service, but depending on the power direction in different terminals this may or may not be useful. For instance, in a system similar to Figure 5-1 with the power directions shown, if a permanent fault occurs in positive pole between station A and B, this portion of line can be isolated and power transmission in positive pole from station B to C resumed. However, if a permanent fault between stations B and C cause this portion of transmission line to be isolated, power transmission in positive pole will no longer be possible as both stations A and B are acting as rectifiers.

AC faults
An ac fault at a rectifier side will reduce that rectifier's capacity to deliver power, perhaps down to zero. The remaining rectifiers will automatically increase their outputs to substitute the lost power up to their capacity. Once the ac fault is cleared normal operation is resumed.

AC fault at an inverter side usually cause commutation failure in an LCC. Commutation failure will cause a bypass pair to be formed (upper and lower valves conducting on the same leg) within the converter which will appear like a short circuit to the dc line (or cable). As a result dc voltage in both poles drop to zero and power transmission is stopped. As soon as this is sensed at the rectifiers they automatically reduce the dc current. Once the ac fault is cleared and voltage is established at the faulty inverter ac terminals commutation is resumed and power flow can be returned back to normal. LCC terminal does not contribute to the short circuit current on the ac side of the system.

Small Taps
An important feature of the LCC based multi-terminal systems is that if the terminal operating as inverter is much smaller (one third or less in MW rating) than the terminals operating as rectifier, it is difficult to bring it back to normal operation when it fails commutation. This is because even if the larger rectifiers reduce their currents to their minimum level (0.05-0.1pu based on the terminal's rated current) the current flowing into the bypassed inverter is still quite large compared to its rated current. For instance if a ±500 kV system consists of a 3000 MW rectifier and two inverters at 500 MW and 2500 MW, when the 500 MW converter fails commutation the entire rectifier current will flow into it. Even if rectifier reduces its current down to 0.1pu there is still 300 A flowing into the inverter which is equal to 0.6pu based on its current rating. As a result recovery from an ac fault takes longer for this converter and requires special control actions.

5.3.2. VSC based systems

DC faults
The performance of a VSC based system in the event of a fault on dc transmission lines depends on the way it is grounded. In a solidly grounded bipolar system, a pole to ground fault will cause large fault currents that are supplied from all VSC's through their valve diodes. As a result the dc voltage in the faulty pole is dropped and power flow in that pole is stopped. The ac voltage at all terminals also drops as the only impedances between the fault and the ac system are from the transformer, phase reactor and the dc line. The drop in ac voltages at all terminals will cause the power flow in the healthy pole is also substantially reduced. For systems that are not directly grounded usually a pole-to-pole dc fault will cause the similar problem.

To clear the dc fault the ac circuit breakers at all terminals must be opened to stop feeding the fault. Alternatively, dc breakers can be used to clear the fault. Currently dc breakers of proper rating are not available for this application, but research toward developing mechanical or solid state dc breakers is continuing.

AC faults
Voltage source converters react to ac faults by reducing their internal voltage and hence effectively maintaining the same ac current. Power flow of course is reduced in the corresponding converter, but dc voltage is affected only transiently and therefore power flow in healthy converters can continue.

5.3.3. Hybrid (combined LCC and VSC) systems

DC faults
Performance in case of a dc fault is similar to the VSC based systems. Fault can be fed through the VSC terminals and is cleared by opening ac or dc breakers (or both).

AC fault
An ac fault can cause an LCC inverter to fail commutation and form a natural bypass pair. DC voltage will then collapse and LCC converter will appear as a short circuit on the dc side. A VSC connected to the same dc line will feed the short circuit through its diodes until it is separated from the system by ac or dc breaker opening. The situation is similar to a dc fault in a VSC based system. Note that commutation failure in an LCC inverter is not a rare event and can occur due to various events in the corresponding ac system. A voltage sag as small as 10% or a phase jump can cause a commutation failure. A hybrid system requires VSC terminals to be separated every time a commutation failure occurs in an LCC terminal. Currently there are no hybrid systems in operation or planned anywhere.

5.4. Active Power Control

Active power flow in an HVdc link, whether it is point-to-point or multi-terminal is performed through the dc voltage and current control. The following paragraphs describe how the active power control is achieved through dc voltage and current control for an LCC based multi-terminal bipolar system. For a VSC based system implementing these concepts is similar except for the fact that commutation failure is not an issue for these converters and therefore gamma control modes are not required. In VSC based systems transformer tap changer controls can be used to keep steady state modulation index within the desired band.

5.4.1. Converter level controls - LCC

When a number of terminals are connected in parallel, dc voltage is common among them, except for the small voltage drop due to the line resistance. Therefore in normal operation the dc voltage is controlled by one converter and all the other converters, whether rectifier or inverter, control their own dc current. All terminals however are equipped with both voltage and current controllers that can be activated under abnormal conditions.

The dc Voltage Controlling Terminal (VCT) is either the largest inverter or the largest rectifier. In the text below only the latter case will be considered, the case of largest inverter controlling the dc voltage is similar.

The dc voltage reference for the rectifier controlling the dc voltage is Vref, for all other rectifiers it is set to Vref + Vmrg where Vmrg is the voltage margin (typically 5%). As a result the dc voltage control mode is not activated in these terminals unless the dc voltage is more than 5% above its reference level. This back up dc voltage controller is required for conditions when inverters cannot absorb all the dc current delivered by rectifiers due to any system problem. Under these conditions the VCT will reduce its dc current to maintain the dc voltage at Vref, if this is not sufficient and the total rectifier dc currents is still higher than total inverter currents, the dc voltage will rise and the back up dc voltage controllers at rectifier terminals are activated.

Inverters are normally in current control mode with reference current set to Iref_i for the i^{th} inverter. The reference for the dc voltage controller at these terminals is set to Vref – Vmrg to keep them inactive in normal operation. However, the back up voltage controllers are needed when the VCT cannot maintain the dc voltage due to events like ac voltage drop at its terminals. Under these conditions inverters reduce their dc current demand to keep dc voltage at Vref – Vmrg. Each LCC inverter is also equipped with an extinction angle (gamma) controller which is activated when gamma_min is reached. This back up controller is necessary to reduce chances of commutation failures.

The controller normally active at the VCT is the dc voltage controller. However, this terminal is also equipped with a dc current controller with set point at $Iref\_{VCT}$ + Imrg to avoid pushing too much current when a LCC inverter experiences ac under voltage and enters gamma control mode. Converter transformer taps are also controlled at all terminals to maintain firing angle (α) at rectifiers and extinction angle γ at inverters within a specified band.

5.4.2. Converter level controls – VSC

Similar to the LCC based systems, for VSC based system in normal operation the dc voltage is controlled by one converter and all the other converters, whether rectifier or inverter, control their own dc current. All terminals however are equipped with both voltage and current controllers that can be activated under abnormal conditions.

The dc Voltage Controlling Terminal (VCT) is usually the largest rectifier that will act similar to a slack bus in an ac system. The dc voltage reference for the rectifier controlling the dc voltage is Vref, for all other rectifiers it is set to Vref + Vmrg where Vmrg is the voltage margin (typically 5%). As a result the dc voltage control mode is not activated in these terminals unless the dc voltage is more than 5% above its reference level. This back up dc voltage controller is required for conditions when inverters cannot absorb all the dc current delivered by rectifiers due to any system problem. Under these conditions the VCT will reduce its dc current to maintain the dc voltage at Vref, if this is not sufficient and the total rectifier dc currents is still higher than total inverter currents, the dc voltage will rise and the back up dc voltage controllers at rectifier terminals are activated.

Inverters are normally in current control mode with reference current set to Iref_i for the i^{th} inverter. The reference for the dc voltage controller at these terminals is set to Vref – Vmrg to keep them inactive in normal operation. However, the back up voltage controllers are needed when the VCT cannot maintain the dc voltage due to events like ac voltage drop at its terminals. Under these conditions inverters reduce their dc current demand to keep dc voltage at Vref – Vmrg. Slow transformer tap changer controls can be used to keep steady state modulation index within the desired band.

5.4.3. Power, voltage and current settings

The power reference for each terminal is determined by the system operators and sent to the HVdc master controller. The desired Pref_i for each terminal is calculated such that the sum of the inverter powers plus losses is equal to the sum of the rectifier powers. Losses are calculated from a transmission line resistance model. For long or high resistance transmission lines where losses are significant this model is periodically updated based on the actual dc voltage and current measurements at all terminals to reflect the effect of changing temperature and other factors. Using this model the master controller also calculates the desired dc voltage at each terminal for the required power flow. Power and voltage references are then sent to all terminals through communication channels. These channels do not need to be fast as variations in Pref and Vref values are generally slow. At each terminal Pref_i is divided by the actual dc voltage of the terminal to find Iref_i. Iref_i therefore responds to dynamic changes in dc voltage.

A central current balancing function is usually included in the master controller to allow for optimum utilization of the HVdc system during abnormal operating conditions. An example of these conditions is when one converter (connected to one pole) at a rectifier terminal is unexpectedly switched off. The healthy converter usually can increase its current to make up at least for part of the lost capacity; however this is not possible if the current references at the inverter terminals are adjusted at the same time. A central balancing function will ensure all the available capacity is utilized for power transmission.

5.5. Reactive Power Control

Voltage source converters are capable of generating or absorbing reactive power. This capacity is usually used to control the ac voltage or reactive power exchange at the terminal. In case of an LCC based system the reactive power exchange with the ac system is usually kept within a limited band by switching filter and/or capacitor banks. At any operating point a minimum number of filters need to be in service to ensure the harmonics generated by the converters are properly filtered. If further reactive power support is required to maintain the exchange with the ac system within the specified limits more filter banks can be switched on. Reactive power at an LCC terminal can also be controlled by modifying its dc voltage and current (while still maintaining the same power), but this will affect all other terminals and is normally not desirable.

5.6. Supplementary Controls

An HVdc transmission has the advantage, compared to an ac transmission system, that the power can be very accurately controlled at all times. This can be used to modulate the power to stabilize parts of the surrounding ac system. One typical such application is to modulate the dc power based on a frequency measurement to stabilize a connected generator station. This is of course also possible to implement in a multi terminal HVdc installation. It is also possible to apply modulation to several converters simultaneously, for example two rectifiers, as long as the other terminals have the current capability to facilitate the current order request.

Power flow controllability feature of the HVdc can also be utilized for purposes like frequency stabilization, spinning reserve sharing between ac systems and oscillation damping in ac lines running parallel to dc. Runbacks and runforwards can also be introduced in response to particular ac system events to maintain system stability. These functions are being used in various existing HVdc links including Cook Strait (New Zealand), Cahora Bassa (between Mozambique and South Africa) and Nelson river (Canada).

5.7. DC Grid

The continuous growth in demand for electric power and the need to integrate the newly developed renewable energy sources to the system require expansion of power transmission systems around the globe. Building new overhead AC transmission lines however is now facing various obstacles due to shortage of land and environmental concerns. The alternative to the overhead transmission lines are underground ac or dc cables. High voltage ac cables are very limited in length (about 50km) due to their large charging currents. DC cables however do not have this limitation and can be used at any length. With more and more HVdc links, it will soon be interesting to consider joining these links into an HVdc grid. This is already discussed by various interested parties as “Super grid” [4]. Figure 5-7 shows one suggested topology for the Western Europe super grid extending to North Africa.

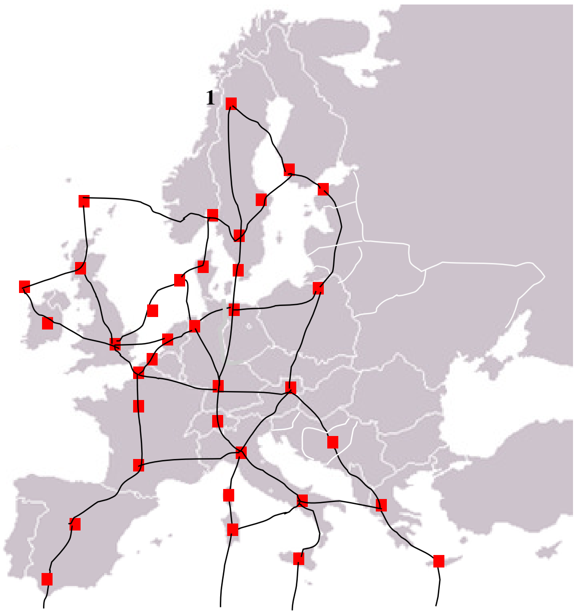

Figure 5-7 A suggested configuration for the Europe supergrid.

As explained previously in section 5.2.1, in an LCC based multi-terminal system changing power direction in any individual terminal requires its connections to the dc conductors to be reversed. Voltage source converters on the other hand can change their power direction without changing their dc voltage polarity and therefore are more suitable for dc grid.

AC disturbances in the ac systems connected to the inverter terminals in and LCC based multi-terminal system can cause commutation failure that halts the entire power transmission until the converter recovers. Voltage source converters are on the other hand highly immune to ac faults and their dc side voltage is only slightly disturbed. As a result power flow in the rest of the HVdc system can continue while one terminal cannot deliver power due to an ac system disturbance. This is another major advantage of VSC based systems for dc grid application.

In a multi terminal HVDC system, there is the need for a high level master controller that will coordinate the current references and the power orders of the individual terminals. The master controller function is to ensure that none of the terminals is overloaded and it receives the desired current ordered as well as maintaining the balance of the actual dc current between terminals. High speed reliable communications are essential for the power order and current reference coordination. If a terminal is removed from service the master controller will have to recalculate the new references. It also takes into consideration whether the station is a rectifier or an inverter.

5.7.1. Power Flow Control

Consider a grid consisting of four terminals and four HVdc lines (or cables) connected as shown in Figure 5-8 (A) below. Each terminal can control its own dc voltage. As there are four nodes and four branches, dc current can be fully controlled in every branch. In the arrangement shown in Figure 5-8 (B) however, there are more branches than terminals and therefore the power flow in all braches cannot be fully determined. But it is still possible to avoid overloading any branches, although the full capacity of the grid cannot always be utilized. This is normal as extra transmission capacity is required to allow for rerouting power in the event of any branch failure.

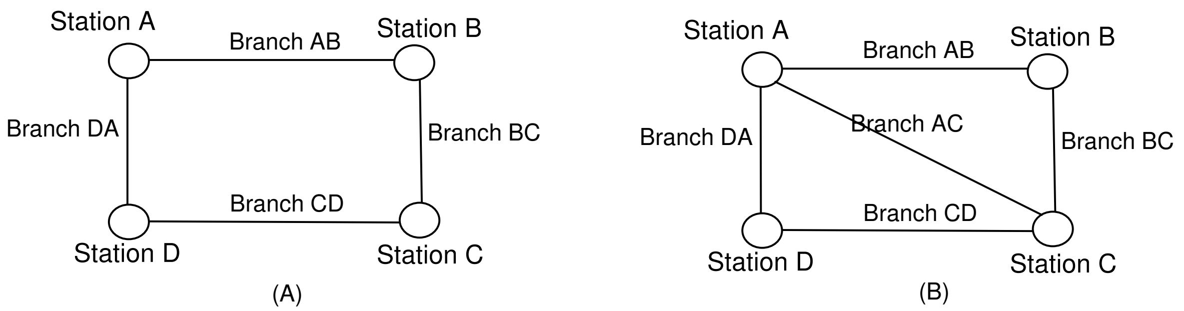

Figure 5-8 Sample dc grid configurations

5.7.1.1. Protection

For the dc grid to be practical it has to be very reliable. Unlike a point-to-point or multi-terminal HVdc link, a total dc grid black out cannot be allowed under any circumstances (unless for simultaneous occurrence of multiple contingencies). The faulted parts of the dc grid should be quickly separated to allow continued operation of the rest of the system. Protection scheme must be designed to allow zone 2 and 3 protections operate should zone one fails to separate the faulted section.

As discussed earlier in section 5.2.2 in a VSC based system faults in dc transmission line or cable are fed through diodes in all VSC's and can be cleared only by opening ac or dc breakers (if present). Tripping all ac breakers will cause a temporary (several hundred milliseconds) system black out that cannot be allowed. Therefore development of a dc grid is dependent on the development of dc circuit breakers. DC breakers with proper ratings are not available today, but research is continuing both in developing the mechanical and solid state circuit breakers.

5.8. References

3. R.N. Nayak, Y.K. Sehgal, S. Sen, "Planning and Design Studies for ±800kV, 6000MW HVDC System", Cigre' Session 2008, paper B4-117.
4. G. Asplund, "HVDC Grids – Possibilities and Challenges", Cigre' SC B4 Bergen Colloquium 2009.
5. V.F. Lescale, et. al. "Challenges with Multi-Terminal UHVDC Transmission", POWERCON 2008.

6. HVdc Theory

This section covers basic HVdc theory for LCC and VSC converters and is intended to provide a background for readers who may not be familiar with the topic and thus reduce the need to refer to other sources.

6.1. Line Commutated Converter (LCC)

6.1.1. HVdc Theory

If we consider a single phase ac source with a resistive load as shown in Figure 6-1 with the typical output as shown in Figure 6-2.

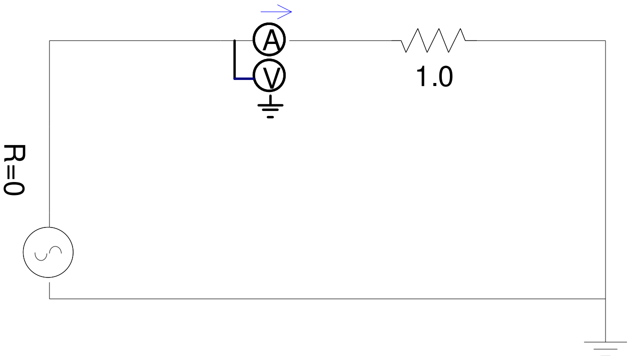

Figure 6-1 Single Phase AC Source

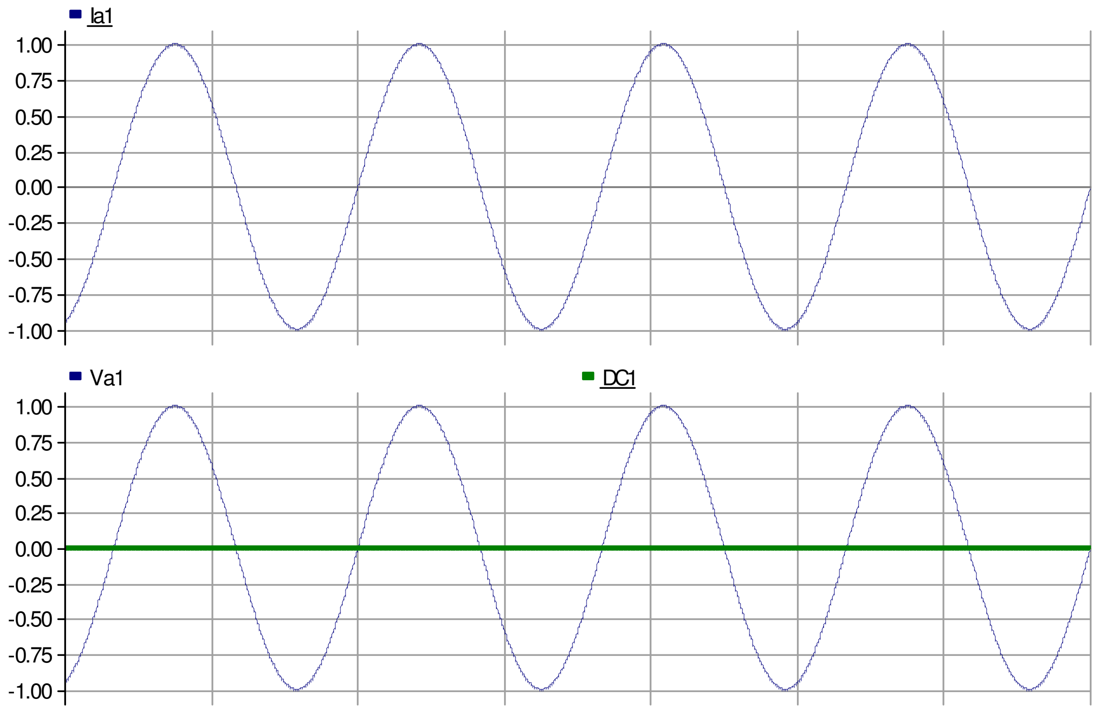

Figure 6-2 Current and Voltage

It is clear that the DC voltage of a sinusoidal waveform is zero, as the voltage is above and below zero for an equal time.

If a diode is added to the above circuit, as shown in Figure 6-3, the output voltage and current across the resistor R would be half of a sinusoidal wave as shown by the green waveforms in Figure 6-4. In this simple circuit the current only flows as long as the diode is forward biased, meaning its anode is more positive than its cathode and will act as an uncontrolled one way switch.

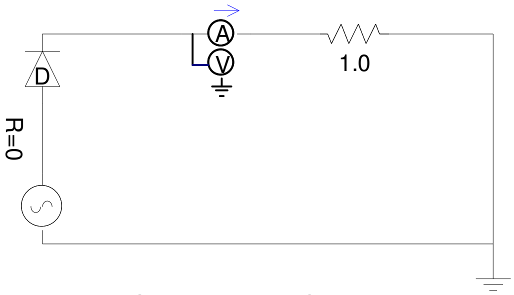

Figure 6-3 Single Phase Circuit with Diode

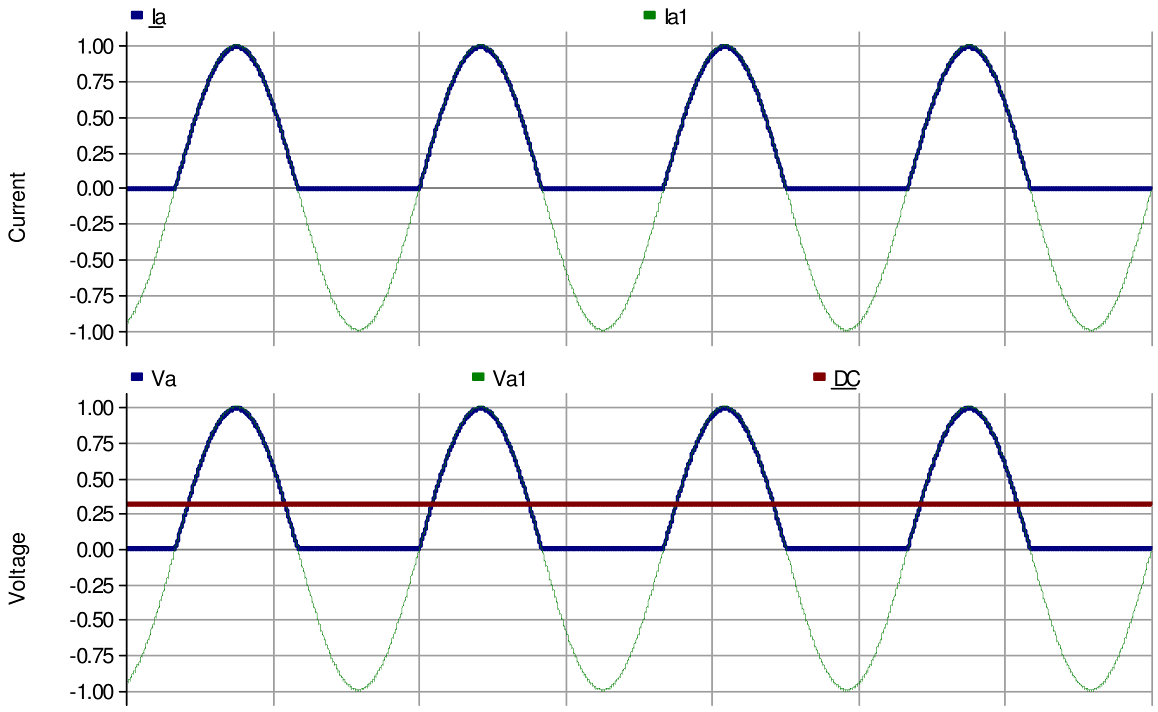

Figure 6-4 Current and Voltage through Diode

Comparing the circuits with and without the diode, it is evident that for the case with the diode present, the voltage, on average, is above zero. This will create a dc voltage, as shown.

If instead of the diode a controlled device is used, to perform the switching, then obviously one should be able to control the output dc voltage by controlling the turn on of the switch as the amount of time the voltage is above zero can be controlled. Such device can be a thyristor which has a controlled turn on but no controlled turn off.

Figure 5 is basically similar to Figure 6-3, however the diode was replaced with a thyristor. A thyristor is a device that allows one to control when the current starts to flow. It will always turn off at a current zero crossing.

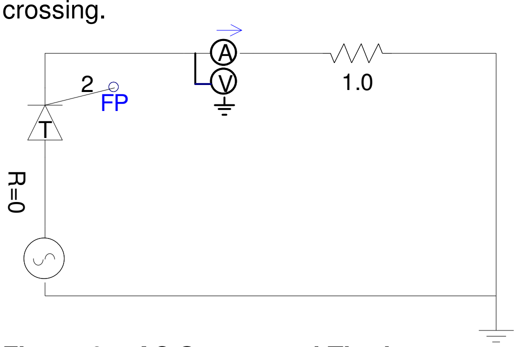

Figure 6-5 AC Source and Thyristor

By delaying the turn on of the thyristor from the zero crossing of the Sin wave by a small angle α as shown in Figure 6-6, then it is clear that the output dc voltage will be lower since the area of the half wave is reduced. The area is proportional to cos(α).

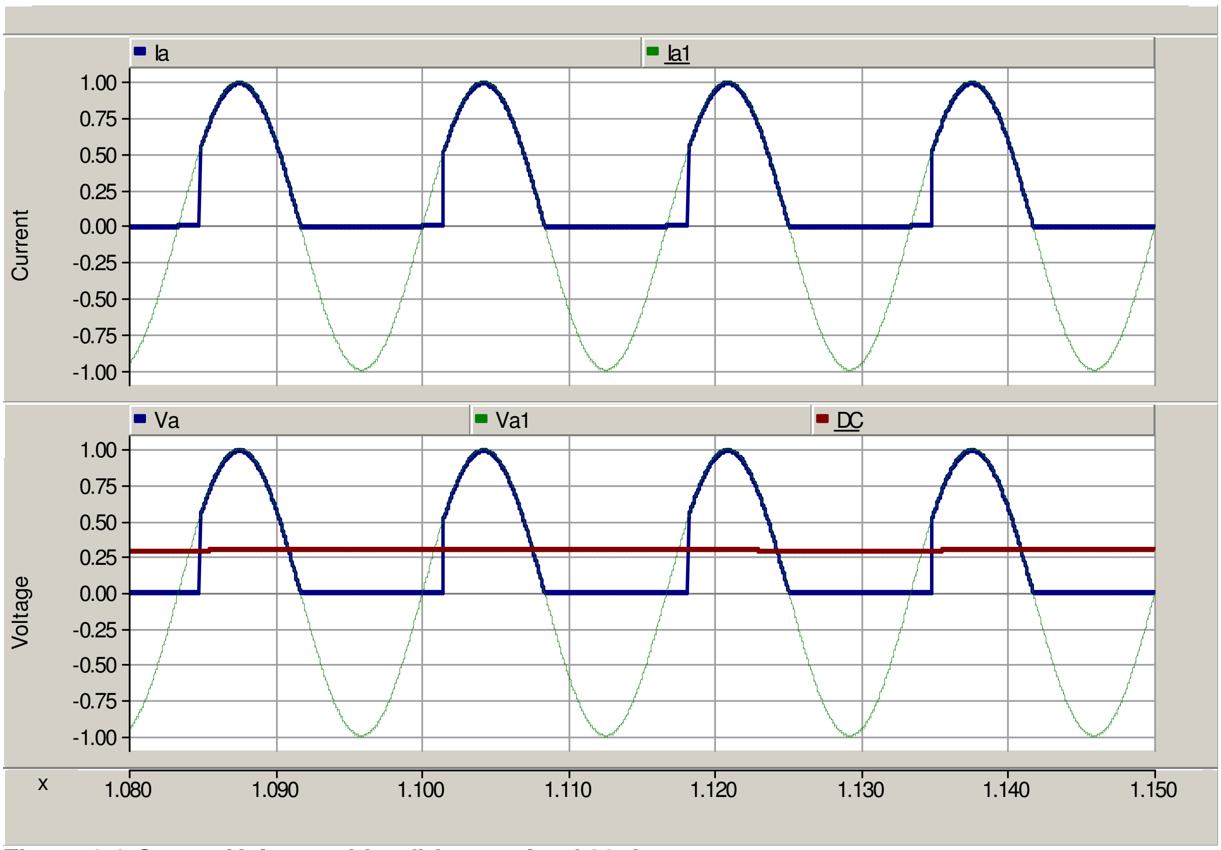

Figure 6-6 Output Voltage with a firing angle of 30 degrees

6.1.2. Rectifier Operation

If the discussion above is extended to a three phase system as shown in Figure 6-7, it is clear one will need 6 switches, two in each phase to take care of the positive and negative half cycles associated with the individual phases.

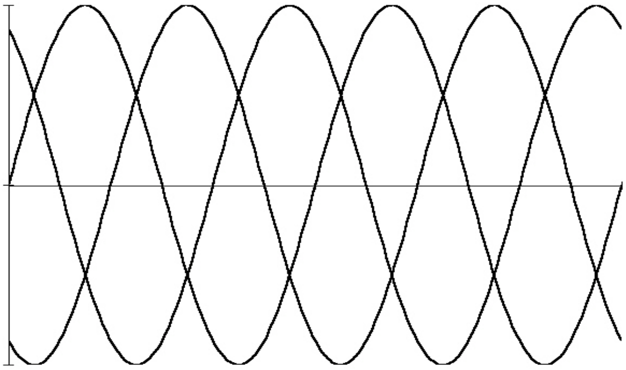

Figure 6-7 Three phase voltages

This configuration is referred to as the three phase, six pulse bridge circuit as shown in Figure 6-8. This is also referred to as a Greatz Bridge

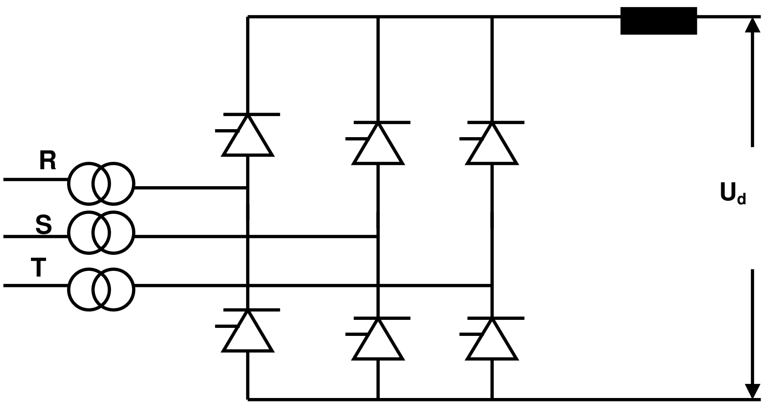

Figure 6-8 Three phase, six pulse bridge circuit

Referring to Figure 6-8, there are six controlled switching elements and in the case of line commutated HVdc, these would be thyristor valves. These valves can be controlled at turn on only and act as unidirectional switches. There are two valves for each of the three phases. This means there are two valves for the R phase and the same for the remaining two phases.

The valves are arranged in two groups of three, with three of them with their cathodes C connected together and are referred to as the cathode valves, and three of them with their anodes A connected together and are referred to as the anode valves.

In this six pulse converter or bridge the valves are turned on (triggered) sequentially, with two valves conducting at any particular moment in time to complete the current path as shown in Figure 6-9. The six valves are triggered once per the fundamental frequency cycle which means the six pulse bridge is operating at a frequency of six times the fundamental ac system frequency, which means that one valve is triggered every 60^0. For example, if valve 1 is triggered first, then valve 2 will be triggered 60^0 later and so on. Each of the valves will carry the current for 120^o. The current for the cathode valves moves between valves 1, 3, and 5. The current for the anode valves moves between valves 2, 4, and 6. Under normal operating conditions, there cannot be two valves in the same phase conducting at the same time. For example valves 1 and 4 cannot conduct at the same time. Such condition would produce a short circuit on the dc terminals and results in U_d = 0kV.

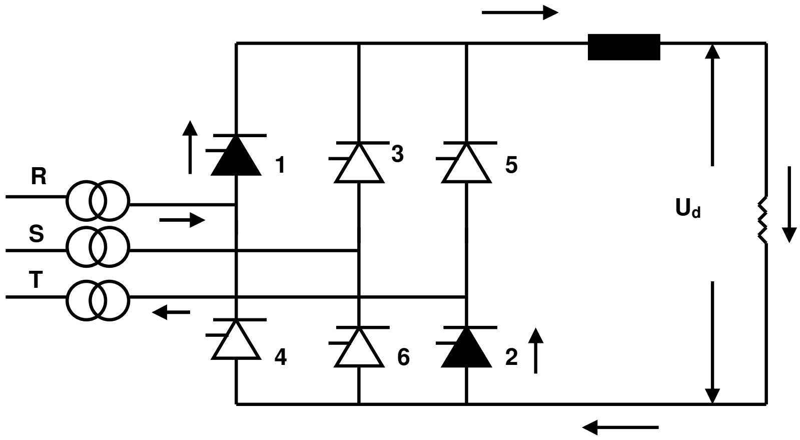

Figure 6-9 Six pulse bridge with the current path

If valve 1 is conducting, the current is flowing in R phase, to the load and returns through valve 2 to T phase. When valve 3 is triggered then the current pass will be as shown in Figure 6-10. The sharing of the current between valves 1 and 3 is referred to as the commutation process, leading to overlapping conduction of the valves.

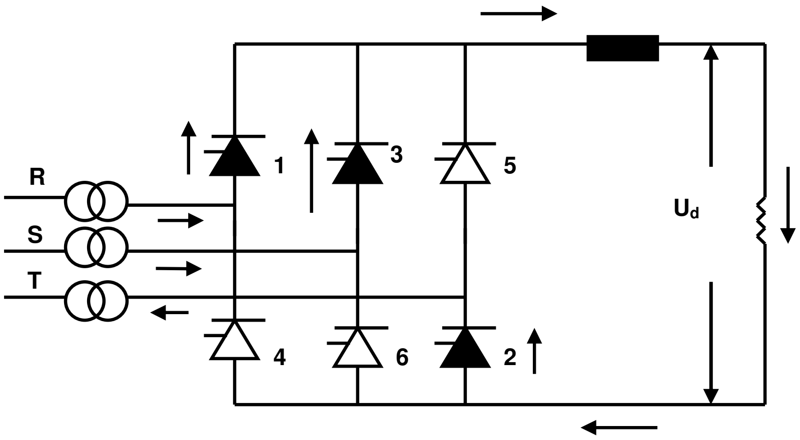

Figure 6-10 Valves 1, 2 and 3 conducting

When the current in valve 1 commutates completely to valve 3, the commutation process is complete, and valve 3 carries the full current as shown in Figure 6-11.

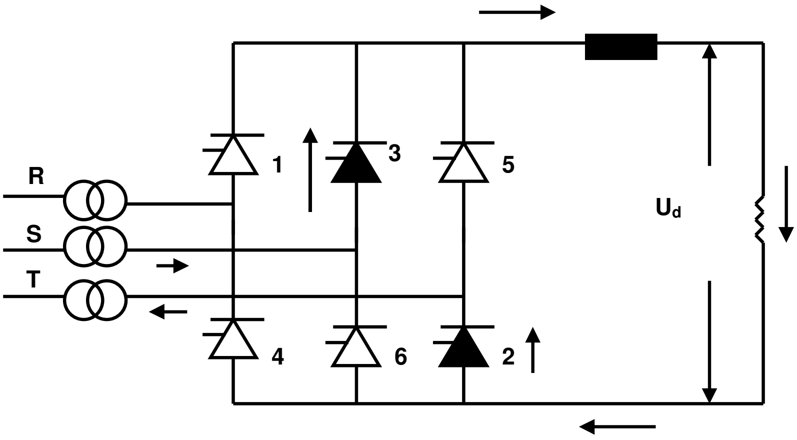

Figure 6-11 Valves 2 and 3 conducting

The same commutation process will take place when valve 4 is triggered as shown in Figure 6-12 and Figure 6-13.

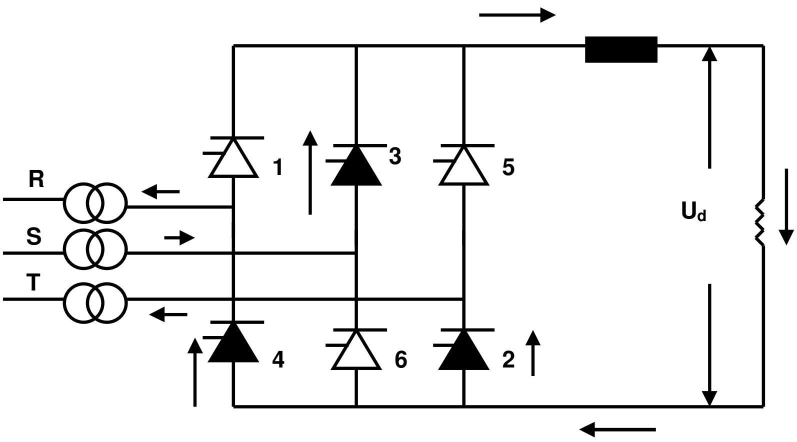

Figure 6-12 Valves 2, 3 and 4 conducting

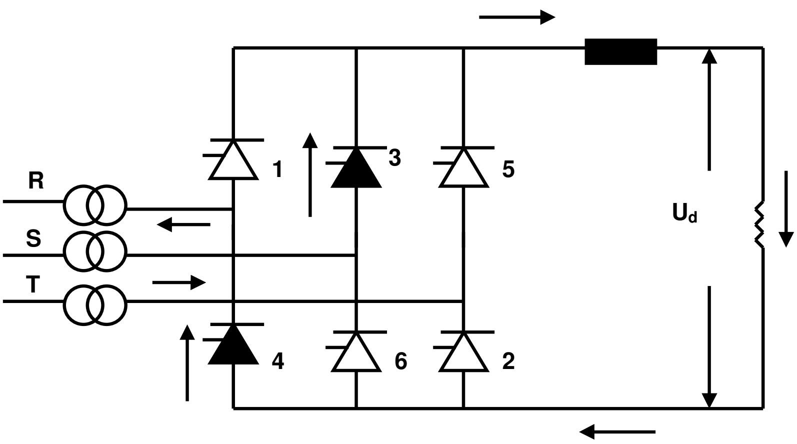

Figure 6-13 Valves 3 and 4 conducting

Similar to the single phase case, it is clear that by controlling the instant the valves are triggered, relative to the zero crossing the dc voltage U_d can be controlled. However in the case of the three phase six pulse bridge a particular valve actually sees the line to line voltage:

- Valve 1 during the bridge operation is connected between phases R and T.
- Valve 2 during the bridge operation is connected between phases S and T
- Valve 3 during the bridge operation is connected between phases S and R
- Valve 4 during the bridge operation is connected between phases T and R
- Valve 5 during the bridge operation is connected between phases T and S
- Valve 6 during the bridge operation is connected between phases R and S

Figure 6-14 shows the impact of triggering the valve with a delay angle α (30deg) from the valve voltage zero crossing.

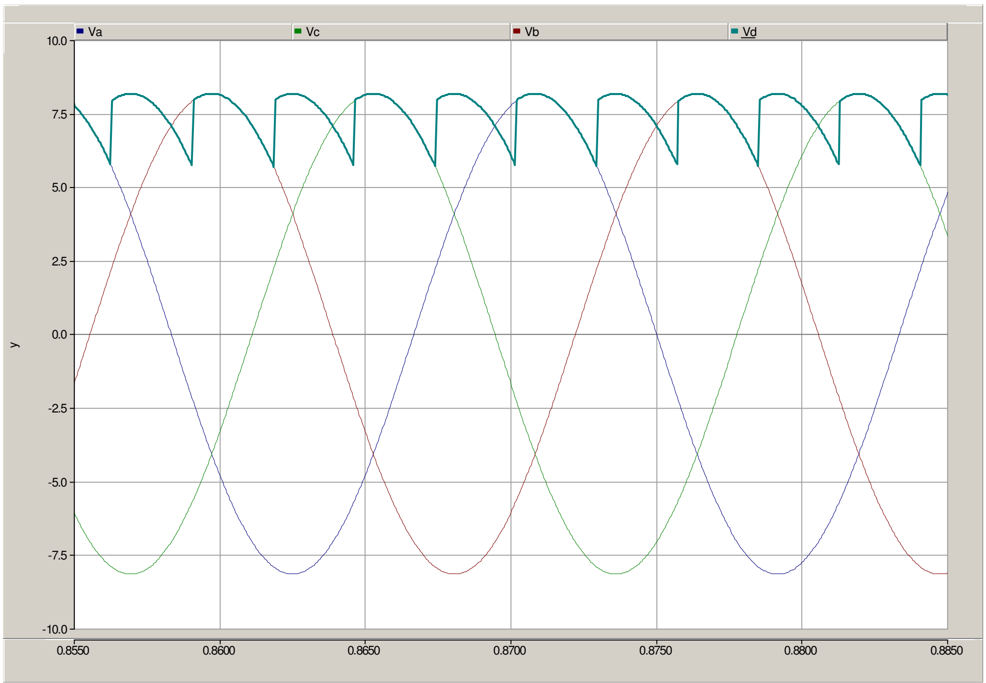

Figure 6-14 Three phase voltages with delay angle

In order to calculate the dc voltage U_d of the six pulse bridge, one has to integrate and find the area under the resulting wave shape.

$$U_d = \frac{3\sqrt{2}\cdot E}{\sqrt{3}\cdot\pi}\cdot\int\cos(\omega t)dt$$

The limits of integration are (π/3 - α) to (π/3 + α), which gives

$$U_d = \frac{3\sqrt{2}\cdot E}{\sqrt{3}\cdot\pi}\cdot[2\sin(\pi/3)\cos(\alpha)]$$

$$U_d = \frac{3\sqrt{2}\cdot E}{\pi}$$

It is clear that U_d is dependent on the valve line to line voltage E and on the delay angle α. The larger the delay angle the lower the dc voltage U_d. At α = 90^0 the dc voltage will equal to zero.

The term $3*\sqrt{2}*E/\pi$ is referred to as the ideal no load direct voltage or the open circuit voltage of the converter U_{dio} .

Earlier in the discussion, the concept of the commutation process was introduced. At that time it was assumed that the commutation process occurs instantaneously. However, this is not realistic as it disobeys the laws of physics due to the inductance in the circuit which is dominated by the inductance in the transformer which will not allow the current to change instantaneously. Figure 6-15 shows the impact of the commutation process.

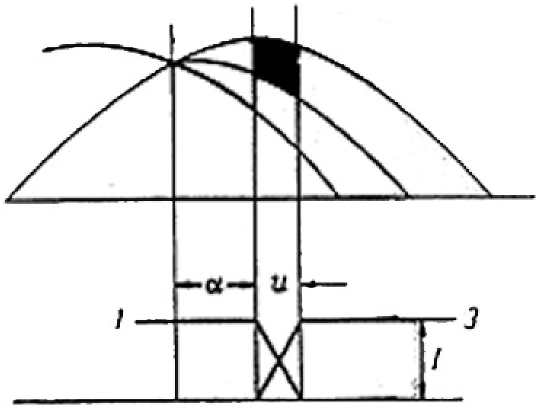

Figure 6-15 Impact of Transformer Inductance on the commutation process

Due to the inductance in the commutation path, it is realistic that commutation of the current from say valve 1 to valve 3, will take some finite time, There will be then an overlap where the current in one path will decay to zero (valve 1) and rise in the other path (valve 3) to its steady state value I. This overlap is termed the overlap angle μ. This angle depends on the inductance in the circuit which is mainly the transformer reactance, which referred to as the commutating reactance X_c. Naturally the overlap angle μ is also a function of the value of the dc current (i.e. increased dc current generally will lead to an increase in the time it takes to commutate the current.

The impact of the commutation process and the overlap angle μ is it causes a reduction in the output dc voltage U_d of the six pulse bridge.

$$U_d = \frac{3\sqrt{2}\cdot E}{\pi}\cdot\cos(\alpha) - \frac{3IX_c}{\pi}$$

$$U_d = U_{dio}\cos(\alpha) - \frac{3IX_c}{\pi} = \frac{1}{2}\cdot U_{dio}[\cos(\alpha) + \cos(\alpha+\mu)]$$

From the first equation, it is clear that the dc voltage U_d is lower by the voltage drop resulting from the flow of current in the commutating reactance X_c.

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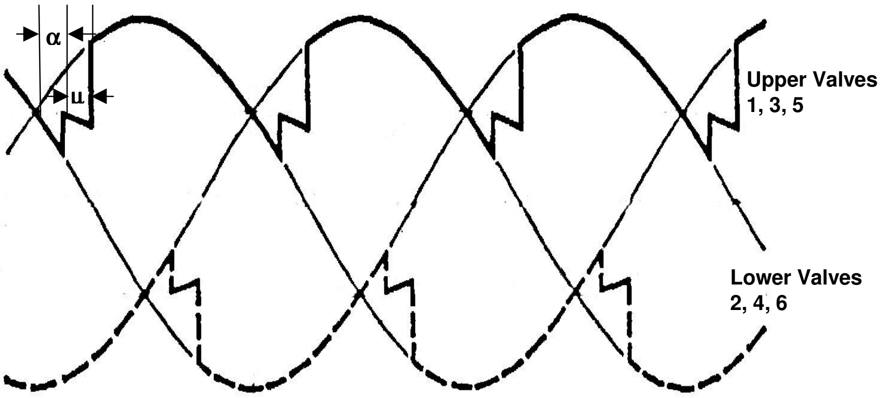

Figure 6-16 Rectifier dc voltage taking into consideration α and μ

Referring to Figure 6-16, the voltages shown are the voltages across the upper part of the bridge (voltage as seen by valves 1, 3 and 5) and the voltages across the lower portion of the bridge (voltages as seen by valves 2, 4 and 6). The complete dc voltage (per-unit, from the high voltage side to ground), can be see calculated as Voltage(upper) – Voltage(lower) and is shown in Figure 6-17.

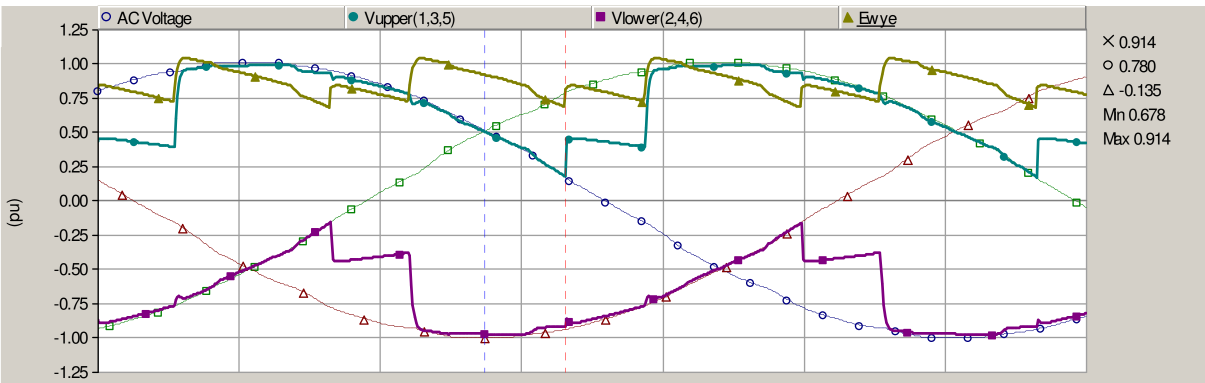

Figure 6-17 Calculation of dc Rectifier Voltage

6.1.3. Inverter Operation

As discusses earlier, at a delay angle of 90^0 the resulting dc voltage is zero. If the delay angle α is increased past 90^0 the resulting dc voltage will be negative. Figure 6-18 shows this condition when the delay α is increased to 140^0.

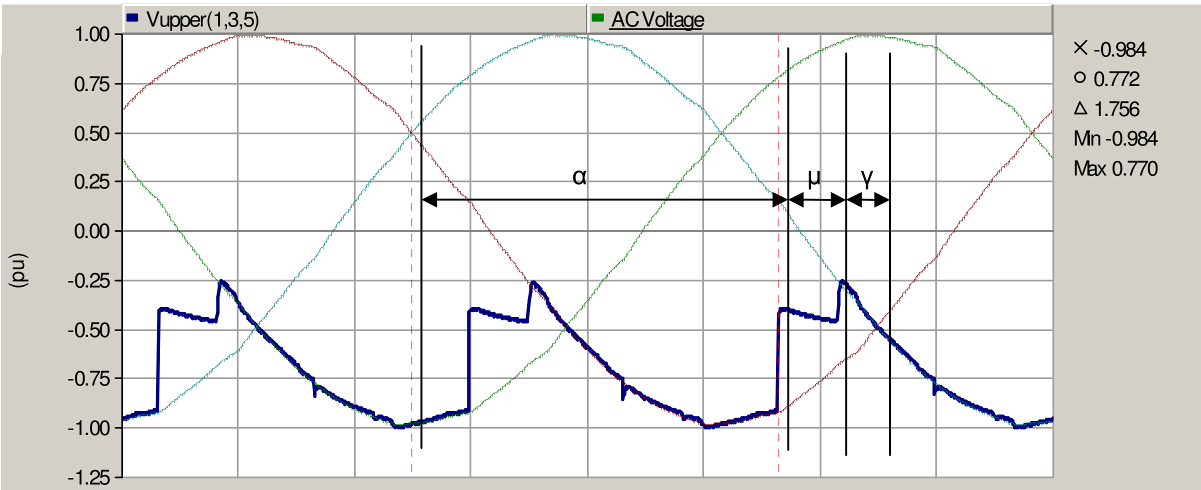

Figure 6-18 Inverter operation

Similar to the rectifier the commutation process between the valves results in a reduction in the inverter internal dc voltage as shown in Figure 6-18.

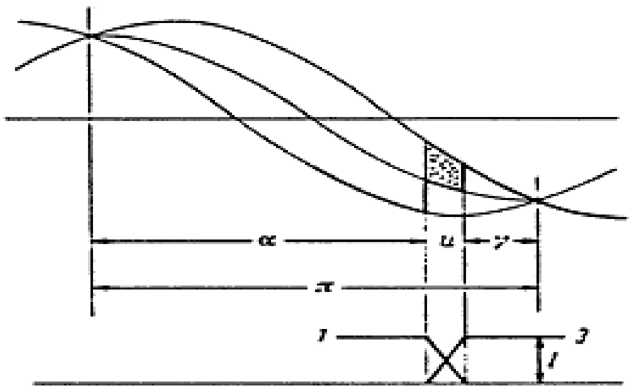

Figure 6-19 Impact of Transformer Inductance on the commutation process [1]

In Figure 6-18, the delay angle α is larger than 90^0 and the angle of overlap μ is defined similar as the rectifier, however there is another angle which is quite important in the inverter operation. This is known as the extinction (or gamma) angle γ. This is angle is defined as the angle between the end of current in the valve and the start of voltage reversal on the outgoing valve. It is very critical for the inverter operation and will be discussed in a greater detail later. Regardless, of the definitions, the relationship between the three angles is:

$\alpha + \mu + \gamma = \pi$ In addition $\gamma + \mu = \beta$

The inverter equations can be derived in the same manner as the rectifier equations.

$$U_d = U_{dio}\cos(\alpha) - \frac{3IX_c}{\pi} = \frac{1}{2}\cdot U_{dio}[\cos(\alpha) + \cos(\alpha+\mu)]$$

$$U_d = \frac{1}{2}U_{dio}[\cos(\pi-(\mu+\gamma)) + \cos(\pi-\gamma)]$$

$$U_d = \frac{1}{2}U_{dio}[\cos(\gamma) + \cos(\mu-\gamma)] = U_{dio}\cos(\gamma) - \frac{3IX_c}{\pi}$$

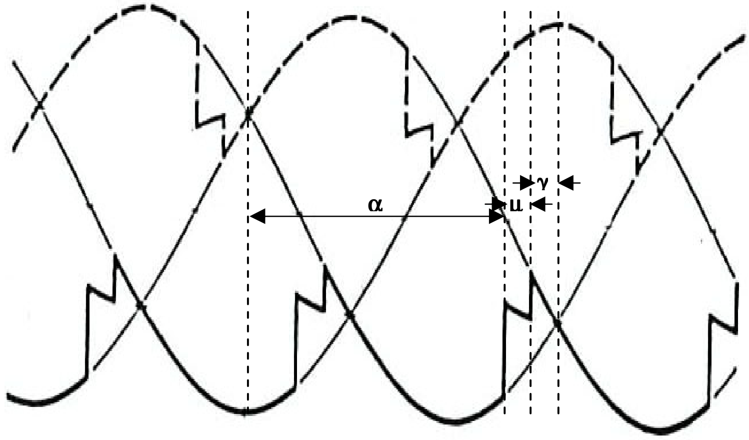

Figure 6-20 Inverter Operation

As with the rectifier, the complete dc voltage for the inverter (from the high voltage side to ground), can be seen calculated as Voltage(upper) – Voltage(lower).

6.1.4. Converter Operation

Now that both the rectifier dc voltage Udr and the inverter dc voltage Udi are determined, it is very simple to calculate the dc current in the dc circuit, as the overall circuit is as shown in Figure 6-21.

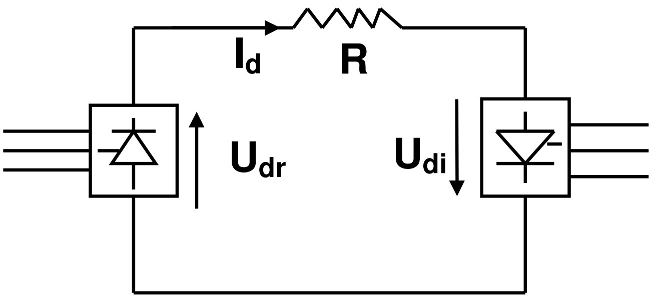

Figure 6-21 DC Power flow

The dc current is determined by the difference between U_{dr} and U_{di} impressed on the transmission system resistance R. It is clear that to change the dc current, the control system can change U_{dr} or U_{di} or both in a coordinated manner. The control of the dc current and hence the transmitted dc power in an HVdc system is fast, as the controls can change the delay angle α very fast.

$$I_{dc} = \frac{U_{dr} - U_{di}}{R_{dc}}$$

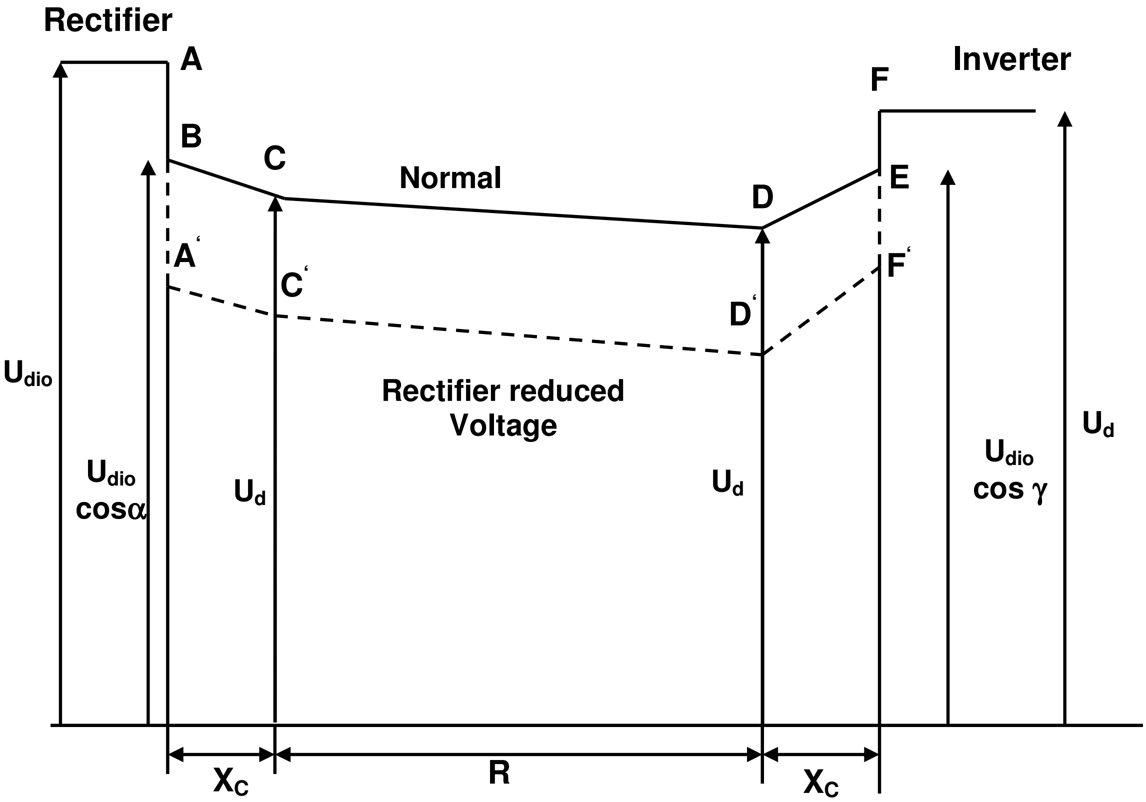

Figure 6-22 Principle of operation of LCC HVdc system

Figure 6-22 shows the principle of operation of the HVdc system and how the different dc voltages relate to each other. The voltage at point A and F represents the the no-load dc voltage U_{dio}. The voltage at point B and E is the voltage U_{dio} after it has been modified by the firing angle. The voltage at point C and D represents the voltage drop across the transformer impedance and the difference between point C and D represent the voltage drop across the DC line (and/or cable).

6.1.5. LCC Harmonics

6.1.5.1. AC Side Characteristic Harmonics

The cyclic triggering of the valves in a six pulse converter produces certain characteristic harmonics. Whether the converter is operating as a rectifier or inverter, these characteristic harmonics are produced. Consider Figure 6-23 and Figure 6-24. These figures show the voltage and current waveforms of each thyristor valve for an inverter and rectifier.

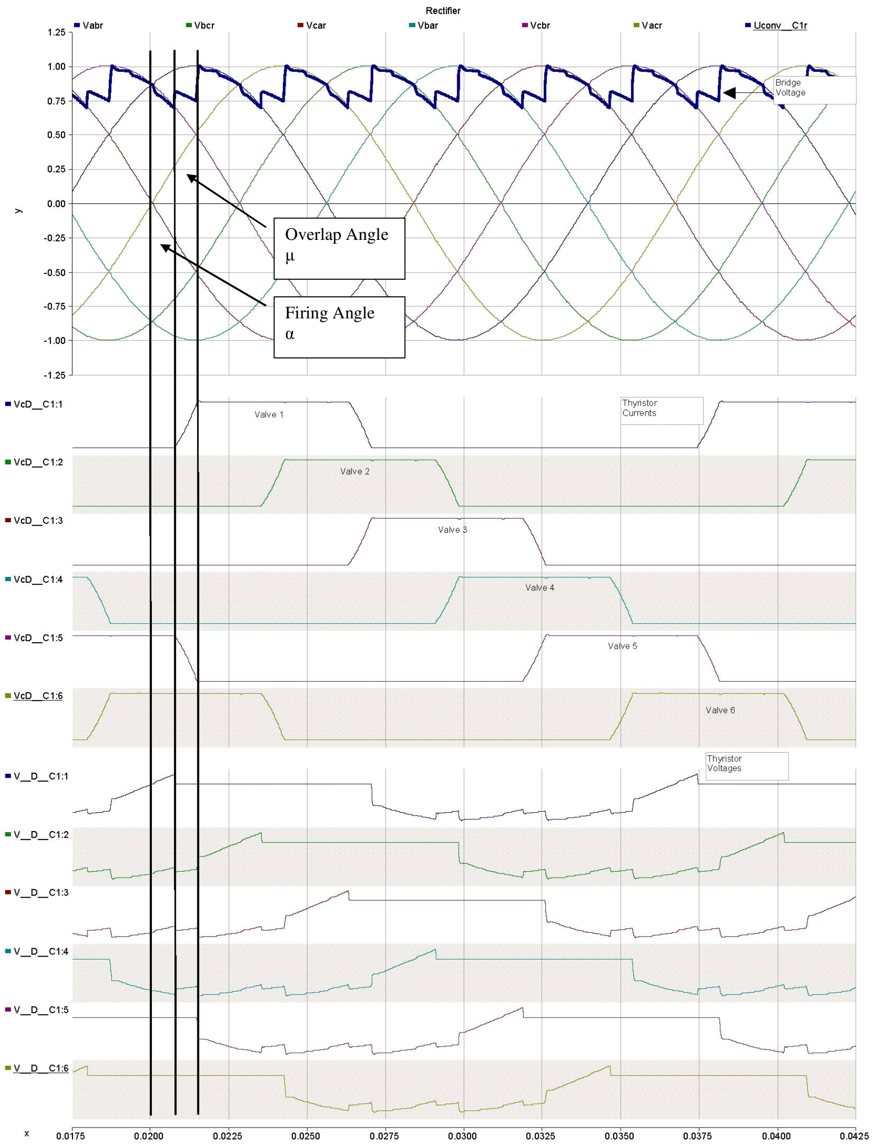

Figure 6-23 Rectifier wave shapes for the dc voltage and the valve side of the transformer currents.

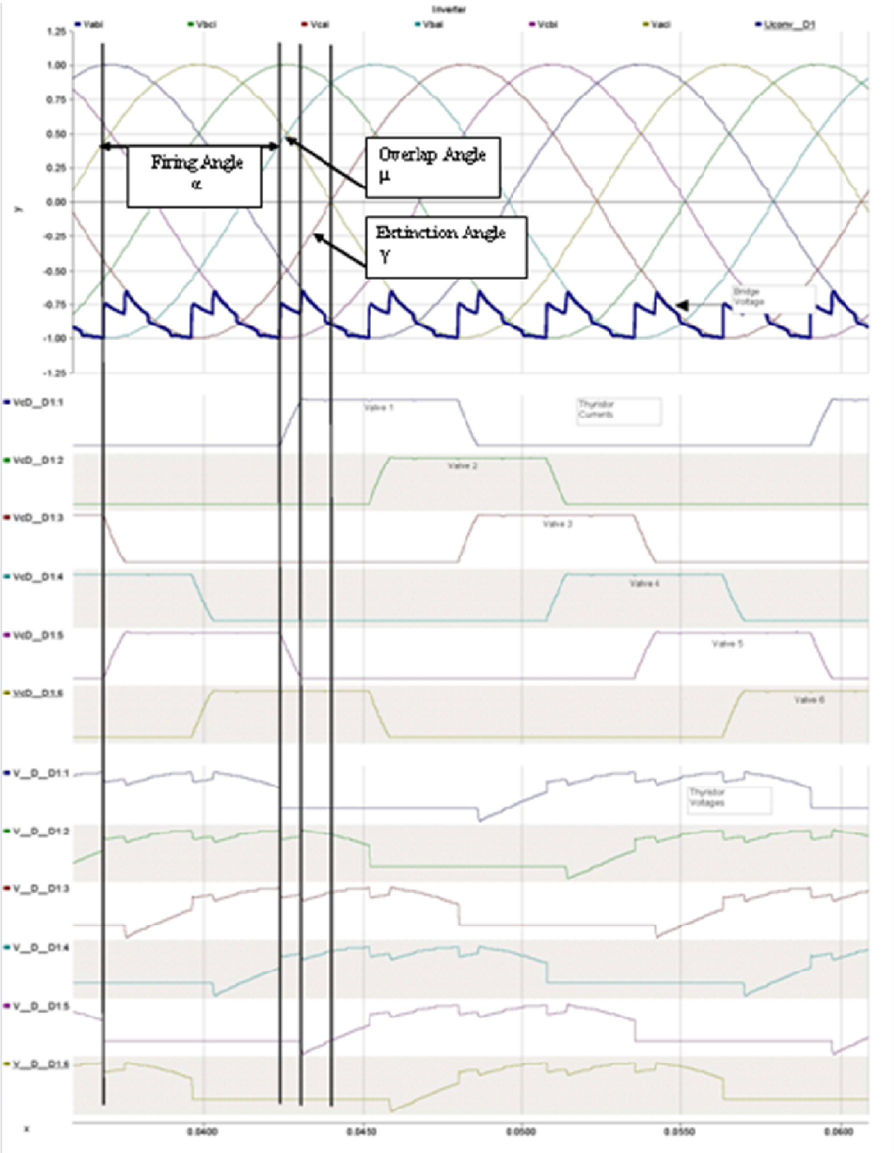

Figure 6-24 inverter wave shapes for the dc voltage and the valve side of the transformer currents.

The currents shown in the above figures, as mentioned above are flowing in each valve. When they are superimposed on each other (rectifier or inverter), the current waveform entering the secondary side of the converter transformer is as shown in Figure 6-25.

It is obvious that the waveforms in Figure 6-25, is composed of a fundamental frequency component and various harmonics. For simplicity, if one ignores the commutation overlap and assumes the smoothing reactor to be very large, the Fourier series for this ac current can be shown to be:

$$I_{A,wye} = K \cdot \left(cos\theta - \frac{1}{5} \cdot cos5\theta + \frac{1}{7} \cdot cos7\theta - \frac{1}{11} \cdot cos11\theta + \frac{1}{13} cos13\theta - \frac{1}{17} \cdot cos17\theta + \frac{1}{19} \cdot cos19\theta + \cdots \right)$$

Based on the above equation, one can clearly see that harmonics (which descend in magnitude as the order increases) will be present at 5, 7, 11, 13, etc (harmonics = k*P+/-1). (where k is 1,2,3.. and P is the pulse number, i.e. 6)

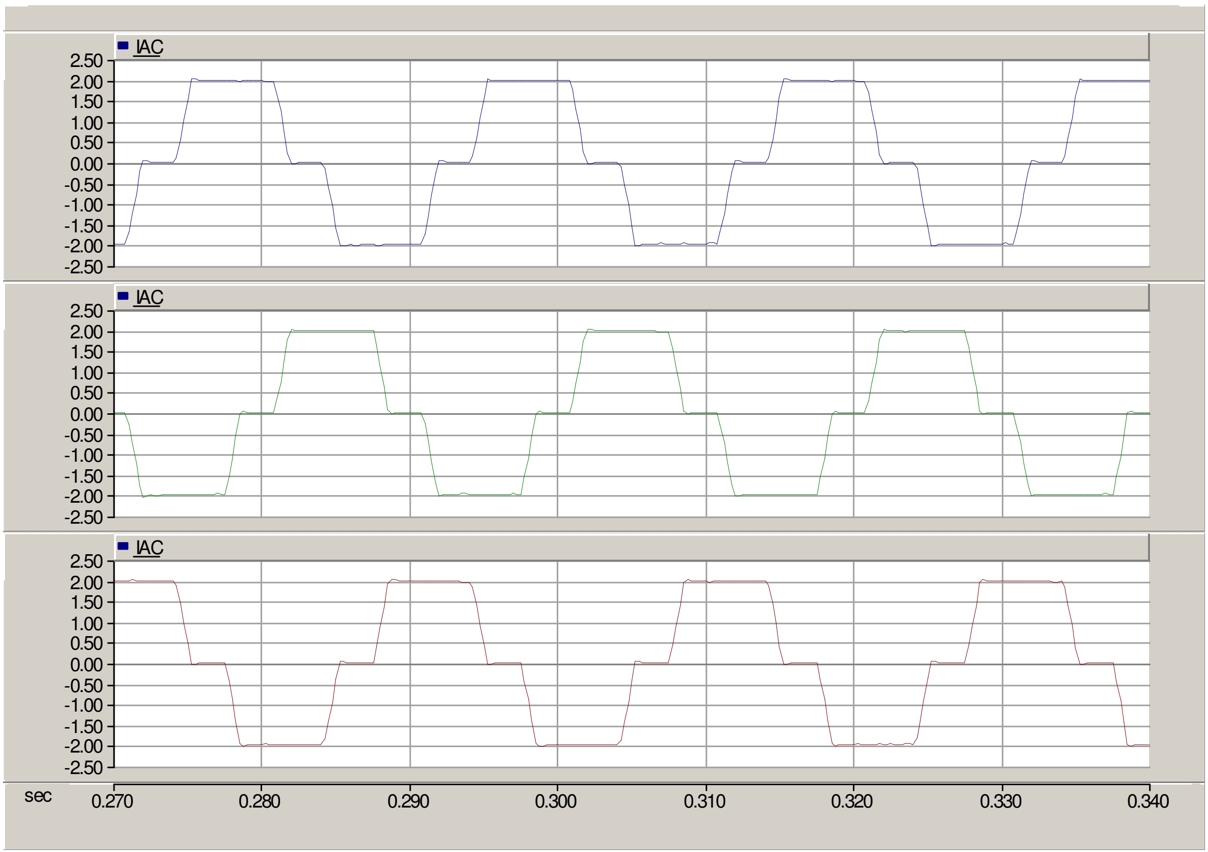

Figure 6-25 Secondary AC Current Waveforms

The waveform shown in Figure 6-25 is the current on the secondary side of a star-star converter transformer. If we consider the currents flowing in a star-delta transformer (which introduces a 30° phase shift in the secondary line to line voltage in relation to the primary side voltage), the currents are as shown in Figure 6-26.

Again, for simplicity, if one ignores the commutation overlap and the assumes the smoothing reactor to be very large, the Fourier series for the delta ac current can be shown to be:

$$I_{A,delta} = K \cdot \left(cos\theta + \frac{1}{5} \cdot cos5\theta - \frac{1}{7} \cdot cos7\theta - \frac{1}{11} \cdot cos11\theta + \frac{1}{13} cos13\theta + \frac{1}{17} \cdot cos17\theta - \frac{1}{19} \cdot cos19\theta + \cdots \right)$$

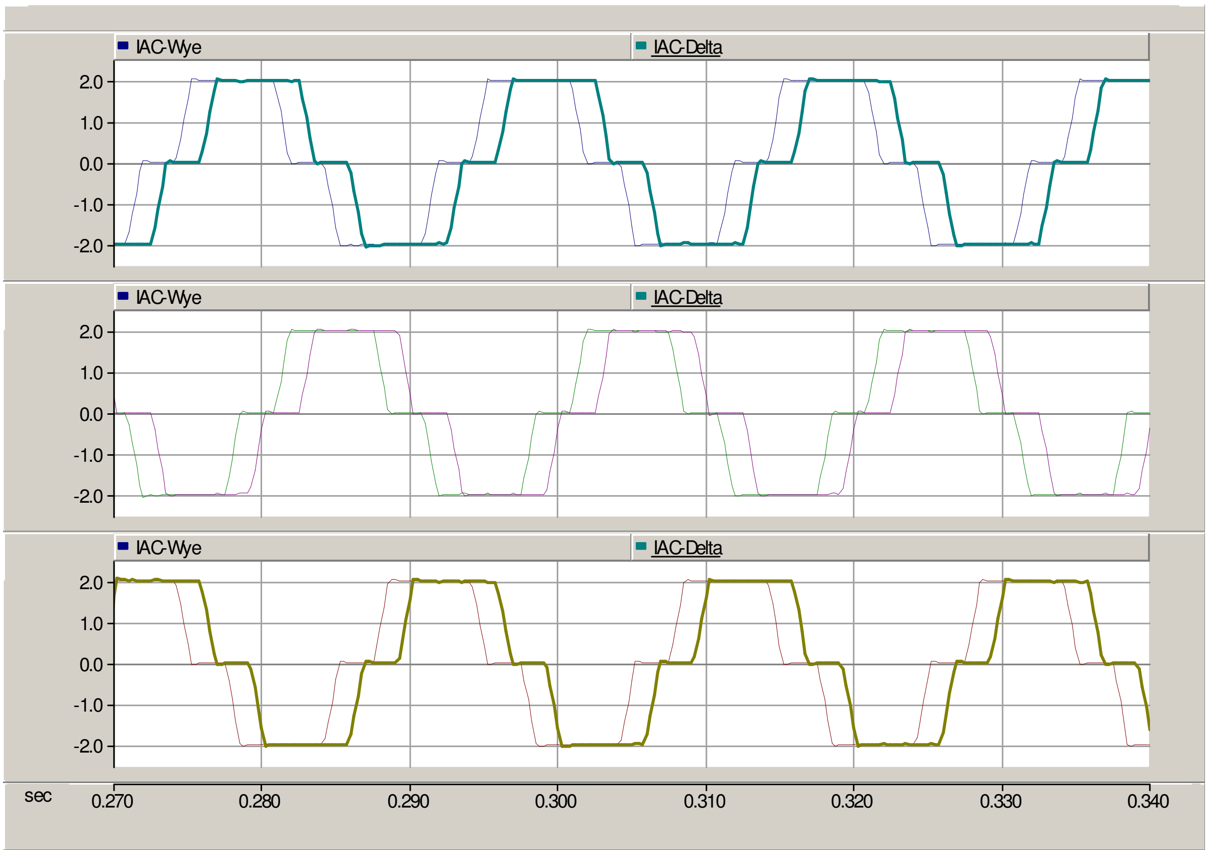

Figure 6-26 Delta secondary Currents (bold) compared to Wye Currents

If the converter consists of two bridges one with star/star connected transformer and the other with a star/delta transformer, their voltages will be 30° out of phase and therefore the harmonics will also be out of phase. Since 30 degrees of main frequency correspond to half cycle of 6th harmonic, the 6th harmonic will be in phase opposition in the two bridges, while for the 12th harmonic they will be in phase.

Adding the two equations, it is obvious that the triple – n (where n is an integer) harmonics cancel out and:

$$I_{A,delta} + I_{A,wye} = K \cdot \left(2cos\theta - 2\frac{1}{11} \cdot cos11\theta + 2\frac{1}{13}cos13\theta + \cdots\right)$$

The twelve pulse configuration (as it is known) is shown in Figure 6-27.

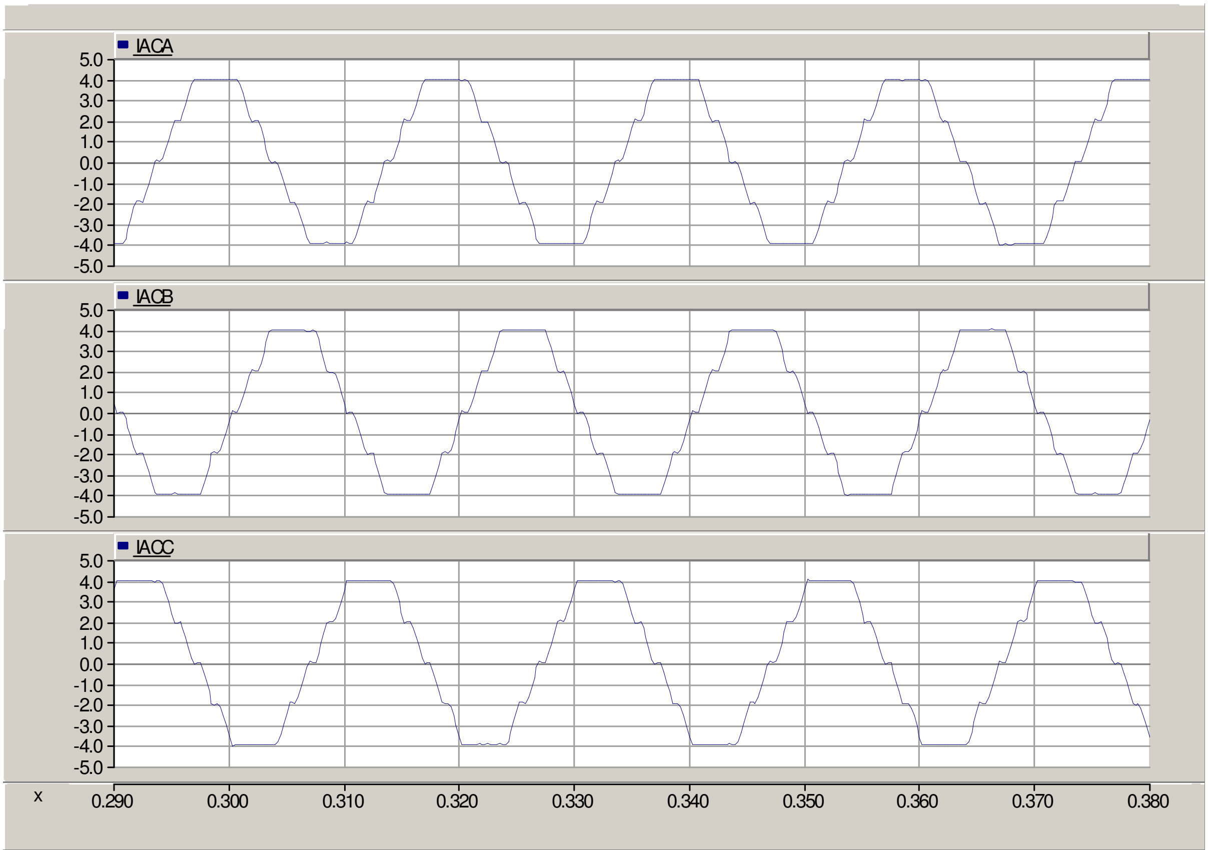

Figure 6-28 12-pulse currents

Figure 6-28 shows the summation of the wye and delta harmonics.

The current harmonics for a 12 pulse system will be of the order 12n±1. This means:

- 11th and 13th harmonic for n=1
- 23rd and 25th harmonic for n=2
- Etc

If we now consider the variation of the overlap angle on the harmonic generation, the harmonics can be calculated by:

$$\frac{In}{Id} = N_6 \cdot K_6 \cdot |F_1|$$

Where

$Id = Direct\ Current$

$N_6 = number\ of\ 6\ pulse\ groups$

$$K_6 = \frac{\sqrt{6}}{2\pi n D}$$

$n = 1,2,3, \dots$

$$F_1 = \frac{e^{-j(\alpha(n+1))} - e^{-j(\alpha(n+1))}}{(n+1)} - \frac{e^{-j(\alpha(n-1))} - e^{-j(\alpha(n-1))}}{(n-1)}$$

Where

$D = cos\alpha - cos\delta$

$\alpha = delay(firing)angle$

$\delta = \text{ extinction angle}$

$\mu = \text{overlap angle}$

The following figures shows the variation of the ac harmonic currents based on the overlap and firing angle[1].

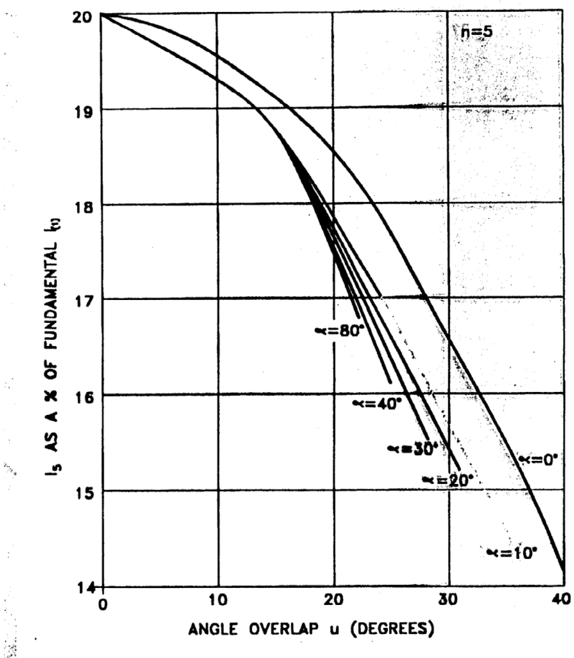

Figure 6-29 The variation of the 5th harmonic with α and μ.

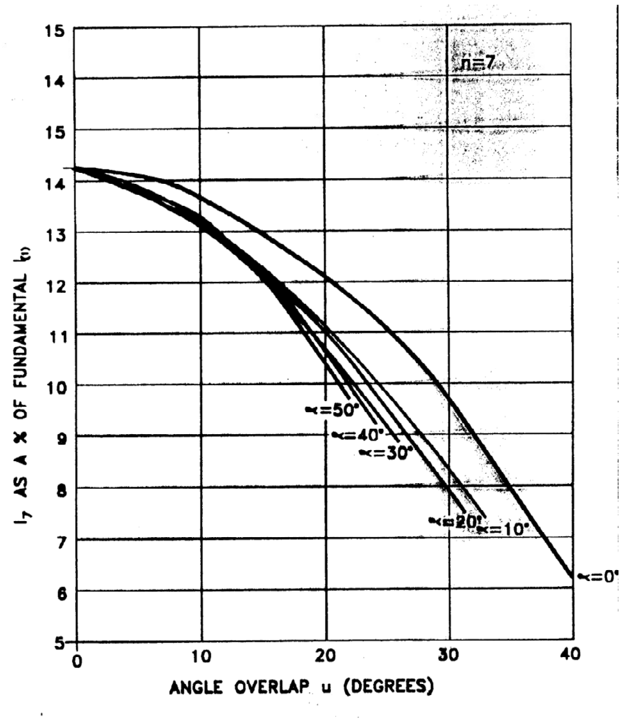

Figure 6-30 The variation of the 7th harmonic with α and μ.

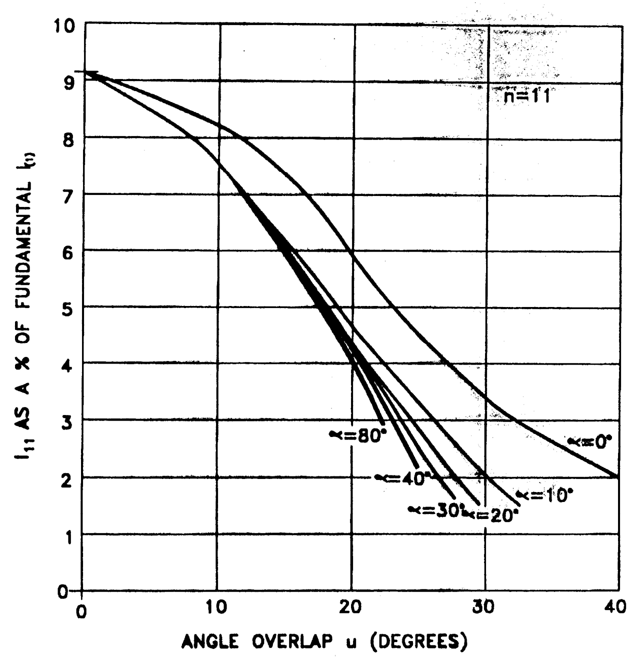

Figure 6-31 The variation of the 11th harmonic with α and μ.

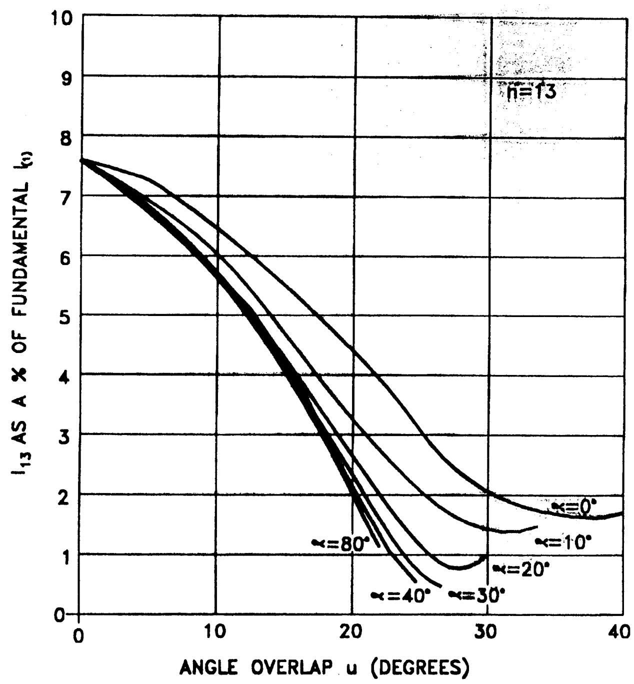

Figure 6-32 The variation of the13th harmonic with α and μ.

From the preceding figures, it is obvious that the magnitude of the harmonics in the ac line current are reduced as the overlap angle increases.

6.1.5.2. DC Side Characteristic Harmonics

Referring to Figure 6-23 and Figure 6-24 above, it is evident that harmonics are also present on the dc side of the converter.

As described above, each wye-wye and wye-delta bridges create their own characteristic 6-pulse harmonics as shown in Figure 6-33.

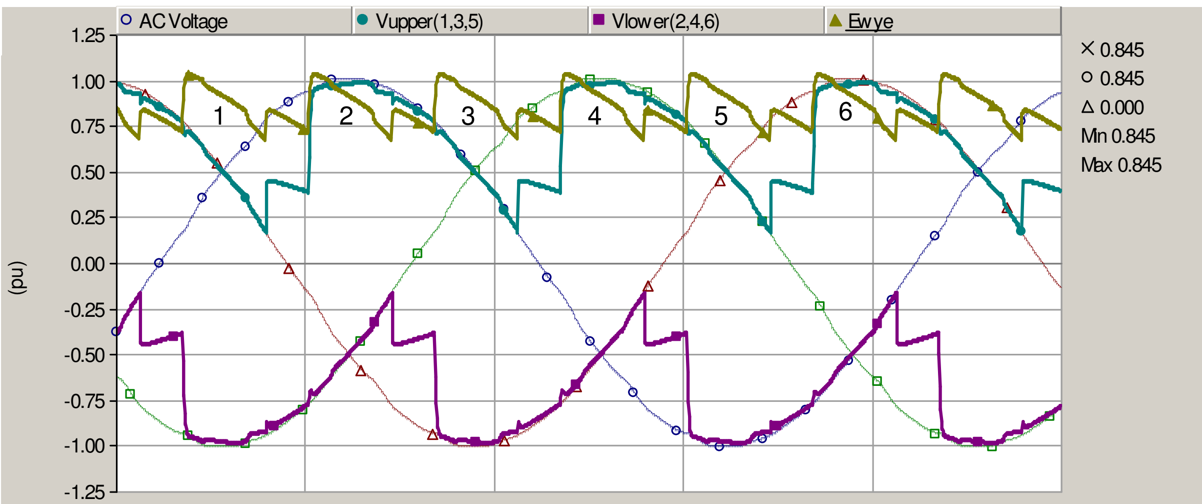

Figure 6-33 6-Pulse Wye Bridge

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For the six pulse converter the characteristic harmonics in the dc voltage are of the order 6n. Where n is an integer taking the values 1,2,3, … .n.

Therefore the voltage harmonics are:

- 6th harmonic for n=1
- 12th harmonic for n-2
- 18th harmonic for n=3

$$U_n = \frac{U_{dio}}{\sqrt{2}\cdot(n^2-1)}[(n-1)^2\cos^2((n+1)\frac{\mu}{2}) + (n+1)^2\cos^2((n-1)\frac{\mu}{2})$$
$$-2(n-1)(n+1)\cos((n+1)\frac{\mu}{2})\cos((n-1)\frac{\mu}{2})\cos(2\alpha+\mu))^{1/2}$$

At α=0 and μ=0 the eqn. is reduced to:

$$U_{no} = \frac{\sqrt{2}\cdot U_{dio}}{(n^2-1)}$$

As α increases, the harmonics increase and at α= π /2 and μ = 0

$$U_n = \frac{\sqrt{2}\cdot U_{dio}\cdot n}{(n^2-1)}$$

The following figures show the dependence of the dc harmonics on α and μ[1]..

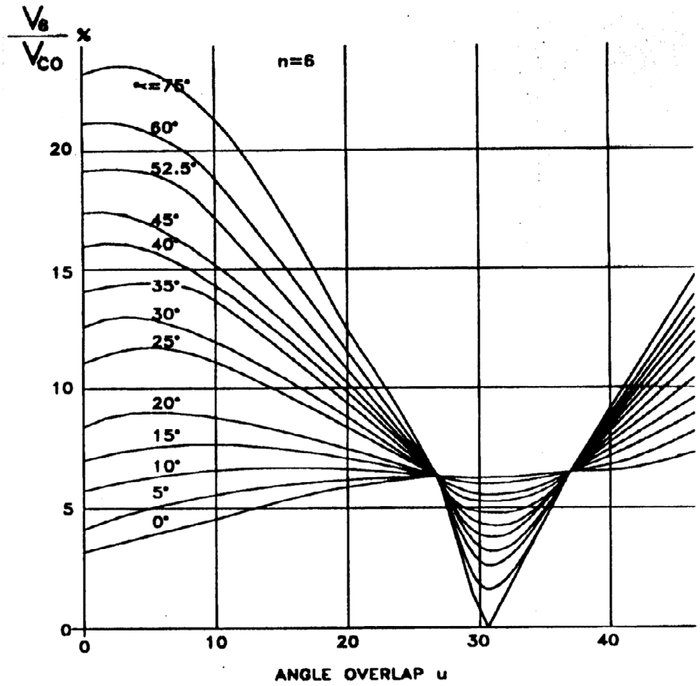

Figure 6-34 the variation of the 6th harmonic with α and μ.

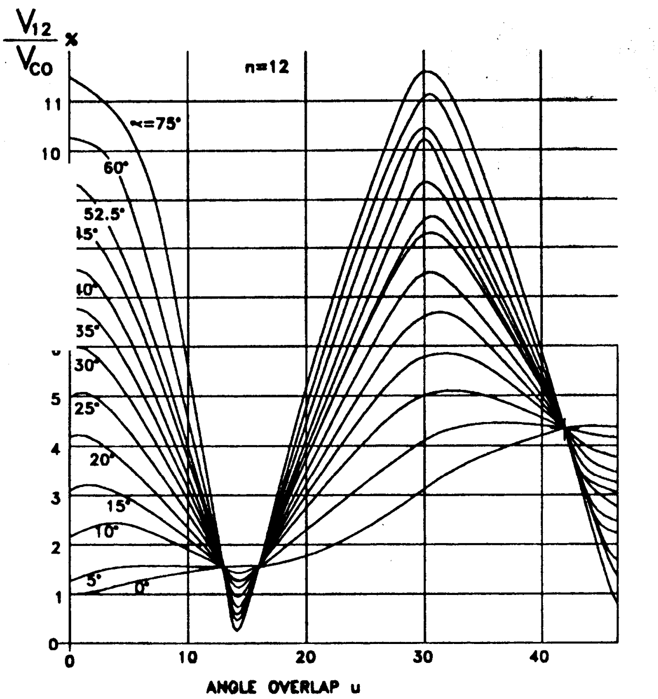

Figure 6-35 the variation of the 12th harmonic with α and μ.

As with the ac-side current harmonics, if one utilizes a star-star and a star-delta transformer and there associated converters connected in series, one can take advantage of the 30° phase shift to cancel out some of the harmonics, leaving only harmonics of the order 12, 24, 36, etc, as shown in Figure 6-36.

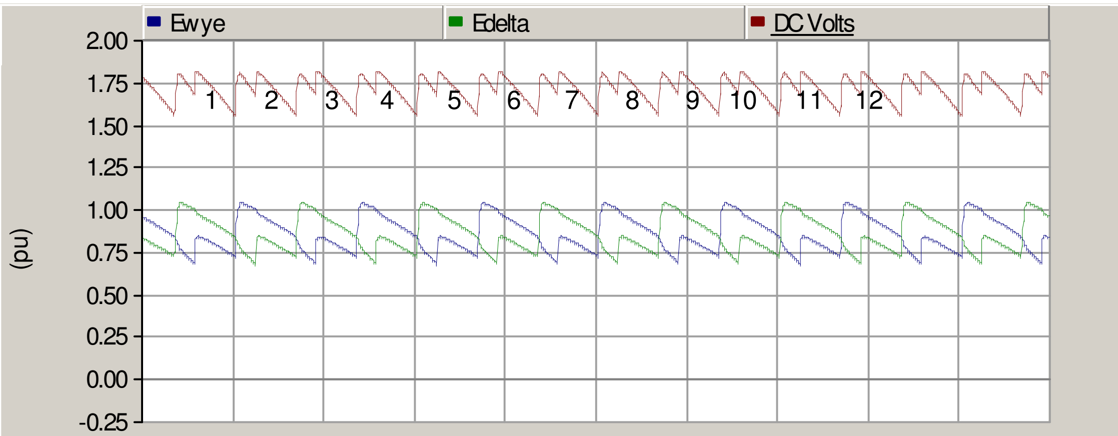

Figure 6-36 12 pulse dc voltage waveform

6.1.5.3. Non Characteristic Harmonics

Non-Characteristic Harmonics can occur on both the ac and dc side of the converter bridge. Possible causes of these harmonics are:

- Negative Sequence ac voltage unbalance.

  The HVdc control action, firing on the ac voltage unbalance will cause a second harmonic ripple on the dc current, which will in turn cause a third order harmonic on the ac side. When specifying the dc link, it is important to indicate the expected worst-case voltage unbalance so the system can be designed to operate properly.

- Unbalance of Converter Components

  When manufacturing the power system components, there will always be a manufactured tolerance to consider. For example, the final inductance in the star converter transformer may be slightly different the final inductance of the delta converter transformer, one will not get an perfect cancellation of the six-pulse harmonics (5th, 7th, etc). This is usually considered in the design, and all equipment must be designed with very tight tolerances (2%-3%)

- Firing Error

  If the valves connected to the anode bus are fired earlier by an angle ε and the valves connected to the cathode bus are fired later by the same angle ε then:

  $$\frac{I_n}{I_1} = \frac{2\sin(n \cdot \varepsilon)}{2n\cos(\varepsilon)} - \frac{\varepsilon}{n}$$

  For a one degree error which means a one degree shift between the positive and the negative current pulses, it will produce approximately 1.74% of second harmonic current.

  If the firing of the two valves connected to the same phase is late by an angle ε while the other four valves fire at the right instant. Third harmonics are produced and their ratio to fundamental is:

  $$\frac{I_n}{I_1} = \frac{\sin(n \cdot \omega / 2)}{n\sin(\omega / 2)}$$

  Where: $\omega = 2\pi/3 +/- \varepsilon$

  In order to minimize this, equidistance firing has been employed by most manufacturers. When specifying a dc link, it is important to indicate that the valves must be fired within 0.1° of their intended firing angle

- Interharmonics

6.2. Voltage source Converters

Line commutated devices were described in section 5 and it was stated that a thyristor was only controllable in the on direction. This limitation is one of the main causes of the harmonics associated with a line commutated converter.

A voltage source converter utilizes a device such as an IGBT (insulated gate bipolar transistor) or GTO (gate turn-off thyristor) which can be controlled in both the on and off directions. This capability gives one the ability to precisely control the converters.

Consider the circuit in Figure 6-37.

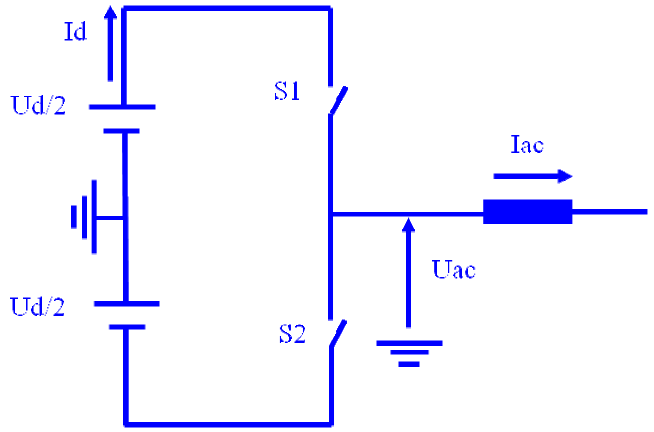

Figure 6-37 Basic VSC Circuit

If S1 is closed, the voltage Ud/2 appears at Uac as shown in Figure 6-38.

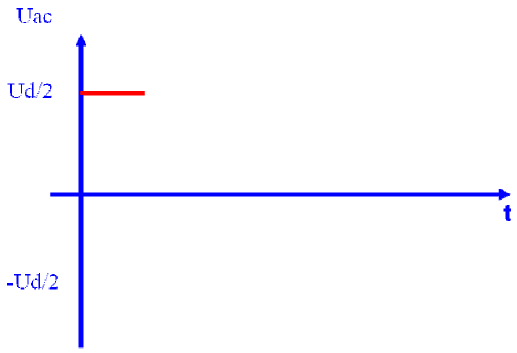

Figure 6-38 Voltage with S1 closed

If S1 is opened and S2 is closed, the voltage –Ud/2 appears at Uac as shown in

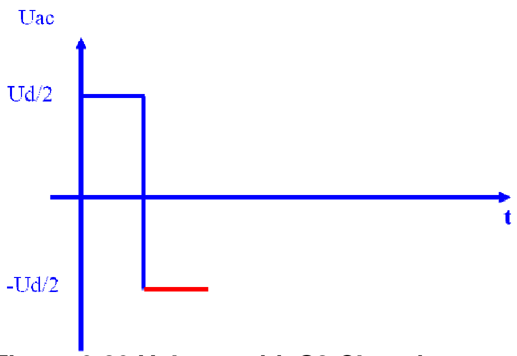

Figure 6-39 Voltage with S2 Closed

To complete the cycle, S2 is opened and S1 is closed as shown in Figure 6-40

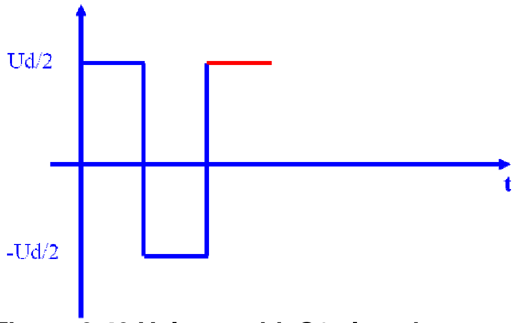

Figure 6-40 Voltage with S1 closed

It is clear that Uac can be set to Ud/2 or –Ud/2 independent of Iac, hence the name Voltage Source Converter. In reality, S1 and S2 is an IGBT (or equivalent) in parallel with a diode to allow current to flow in both directions as shown in Figure 6-41.

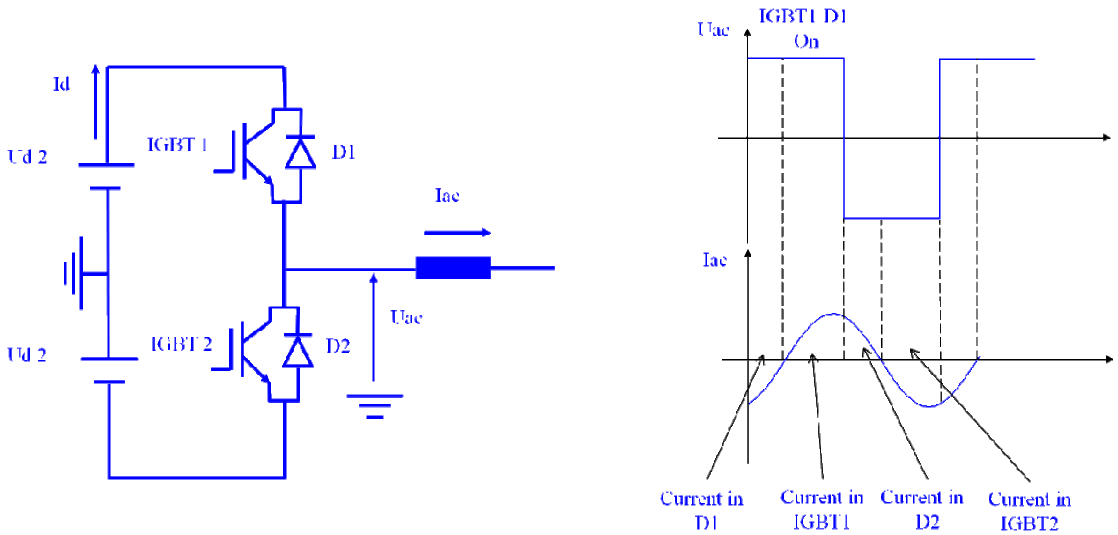

Figure 6-41 Current Path in a VSC

A three-phase converter can be made by using three legs of the circuit in Figure 6-41 as shown in Figure 6-42.

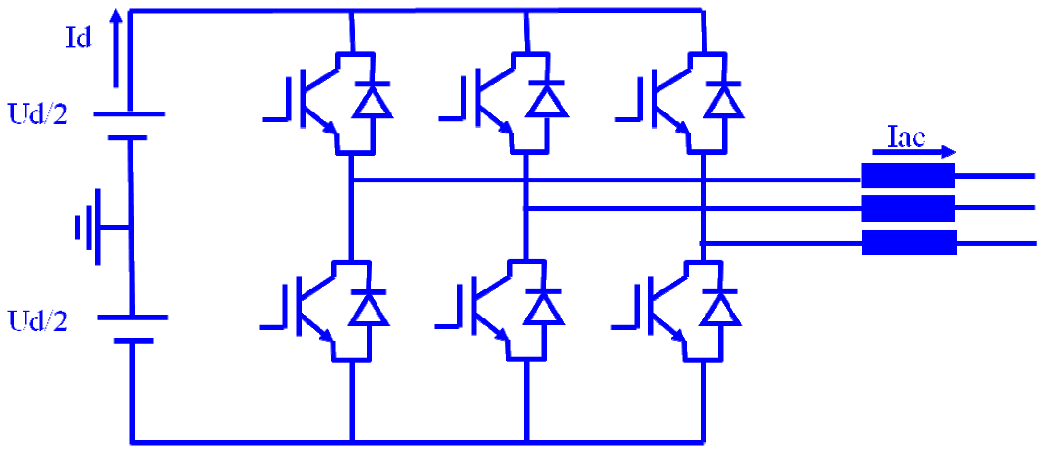

Figure 6-42 Three Phase VSC

Although this topology works in theory, it is not practical due to the following constraints:

- Low power rating
- Harmonic voltages of the Magnitude Vn, order n = 1,2,3,..., $V_n = (\sqrt{2}/2n\pi)U_d$
- Fixed relation between AC and DC voltages (Uac=1.56Ud), not suitable for HVdc transmisson

In the past, manufacturers tried to get around these shortcomings by the following means:

- 2 converters connected through YY and YD transformers with there associated converters series connected(As with LCCs)
  - Doubles the power rating
  - Removes 5th,7th etc. Harmonics
- 2 converters connected through YY and YD transformers
  - 5^{th}, 7^{th}, … harmonics currents will circulate between the converters but do not enter the system
- Inter-phase reactors and transformers can be used to make a quasi 24-pulse system
  - Magnetic circuit is complicated
  - Some 11^{th} and 13^{th} harmonics remain in the output voltage
  - Small 11^{th}, 13^{th} … harmonics will circulate between the converters

In order to get around these issues, the major manufacturers have implemented various techniques and topologies to increase the power rating and reduce the harmonic impact. These techniques, and there harmonic impact will be discussed below.

6.2.1. Three-Level Converters

The basic two-level "square wave" converter as described above, generates a high level of harmonics. In order to reduce the harmonics, one can extend the principles of a two-level converter to a three level converter as shown in Figure 6-43.

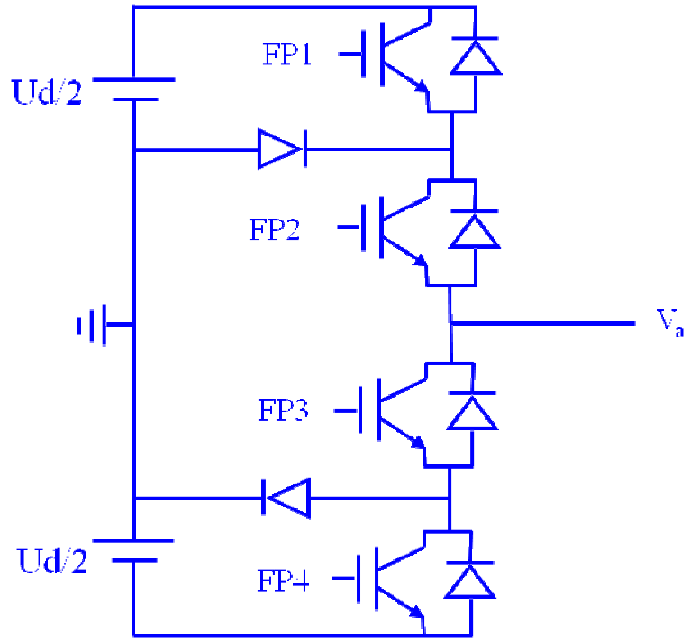

Figure 6-43 One phase of a 3-level 3-phase VSC

By switching each level in sequence, a voltage waveform closer to a sine wave is created as shown in Figure 6-44. By issuing the firing pulses as shown, the voltage Va can be created.

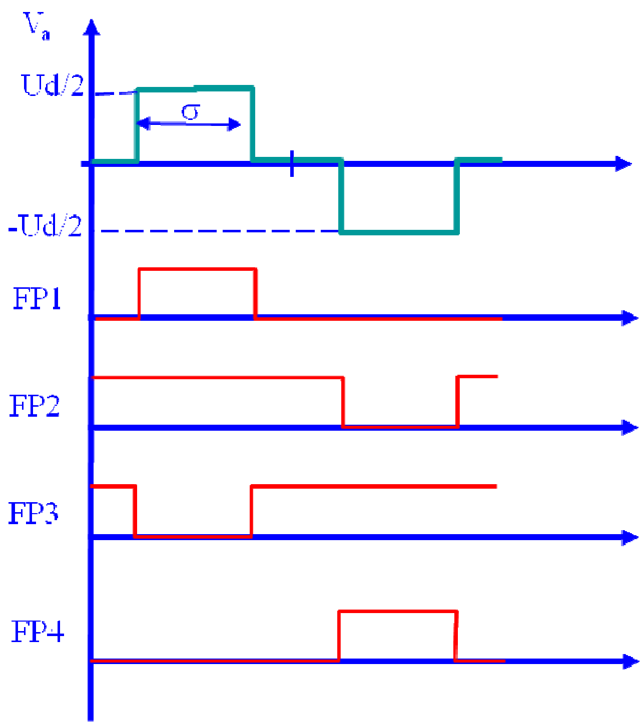

Figure 6-44 3-Level VSC waveforms

The harmonics for the three level converter is reduced from:

Harmonic Voltage for a two-level converter

$$V_n = (\sqrt{2}/n\pi)U_d$$

to:

Harmonic Voltage for a three-level converter

$$V_n = (\sqrt{2}/n\pi)U_d\ sin(n\sigma/2)$$

Based on angle δ, which referering to Figure 6-44, is the width of the firing pulse, the reduction in the harmonic magnitude comparing a three level to a two level converter is as shown in Figure 6-45. As the pulse width gets closer to 180°, the harmonic reduction is less.

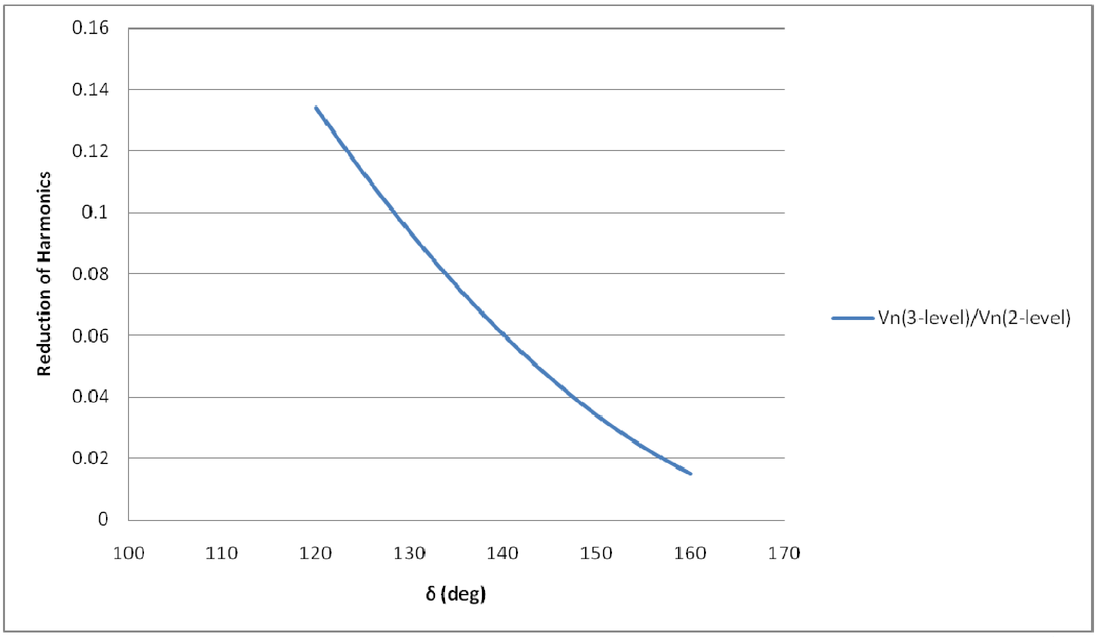

Figure 6-45 Harmonic Reduction of a three-level converter compared to a Two-Level Converter

Figure 6-46 shows the various harmonic voltage levels for a three-level converter based on the equation above.

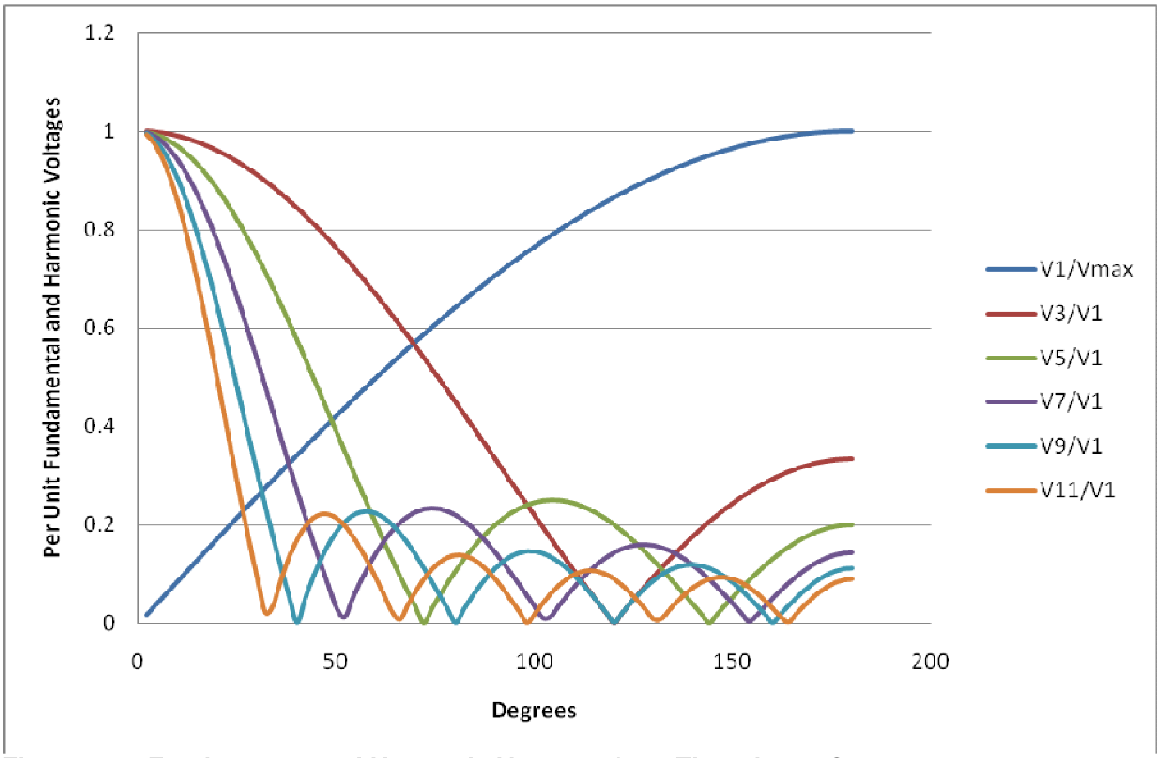

Figure 6-46 Fundamental and Harmonic Voltages for a Three Level Converter

6.2.2. Pulse-Width Modulation (PWM)

Consider the two-level circuit topology as shown in Figure 6-47.

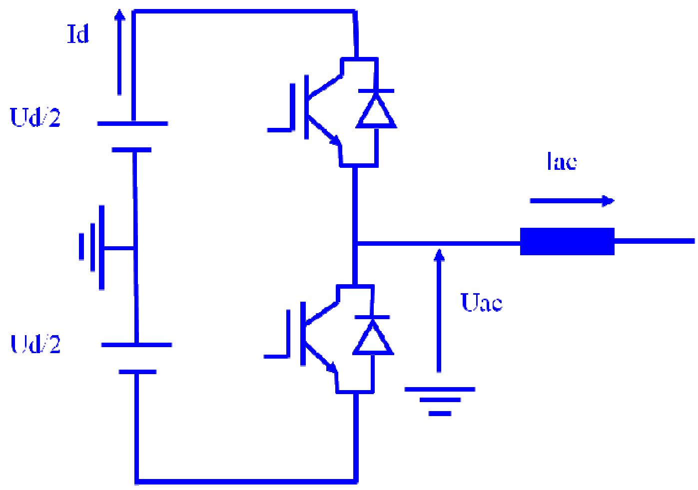

Figure 6-47 Two-Level Converter

As was established earlier, a VSC converter can precisely control its turn on and off times. For the methods described above, there is only one turn-off and one turn-on per device, per cycle. With these converters, the ac output is controlled by varying the pulse width and amplitude. Another method is to have multiple pulse per half-cycle and vary the width of the pulses to vary the amplitude of the ac voltage.

This technique is known as pulse width modulation (PWM). There are some drawbacks to this method (multiple pulses require multiple switching which increases losses), but these will not be discussed here.

Consider Figure 6-48, in order to produce the pulses required, a 3-phase sinusoidal waveforms, each out of phase by 120° are compared to a triangular waveform.

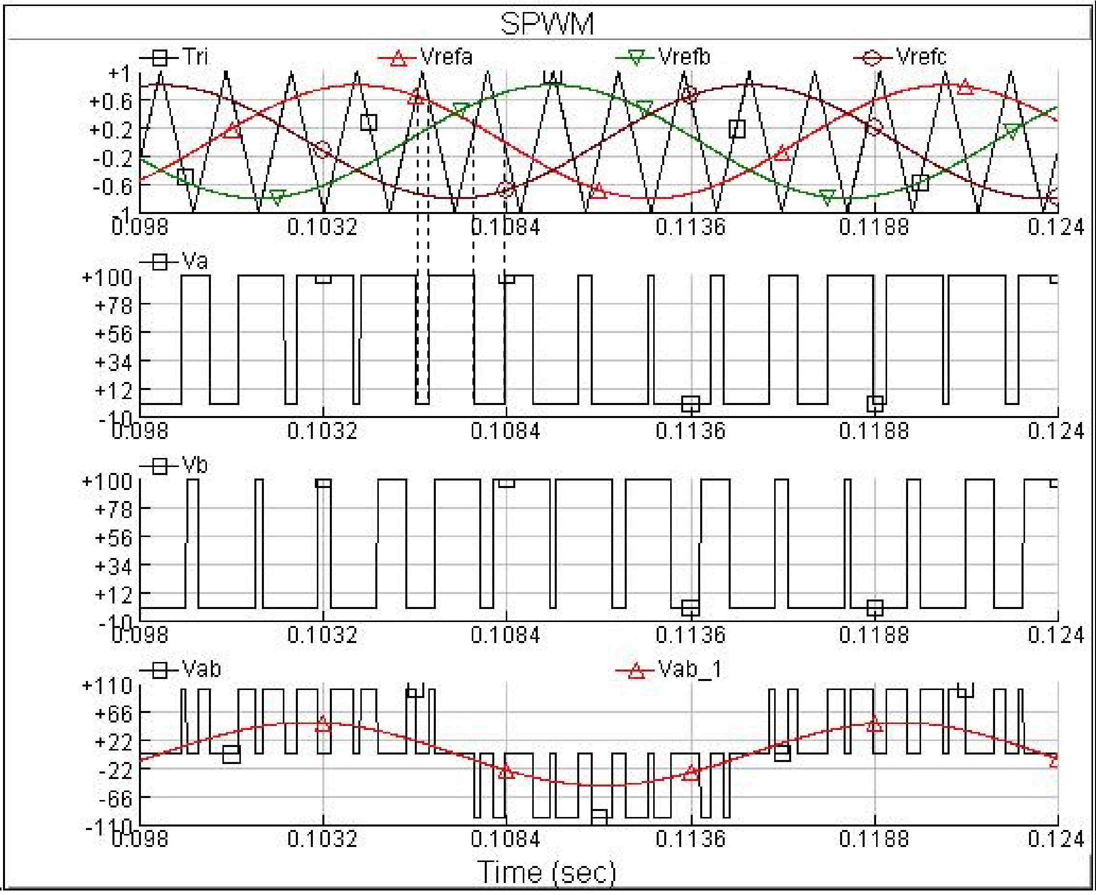

Figure 6-48 Pulse Width Modulation

The triangular waveform has a frequency of an odd multiple of the fundamental frequency of the reference sine waves. In Figure 6-48, the sine waves are at 60 Hz, and the triangular reference wave is at 9x the sine wave frequency (540 Hz). The frequency of the triangle waveform establishes the converter switching frequency. The sine reference waves are controllable in magnitude and frequency. The amplitude modulation ratio is defined as:

$$Ma = \frac{\hat{V}control}{\hat{V}tri}$$

Where $\hat{V}control$ is the amplitude of the sine wave and $\hat{V}tri$ is the amplitude of the triangular wave, and is usually kept constant.

The frequency modulation is defined as:

$$Mf = \frac{fs}{f1}$$

Where f1 is the fundamental frequency, and fs is the switching frequency.

Which switch is on and which one is off is decided by referencing the appropriate sine wave to a triangle carrier wave. Below is a table, which outlines the switching order of the PWM switching sequence.

Voltages	Switch On (Or Valve)
Vrefa<Vtri	G1
Vrefa>Vtri	G4
Vrefb<Vtri	G3
Vrefb>Vtri	G6
Vrefc<Vtri	G5
Vrefc>Vtri	G2

From the table above and Figure 6-48, one can easily see how the desired voltage can be obtained by changing Ma and f1. The frequency of the generated voltage is the same as the fundamental frequency of the reference wave. The magnitude of the peak voltage is determined by the following equation.

$$Vll_1 = \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot Ma \cdot Vd$$

Where Vd is the DC voltage level.

PWM is a very fast and effective control method but still generates harmonics

The harmonics in the inverter output appear as sidebands, centered around the switching frequency and its multiples.

The frequencies at which the voltage harmonics are produced can be found by:

$$F_h = (n \cdot Mf \pm k) \cdot f1$$

$$h = n \cdot (Mf) \pm k$$

That is the harmonic order h corresponds to the kth sideband of n times Mf. For odd values of n, the harmonics only exist for even values of k and vice versa. Van and Vbn have a phase difference of (120*Mf)°. This phase difference will be equivalent to zero if Mf is an odd multiple of 3. This results in an odd symmetry and the even harmonics disappear, leaving only the odd ones. When we have over-modulation (Ma ≥ 1), more sideband harmonics appear around the original sideband harmonics. However, the original harmonics may not be as large, so harmonic losses still may not be factors as one would think, and in some instances may actual give better performance.

Figure 6-49 shows a generalized harmonic spectrum for a PWM converter

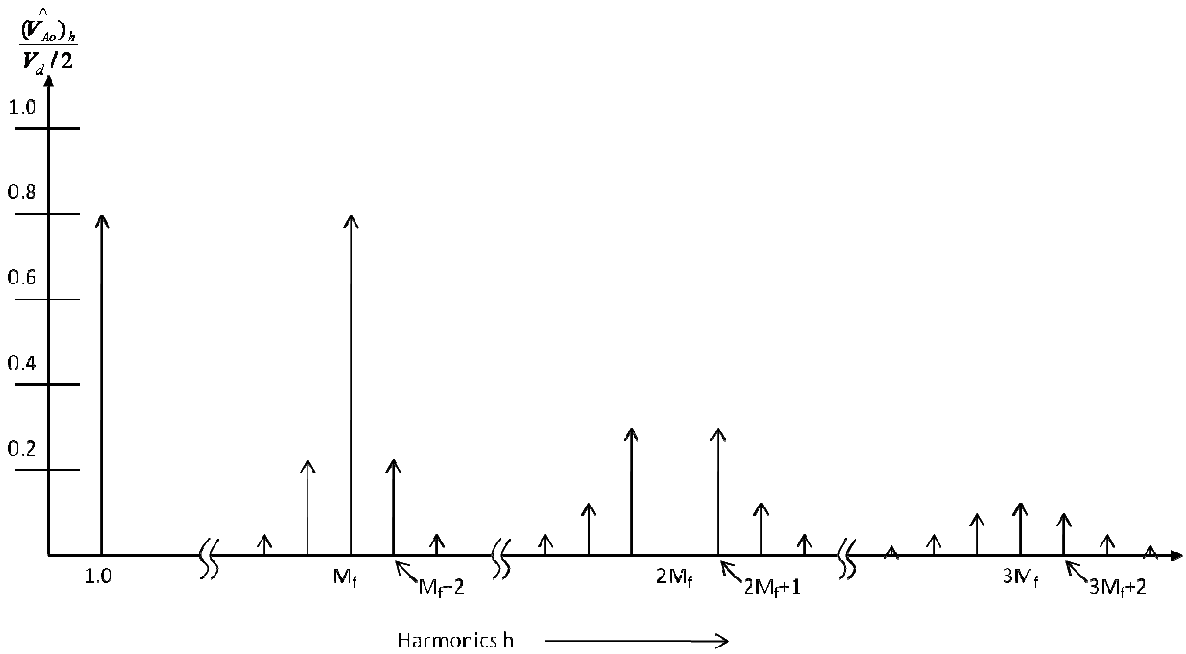

Figure 6-49 PWM Harmonics

6.2.2.1. Three-Level Converter with PWM

By Combining a three-level converter and PWM, one can get even better performance than with either option on its own. Figure 6-50 shows a three-level converter and the PWM utilized.

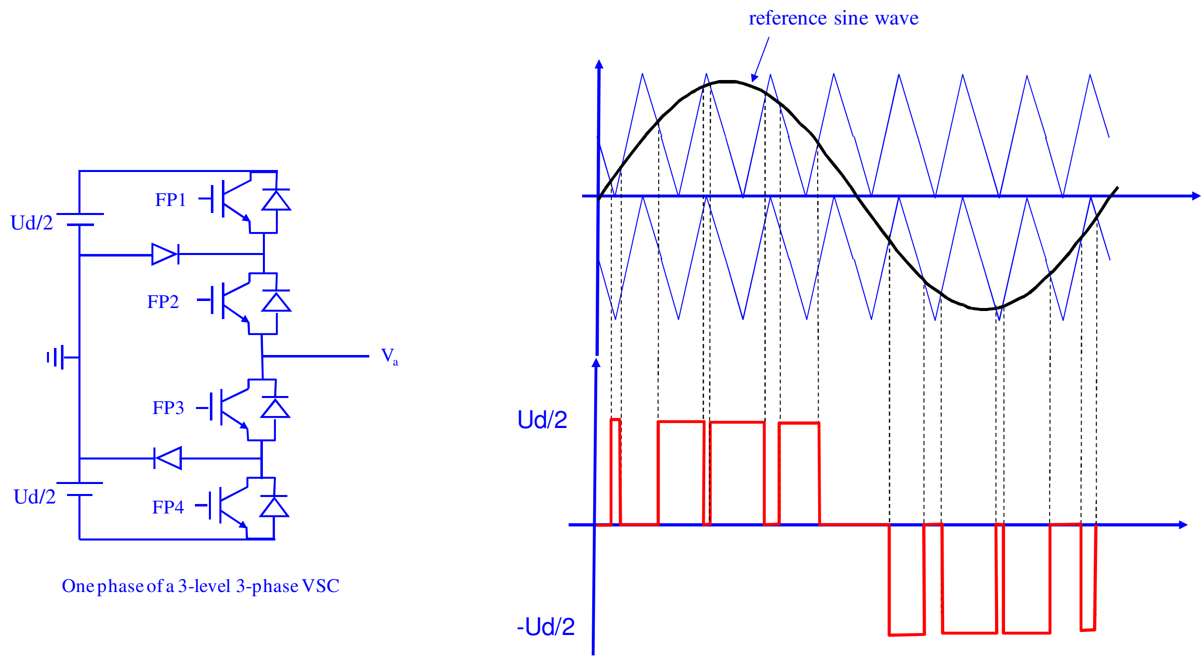

Figure 6-50 Three Level converter with PWM

6.2.2.2. Optimal PWM

For a waveform with odd and half wave symmetries as shown in Figure 6-51, the harmonics are

$$V_k = 4 \cdot \frac{E}{K \cdot \pi} \cdot (1 - 2\cos(ka_1) + 2\cos(ka_2) - \cdots 2\cos(ka_2))$$

In OPWM technique a_1 … a_n are chosen such that the fundamental is at the desired level and n-1 selected harmonics are removed. Switching angles a_1 …a_n are calculated by simultaneous solution of the above n equations

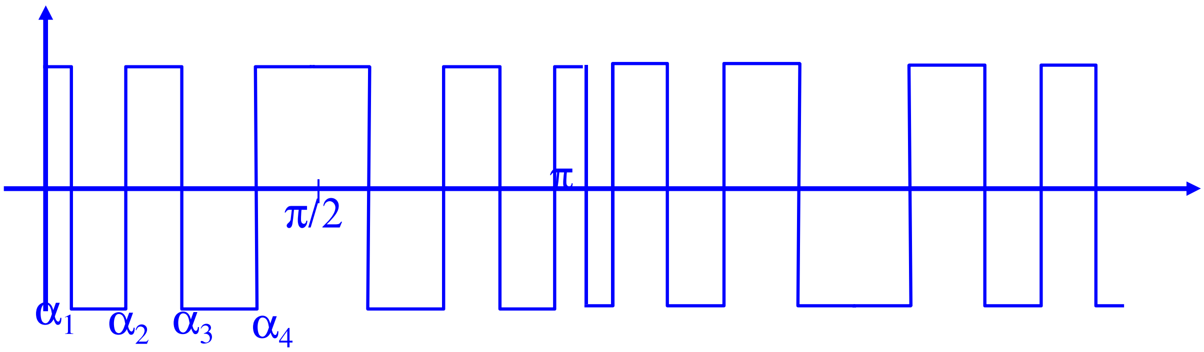

Figure 6-51 OPWM Waveform

The advantages of OPWM over regular PWM are reduced valve switching (which equates to lower losses) and one can completely remove selected harmonics.

6.2.3. Multi-Module VSC

As indicated earlier, individual IGBTs can be connected in series to increase the power rating. This concept can be expanded further by stacking simple converter units (as shown in Figure 6-47). This multi-module arrangement is shown in Figure 6-52.

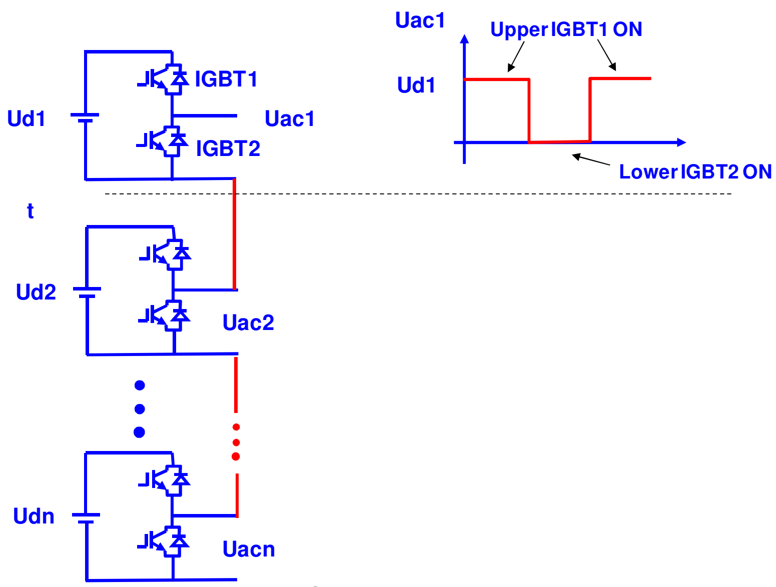

Figure 6-52 Multi-Module Converter

By controlling the converter switchings, the output of each level (or sub-module) can be shifted to produce a “stairway” output waveform as shown in Figure 6-53.

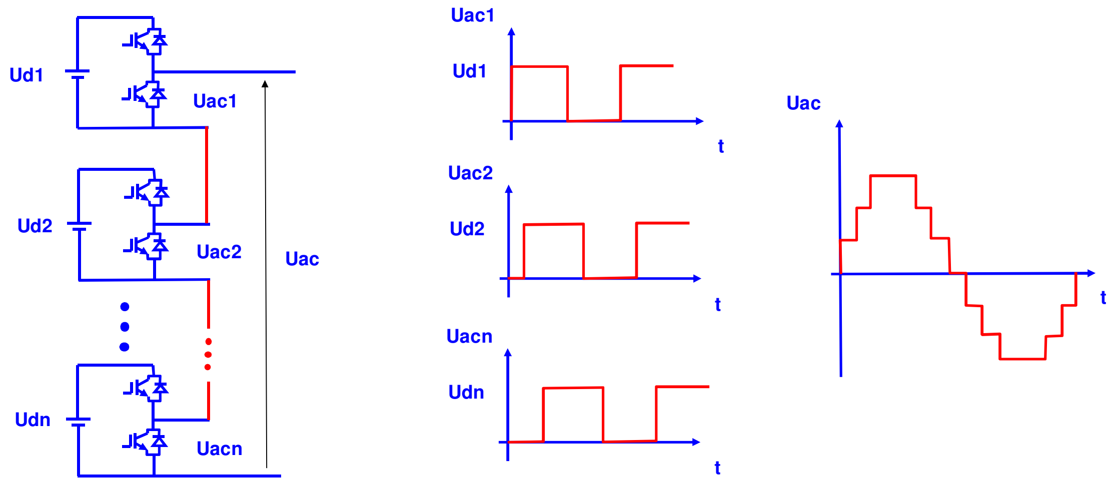

Figure 6-53 Multi-Module VSC Output

If enough sub-modules are connected in series, a waveform very close to sinusoidal can be produced as shown in Figure 6-54.

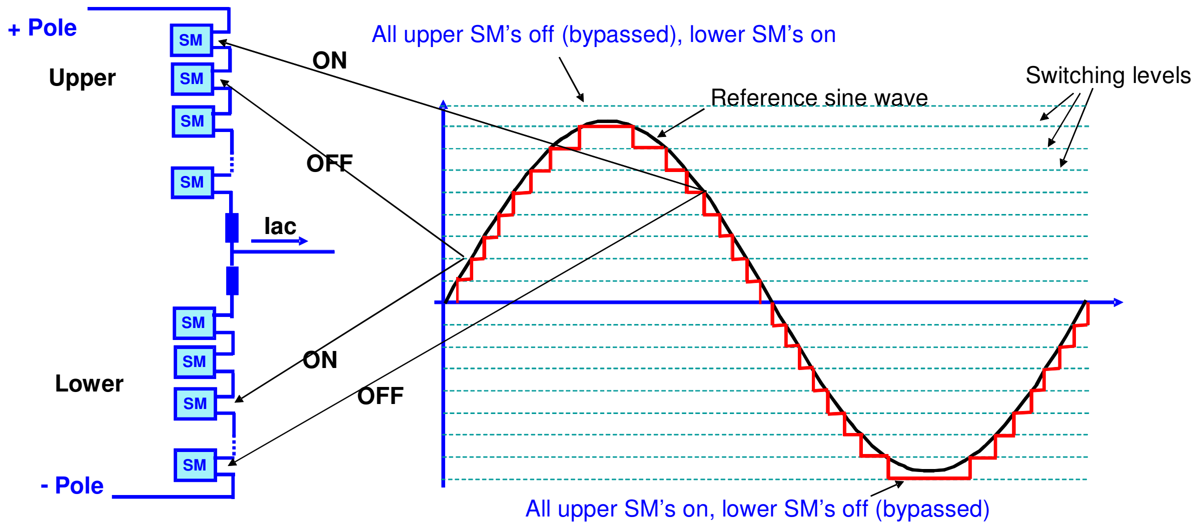

Figure 6-54 Switching of Multiple Levels

In Figure 6-54, a reference sine wave is compared with fixed levels, every time it crosses a level a sub-module is turned on or off.