Bachelor thesis

High Voltage Direct Current Transmission systems
Principles and applications
Lappeenranta University of Technology
Department of Electrical Engineering

Supervisor        professor Jarmo Partanen
Instructor        Professor Jarmo Partanen

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Mohamed Ashraf Issa
Soittajantie 2 A 9
00420 Helsinki
puh. +358 41 522502
e-mail ashraf.issa@lut.fi
<table>
<thead>
<tr>
<th><strong>Abstract</strong></th>
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<td>The aim of the thesis is a brief study for the High voltage Direct Current (HVDC) transmission system as efficient way for the transmission of the electrical energy over long distances as overhead lines and as submarine cables through a conversion process from AC to DC at the source end (rectifier) and from DC to AC at the load end (inverter).</td>
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CONTENTS

1 Introduction..................................................................................................................................1

2 The main feature of HVDC system.................................................................................................2
  2.1 The economical impacts of HVDC transmission system.........................................................2
  2.1.1 The investment and the cost of the transmission lines.......................................................2
  2.1.2 The cost structure of HVDC system.....................................................................................3
  2.1.3 The investment and the optimum voltage level.................................................................3
  2.2 The environmental impacts of HVDC system...........................................................................5
  2.2.1 The electric field effects......................................................................................................6
  2.2.2 The magnetic field effects..................................................................................................6
  2.2.3 The corona effects.............................................................................................................6
  2.2.4 Air ions effects..................................................................................................................6
  2.3 The advantages and the disadvantages of HVDC system.......................................................6
  2.3.1 The advantages of HVDC system.....................................................................................6
  2.3.2 The disadvantages of HVDC system..................................................................................7

3. HVDC Transmission system........................................................................................................8
  3.1 Typical process of HVDC system.............................................................................................8
  3.2 Typical components of HVDC system....................................................................................9
    3.2.1 the converter at each terminal.........................................................................................9
    3.2.2 The harmonic filters......................................................................................................10
      3.2.2.1 AC side filter banks...............................................................................................10
      3.2.2.2 DC side filter banks..............................................................................................11
      3.2.2.3 High frequency (RF/PLC) filters...........................................................................12
    3.2.3 smoothing inductor Ld .................................................................................................12

4. The configuration of HVDC system..........................................................................................13
  4.1 Back-to-Back HVDC system..................................................................................................13
  4.2 Monopolar HVDC system.....................................................................................................14
  4.3 Bipolar HVDC system.........................................................................................................15
  4.4 Multiterminal HVDC system................................................................................................16

5. Twelve-pulse converter arrangement.........................................................................................17
6. Areas for devlopment of HVDC transmission lines .........................19
6.1 High power semiconductor devices .................................................19
6.1.1 Line-Commutated conversion based on thyristors .........................20
6.2 Converter control .................................................................22
6.3 Conversion of exiting AC lines .................................................22
6.4 DC breaker ...........................................................................23

7 The application of HVDC system .....................................................23
7.1 Practical projects based on HVDC system application .......................25

8 Control of HVDC system ...............................................................26
8.1 Introduction .............................................................................26
8.2 Principles of HVDC transmission system control ............................25
8.3 The control characteristic of a typical rectifier and inverter stations ......26
8.3.1 Modification of the control charateristics ....................................30
8.3.2 Hierarchical control structure of HVDC system .......................33

9. Principles of HVDC system protection ..........................................36
9.1 Introduction .............................................................................36
9.2 Basic requirements in HVDC protection system design .................37
9.2.1 AC side protection ..............................................................37
9.2.2 AC line protection ..............................................................37
9.2.3 AC bus protection ..............................................................38
9.3 Converter transformer protection .................................................38
9.4 The protection of filters and reactive support ..................................38
9.5 DC side protection .................................................................39
9.6 Valve protection .................................................................40
9.6.1 The protection of valve short.circuit ........................................40
9.6.2 Converter protection agains overcurrent ....................................41
9.7 The commutation failure protection ............................................42
9.8 Missfire and Arc Through valve prtection ....................................43
9.8.1 Overvoltage protection in the converter station .........................44
9.8.1.1 The tasks of voltage stress protection .................................44
<table>
<thead>
<tr>
<th>Symbols and abbreviations</th>
<th>Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_d$</td>
<td>DC current in the line</td>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>ASEA</td>
<td>Allmana Svenska Elektriska Aktiebolaget</td>
</tr>
<tr>
<td>$V_{d}$</td>
<td>The voltage on the DC-side of the converter</td>
</tr>
<tr>
<td>$L_d$</td>
<td>Smoothing inductor</td>
</tr>
<tr>
<td>$C_{11}$</td>
<td>Capacitance of $11^{th}$ harmonic filter</td>
</tr>
<tr>
<td>$C_{13}$</td>
<td>Capacitance of $13^{th}$ harmonic filter</td>
</tr>
<tr>
<td>$C_{hp}$</td>
<td>Capacitance of the high pass filter</td>
</tr>
<tr>
<td>$Q_f$</td>
<td>Per-phase reactive power</td>
</tr>
<tr>
<td>$V_s$</td>
<td>rms phase voltage</td>
</tr>
<tr>
<td>$V_{as1n1}$</td>
<td>Phase to neutral voltage corresponding to converter 1</td>
</tr>
<tr>
<td>$V_{as2n2}$</td>
<td>Phase to neutral voltage corresponding to converter 2</td>
</tr>
<tr>
<td>$i_{a1}$</td>
<td>Per phase current corresponding to converter 1</td>
</tr>
<tr>
<td>$i_{a2}$</td>
<td>Per phase current corresponding to converter 2</td>
</tr>
<tr>
<td>$i_a$</td>
<td>The total per phase current</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Per phase AC side commutating inductance</td>
</tr>
<tr>
<td>$K$</td>
<td>Refer to an integer</td>
</tr>
<tr>
<td>$N$</td>
<td>Transformer ratio</td>
</tr>
<tr>
<td>$H$</td>
<td>Harmonic order</td>
</tr>
<tr>
<td>$U$</td>
<td>Overlap angle</td>
</tr>
<tr>
<td>$V_{LL}$</td>
<td>Line to line voltage</td>
</tr>
<tr>
<td>$V_{d1}$</td>
<td>Power transfer corresponding to converter 1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Extinction angle</td>
</tr>
<tr>
<td>$\phi_f$</td>
<td>Power factor angle</td>
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<tr>
<td>$V_{d1}$</td>
<td>Power transfer corresponding to converter 1</td>
</tr>
<tr>
<td>$V_{d2}$</td>
<td>Power transfer corresponding to converter 2</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>delay angle</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------------</td>
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<tr>
<td><strong>SIL</strong></td>
<td>Surge Impedance Loading</td>
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<tr>
<td><strong>VDCOL</strong></td>
<td>Voltage Dependent Current Order Limiter</td>
</tr>
<tr>
<td>H</td>
<td>Henry</td>
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<tr>
<td>A</td>
<td>Amber</td>
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<td>Milli</td>
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<td>Hz</td>
<td>Hertz</td>
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<td>Kilo</td>
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<td>M</td>
<td>Mega</td>
</tr>
<tr>
<td>Y</td>
<td>Star connection</td>
</tr>
<tr>
<td>Δ</td>
<td>Delta connection</td>
</tr>
<tr>
<td>$\alpha_r$</td>
<td>Reverse active mode coefficient</td>
</tr>
<tr>
<td>$\alpha_f$</td>
<td>Forward active mode coefficient</td>
</tr>
<tr>
<td>$I_{co}$</td>
<td>Leakage current</td>
</tr>
<tr>
<td><strong>RoW</strong></td>
<td>Right-of-Way</td>
</tr>
<tr>
<td><strong>PLC</strong></td>
<td>Power Line Carrier</td>
</tr>
<tr>
<td><strong>EPC</strong></td>
<td>Emergency Power Control</td>
</tr>
<tr>
<td><strong>Pref</strong></td>
<td>Power Reference</td>
</tr>
<tr>
<td><strong>Tref</strong></td>
<td>Current Reference</td>
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1 Introduction

The increase in the consumption of the electric energy as a result of the growth in the industrial development of the nations lead to the increasing in the generation and the transmission of the electricity. The remote generation and system interconnections lead to a search for efficient power transmission at high power levels. The increase in the voltage levels is not always feasible, because the problems of the AC transmission in long distances, this lead to the development of DC transmission systems. The idea of High Voltage Direct Current power transmission was under development for many years and started as in the late 1920s. An improved multi-electrode grid controlled mercury arc for high powers and voltages started to develop since 1929 by (ASEA) Allmana Svenska Electriska Aktiebolaget in Sweden. The experimental plants were set up in the 1930s in Sweden and USA to investigate the use of mercury arc valves in the conversion processes for transmission and frequency changing. In 1954, the application become commercially possible when an HVDC link has built which was 98 km submarine cable with ground return, the submarine cable connected the island of Götland and the Mainland of Sweden. The power of the project was 20 MW and the DC voltage was 100 KV. The mercury arc valves were used to convert the AC to DC and vice versa, the control equipment used vacuum tubes. Thyristors was developed by General Electric to be commercially used and applied to DC transmission lines in the early of 1960s in rating approximately 200A and 1 KV, the solid state valves becomes reality and mercury arc valves replaced by thyristors valves which reduced the complexity and the size of HVDC converter stations. The successful use of thyristors for power control in industrial devices encouraged the devlopment of HVDC converters by developing the high power semiconductor devices which help to have large device rating in the rang of 5 KV and 3000 A which allow the transmission to be reach the value of +/- 600 KV.[1]
2 The main features of HVDC system

2.1 The Economical impacts of HVDC Transmission System

DC transmission lines result in lower losses and costs than the equivalent AC lines, but the terminal costs and losses are higher because of the converter stations equipments at both terminals.

2.1.1 The investment and the operational costs of the transmission lines

The investment costs of transmission lines includes the Righ of way costs (R o W), transmission towers, conductors, insulators and terminal equipments, while the operational costs are mainly include the losses costs [2]

Figure (1) shows the transmission corridors for the DC transmission at the upper level of the figure and the AC transmission down level of the fig.(1) for the same amount of energy transferred. which illustrate the economical transmission of the energy through the DC transmission lines for reducing the land being used in addition to visual effect.

2.1.2 The cost structure of the HVDC system

Which depends on the following factors:

1) The power capacity allowed to be transmitted.
2) The transmission types.
3) The environmental conditions.
4) The regulation requirements.
5) The tasks of the optimal design.
6) Different commutation techniques.
7) Variety of filters.
8) Transformers, and others. [7]&[8]

Figure (2) Typical cost structure for converter station [8]

Two different comparisons are needed to evaluate the cost comparison between the high voltage DC system and the high voltage AC system.

1) a comparison between the thyristor based HVDC system and HVAC transmission system.

2) a comparison between VSC based HVDC transmission system and HVAC system or a local generation source connected to the load. [8]

The figure (3) below shows the cost breakdown for the high voltage DC systems which based on thyristors versus high voltage AC system, the dotted lines define the cost breakdown with considering the losses, and the other two lines show the cost breakdown for the high voltages AC and DC systems without considering the losses. The study explained that although the investment costs for HVDC converter station is higher than
in the case of HVAC system, but the costs of over head lines, cables and right-of-way are less in the case of HVDC system than HVAC system in addition the operation and the maintenance of HVDC system are less than in the case of HVAC system. It has been noted that the initial losses levels are higher in the case of HVDC system but they do not vary with the distance, while for HVAC system the losses levels are increasing with the distance.

Figure (3). shows the cost breakdown between HVDC and HVAC systems, the losses taken in consideration as dodet lines[8]

The figure (4) below, shows the second comparison between HVDC transmission system based VSC and HVAC system, the figure illustrerate that HVDC based VSC is better economically than HVAC system or a generation source connected to the load.[8]
2.1.3 Investment and the optimum voltage level

The choice of DC voltage level for the transmission lines has an important role in minimizing the total costs, which consist of the investment and the cost of the losses, so it is important to calculate the optimum DC voltage level in the early design stage for finding out the best solutions for both the investment and the losses evaluation for a given power level. In addition to, energy cost and time horizon, we have also to consider the depreciation period and the desired rate of return. For better estimation of the costs of the HVDC system, the life cycle cost analysis has to be under consideration. It is to be noted that the total costs is varied with the HVDC system configuration, for example the costs of back-to-back DC lines is much less than the costs of point to point DC lines, because the absence of the transmission line costs, in back to back configuration the voltage level has been chosen to minimize the converter stations costs. [7]
2.2 The Environmental Impacts of HVDC System

2.2.1 The electric field effects

The electric fields produced by HVDC lines are the combination of the electric field due to the line voltage and the space charge field that is due to the charge produced by the line’s corona, which lead us to understand the fact that the charge between the conductors and the ground is responsible for the total electric field produced by the HVDC lines.

2.2.2 The magnetic field effects

The environmental impacts of transmission lines magnetic field for HVAC system have been estimated as from 10 to 50 micro Tesla, while the magnetic field associated with HVDC system do not produce any significant effects. We can estimate that the magnetic field of the HVDC lines is in the same range as the earth’s natural magnetic field.

2.2.3 The corona effects

The corona is a luminous discharge due to ionization of the air surround a conductor which caused by the voltage grading exceed a certain value. The ionization which has a very thin layer will surround the conductor surface, within this area a high field strength will cause high velocity particles to collide with the air molecules, then the electrons will remove from the atom of the air molecules and accelerated toward the positive conductor. The high velocity electrons will collide with other air molecules producing additional electrons causes the avalanche process. So the effects of the corona are:

a) Corona loss (the power loss due to corona).

b) Audible noise.

c) Radio and television interference.
2.2.4 Air ions effects

Produced by HVDC lines from clouds which drift away from the line when blown by the wind and may come in contact with humans, animals and plants outside the transmission right-of-way or corridor.[7]

2.3 The advantages and the disadvantages of HVDC systems

2.3.1 The advantages of HVDC over HVAC systems

a) AC transmission via cables is impractical over long distances, such a restriction does not exist with DC lines.

b) DC constitutes an asynchronous interconnection and does not raise the fault level.

c) The power flow in a DC scheme can easily be controlled at high speed and thus with appropriate controls, a DC link can be used to improve the AC system stability.

d) DC station with or without transmission distance can be justified for the interconnection of the AC systems of different frequencies or different control methods see [1].

e) Long distance water crossing.

f) Limited short circuit current.

h) Environmental considerations. [2]

In addition, the DC transmission systems overcomes the following problems of AC transmission systems

1) Stability limits

2) Voltage Control

3) Lines compensation

4) The problems of the AC interconnection
5) Ground impedance

2.3.2 The disadvantages of HVDC Transmission system

Some disadvantages have been detected through the operation of HVDC system which limit its applications such as:

- Inability to use transformers to change voltage levels.
- Generation of harmonics which require AC and DC filters, also the additional costs of the converter stations.
- High cost of the conversion equipments.
- Complexity of HVDC Transmission control.

But over years of developing of the HVDC system operation, significant advantages have been found to overcome the disadvantages listed above, and these are the following:

1) Development of DC breakers
2) Increasing in the ratings of thyristors cells that make up the valves
3) Modular construction of thyristors valves
4) Twelve pulse operation of converters
5) Use of metal oxide, gapless arrestors
6) Application of digital electronics and fiber optics in converters control [2]

3. HVDC transmission system

The power is generated in the form of AC voltages and currents, this power is transmitted to the network as three phase AC transmission lines, in some cases it is desirable to transmit this power using DC lines, especially when the economical considerations of the transmit of a large amount of power over long distances which in the range of 300 to 400 miles meet with other factors such as transient stability and dynamic damping of the electrical system oscillations, the figure (4) below shows a
typical one-line diagram of an HVDC transmission system for the interconnection between the two HVAC systems [3].

![Fig. 5 Typical HVDC transmission system][3]

### 3.1 Typical process of HVDC system

As the figure (5) illustrate, the HVDC transmission interconnect the two AC systems A and B, where each system consists of generation, load, and its transmission lines, and may be its own frequency. From that point, the use of HVDC transmission system to interconnect the two different HVAC systems is desired. If the power will flow from system A to system B, the voltage at system A (from 69 to 230 kV range) will transformed up to the transmission level, then will rectified at converter terminal A, which is in the form of rectifier, the resulted power which is a DC power will transmit over the HVDC transmission line to the converter terminal B which is in the form of inverter, the DC power will be inverted to the AC power, and the voltage will transformed down to the AC voltage level which match the AC voltage of the system B, to be transmitted over the AC transmission and distribution lines.
3.2 Typical components of HVDC system

The HVDC technology components are classified into the following types according to their functional operation.

3.2.1 The converters at each terminal

Each converter terminal consists of a positive pole and a negative pole. Each pole consists of two 6-pulse, line frequency bridge converters, a 12-pulse converter is obtained by series connection of two bridge converters, while the transformers are connected as a Y-Y and a Y-Δ for feeding the two bridges and to form 30° phase shift between the two sets. A 12-pulse converter arrangement is preferred over 6-pulse converter for reducing the filtering requirements as it cause the cancelling of the 5\textsuperscript{th} and the 7\textsuperscript{th} harmonics.[3].

3.2.2 The harmonic filters

HVDC Converters generate harmonic voltages and currents on both DC line and AC system respectively. Harmonics take sinusoidal waveform shape and its value is the multiple of its number with the original power frequency, such as if the frequency of power system is 50 Hz and has injected by 5\textsuperscript{th}, the total frequency has disturbed the network is calculated as (5 x 50 = 250 Hz), so that filters are necessary to avoid the problems associated with the harmonics. Harmonic filters are necessary to avoid the problems associated with the harmonics such as

Such as:

- Extra power losses which resulting in a heating in machines and capacitors connected in the system.
- Overvoltages due to the resonances.
- Instability of converter controls, primarily with individual phase control.
(IPC) scheme of firing pulse generation.

- Interface with ripple control systems used in load management.

### 3.2.2.1 AC side harmonic filter banks

The converter station on the AC side generates harmonic currents which are injected into the AC system so that it is important to use AC side filters to prevent the harmonic currents to go through the system to avoid the power losses and interference with other electronic communication equipment caused by them. AC side filter banks are also included along power factor correction capacitors that supply the lagging reactive power, which is required by the converter both in rectifier and inverter mode of operation. The per-phase filters are used for these purposes, for the two lower order harmonics $11^{\text{th}}$ and $13^{\text{th}}$, a series-tuned filters (band pass) are commonly used, but for the higher order harmonics such as $17^{\text{th}}$ or above, a high pass filters are used to prevent it. Figure (5a&b) shows the per-phase equivalent circuit and combined per-phase filter impedance verses frequency respectively.
Harmonic filters on the AC side have been designed according to the AC system impedance at the harmonic frequencies to the requirements of filtering and prevent resonance cases.

AC system impedance depends on three parts of the AC network as follow:

1) System configuration based on the loads.
2) Generation pattern.
3) Transmission lines.

The designing of the high pass filter has to be able to match the changes which occurred through the operation time that can be a reason to change the system impedance. Reactive power can be provided by the harmonic filters that are required by the converters in rectifier mode of operation or in the inverter mode of operation. At nominal fundamental system frequency, the capacitive impedance dominates over the inductive elements, which is connected in series with the capacitor. The effective shunt
capacitance offered per-phase by the AC filters at the fundamental or line frequency can be approximately calculated as

\[ C_f \cong C_{11} + C_{13} + C_{hp} \]  (1)

### 3.2.2.2 DC side harmonic filter banks

DC side harmonic filter banks are important to minimize the magnitudes of the current harmonics on the DC transmission lines and to prevent the ripple in the DC voltage, which could cause an excessive ripple in the DC transmission line current. The voltage harmonics are of order 12 \( K \), where \( K \) is integer, according to the AC voltages, the magnitudes of the harmonic voltages will depend on the delay angle \( \alpha \), \( L_s \), and the dc current \( I_d \). In the case of the balanced 12-pulse operating condition, the 12-pulse converter can be represented by an equivalent circuit as we can notice in figure 3a,b which show the harmonic voltages are connected in series with the DC voltage \( V_d \). A high-pass filter is used, which is designed to provide low impedance, which is suitable for the 12\(^{th}\) harmonic frequency. [3] & [11]

![Fig.(7) DC side filter voltage harmonics](image)

Fig.(7) DC side filter voltage harmonics

![Fig.(7.a) DC-side equivalent circuit](image)

Fig.(7.a) DC-side equivalent circuit

![Fig.(7.b) High pass filter impedance versus frequency](image)

Fig.(7.b) High pass filter impedance versus frequency

### 3.2.2.3 PLC-RI filters

HVDC converter stations produce high levels of electrical noise in the carrier frequency
band from 20 kHz to 490 KHz, they also generate radio interference (RI) noise in the mega Herts of frequencies. It is necessary to install PLC-RI filters to minimize the impacts of the noise and to eliminate the interference with the power line carrier communication. PLC-RI filters are connected between the converter transformer and the AC bus to limit the high frequency currents. Fig.7 illustrate the configuration of PLC/RI filter.[2]

Fig.8 Configuration of PLC/RI Filter

3.2.3 Smoothing Inductor $L_d$

Using Smoothing inductor $L_d$ which is several of hundred millihenries is necessary for the benefit of HVDC link as its following functions: smoothing the ripple in the direct current in order to prevent the current becoming discontinuous at light loads, preventing consequent commutation failures in the inverter by reducing the rate of rise of direct current in the bridge when the direct voltage of another connected bridge collapses, smoothing reactors limit the crest current in the rectifier due to a short circuit on the DC line, they limit the current in the valves during the converter bypass pair operation due to the discharge of shunt capacitances of the DC line, the smoothing reactor $L_d$ is located before the DC filter and in series with the converter station, both smoothing reactors and the DC-side filters are in combination to limit the flow of the current harmonics in the DC transmission lines.[2] & [3]

4. The Configurations of HVDC System

The configurations of the HVDC systems are classified according to the function and
the location of the converter stations.

4.1 Back-to-Back HVDC system

In this configuration system, the two converter stations are located at the same side, so, there is no a power transmission dc link over long distance. The figure (4) shows back-to-back system. [9]

![Back-to-back HVDC Transmission system with 12-pulse converter](image)

Figure (9) back to back HVDC Transmission system with 12-pulse converter [9]

The figure (9) illustrate that the two ac networks system are interconnected with back-to-back system, and may have a different frequency which is described by asynchronous interconnection, there is a such cases in Japan and South of America where is the dc link is low in its range between 50 KV to 150 KV. Because both converter stations are located in the same area, the civil engineering costs of the project are low and the transmission losses are not significant, only the busbar system as transmission bath. the project costs are much higher in case of the two converter stations are located at two different locations.

The other example is vyborg HVDC back-to-back station it is the only back-to-back in Russia, the power rated is 1065 MW, it has three bipole system, each operating with a voltage of 85 kv (3 x ± 85kV) in opposite to most other HVDC plants, its static inverters do not allow bidirectional energy to transfer, but only in one direction from Russia to the power grid of Finland to export electricity to Nordic contries. The converter station vyborg (3 x 355MW, 3 x ± 85KV, 2100A) is located near the town of vyborg.[16]
4.2 Monopolar HVDC system

In this type, two converter stations are used to be in different sites and separated by a single pole link with a negative or positive dc voltage. The application for the monopolar system is a submarine power transmission cable, where the ground is used as a return current path. The figure (10) shows the monopolar HVDC system based on 12-pulse converters. [9]

![Figure (10) monopolar HVDC power transmission with 12-pulse converter][9]

Fenno-skan is a monopolar link between Finland and Sweden which reduces the electrical distance from 1500 km to 200 km, Fenno-Skan DC link owned by Finngrid and Svenska Kraftnät (Swedish power grid).

4.3 Bipolar HVDC system

The Bipolar HVDC system consists of two monopolar systems. Each of the two systems can be operated as separately systems. The advance of this case that one pole can continue operating while the other pole can be out of service for maintenance or other reasons. So, each pole can be operated independently. The earth can be used as a return path. Bipolar HVDC system is the most commonly configuration used in the overhead power transmission lines. Because of the two poles are different in polarity, one pole is positive and the other pole is negative, and in the case of both of the poles have equal currents, so, the ground current will be zero. But practically, this result could be obtained if the difference in the poles currents is around 1%. The figure below shows the Bipolar HVDC power transmission system based on 12-pulse converters. [9]
4.4 Multiterminal HVDC system

In this type of HVDC system, there is more than two converter stations are located at different sites. The figures (10) illustrate a multi-terminal HVDC system with 12-pulse converters per pole.

The system is operating as follow:

a) If the converters 1 and 3 operates as rectifiers, then converter 2 operate as inverter.

b) If the converters 1 and 3 operates as inverters, then converter 2 operate as rectifier.

c) The system can operate as case (A) or vice versa as case (B), by using mechanical switch.

The block diagram below illustrate Multi-terminal HVDC system based on 12-pulse converters for poles 1, 2, 3.[12]
5. Twelve-pulse converters arrangement

The converter unit consists of two three-phase converter bridges which are connected in series to form a 12-pulse converter unit. This means that the total number of valves in the unit are twelve, and the valves can be back-geared as single valves, double valves, or quadravalves arrangements. The converter is fed by converter transformers connected in Y-Y and Y-Δ arrangements, the two 6-pulse converters reduce the current harmonics generated on the AC side and the voltage ripple on the DC side which are not desired. Figure 11 illustrates that the two 6-pulse converters are connected in series on the DC side to meet the high voltage of the HVDC system, and are connected in parallel on the AC side. [3]
In the presence of the large smoothing inductor $L_d$, we can assume that the current $I_d$ is a pure DC current on the DC-side, then the voltage and the current waveforms can be drawn correctly.[3]

If we assume that the per-phase AC-side commutating inductance $L_s = 0$, $i_d(t) \approx I_d$ and $V_{as1n1}$ leads $V_{as2n2}$ by $30^\circ$, then we can draw the current waveforms as in the figure 13, where each 6-pulse converters operate at the same delay angle $\alpha$.

The total per-phase current is: $i_a = i_{a1} + i_{a2}$  \hfill (3)

Figure (12) A Six pulse converter bridge. [13]
The waveform of the total per-phase current drawn by using double 6-pulse converters which are connected in series to form a 12-pulse converter configuration as illustrated in fig.(11), This configuration is suitable for a higher voltage rating and provid a phase shift of 30° degrees on both terminals of line-to-line voltage by providing different transformers connections as star-delta or delta-star for both primary and secondary winding transformers respectively which will lead to a fewer harmonics and then reducing extra filters could be needed than in the case where the $i_{a1}$ and $i_{a2}$ are drawn separately by the 6-pulse converters.

![Diagram](image)

**Figure (13) Phase to neutral voltage wave forms corresponding to both 6-pulse converters. [3]**

We can write both currents in terms of their Fourier components as:

$$i_{a1} = \frac{2\sqrt{3}}{2N} * I_d (\cos \theta - \frac{1}{5} \cos 5\theta + \frac{1}{7} \cos 7\theta - \frac{1}{11} \cos 11\theta + \frac{1}{13} \cos 13\theta + \ldots) \quad (4)$$

$$i_{a2} = \frac{2\sqrt{3}}{2N\pi} * I_d (\cos \theta + \frac{1}{5} \cos 5\theta - \frac{1}{7} \cos 7\theta - \frac{1}{11} \cos 11\theta + \frac{1}{13} \cos 13\theta + \ldots) \quad (5)$$

Where $\theta = \omega t$, so the total per-phase current $i_a$ becomes as following:

$$i_a = \frac{2\sqrt{3}}{N\pi} * I_d (\cos \theta - \frac{1}{11} \cos 11\theta + \frac{1}{13} \cos 13\theta + \ldots) \quad (6)$$

We can notice that the current $i_a$ has harmonics of order $h$, where $K$ is an integer

$h = 12k\pm1$ \quad (7)
We can notice from the total per-phase current amplitudes $i_a$ seen in equation 6 as result of two 6-pulse converters (a 12-pulse converters arrangement) that the amplitudes are inversely proportional to the harmonic order, which its lowest harmonic order are the 11th and the 13th. Because of the two 6-pulse converters are in parallel on the AC-side, the currents will be add (Kerschhoff current law), but in the case of the two 6-pulse converters located on the DC-side, the total voltage $V_d$ equals to the two voltages of the two 6-pulse converters $v_{d1}$ and $v_{d2}$, where the two voltages waveforms are shifted by 30˚, with respect to each other. $V_d$ will provide 12 ripple pulses per cycle, this results in the voltage harmonics of order $h$

Where, $h = 12K$  

(8)

K is a positive integer, so, the 12th harmonic will be the lowest order harmonic, and the magnitude of the voltage harmonic will be vary with the delay angle $\alpha$, as shown in figure (14). [3]

Figure (14) wave forms interactions of DC voltage corresponding to both 6-pulse converters. [3]

6. Areas for developments of HVDC transmission lines
6.1 High power semiconductor devices

The advanced of high voltage and current semiconductor technology plays the main role in the development and progress in power electronics converter. Today, new semiconductors technology and the developments in the areas of power semiconductor devices, digital electronics, adaptive control, DC protection equipment have changed the way the power switches are protected, and controlled, the major contribution of these development is to reduce the cost of the converter stations and so improving it’s reliability and performance. The cost of the converter can come down if the number of the devices to be connected in series and in parallel brought down. The size of the devices became around 100 mm in its diameter and there is no need for the parallel connection. The increasing in the current rating of the device has made it possible to provide higher overload capability at reasonable costs and reduce the limits on transformer leakage impedance thereby improving the power factor. The voltage ratings are also increase. The development of light triggered thyristors should also improve the reliability of converter operation. The cost of the valves is also reduced by the application of zinc oxide gapless and protective firing methods. The power rating of thyristors is increased by better cooling methods. Deionized water cooling has now become a standard and results in reduced losses in cooling. Two phase using forced vaporization is also being investigated as a means of reducing thermal resistance between the heat sink and the ambient. The development of devices that can be turned off by application of a gate signal would be desirable since the forced commutated converters operating at high voltages are uneconomical. An example is the gate turn off thyristors (GTO) which are already available at 2500 V and 2000 A, but the main disadvantage of the gate turn off is the large gate current needed to turn them off.[1]

6.1.1 Line-Commutated Conversion based on thyristors
In Line-commutated conversion (LCC) HVDC system, the main area of development is the thyristor switch itself which is the continuation of improvement of this technology leads to increase the voltage ratings of the thyristors module and thus a large power can be transferred, a new material such as Silicon Carbide (SiC) is considered to be the promising material for more controllable thyristors. Line Commutated Converstion is the preferred option for large power and long distance HVDC system. In HVDC systems based thyristors technology a several areas for such developments are as the following:

- Active DC side filters.
- Continuously tuned AC filter.
- Capacitor-Commutated Conversion (CCC).
- Air-insulated outdoor thyristor Valves.
- STATCOM-aided conversion.
- Direct connection of generators to HVDC converters.
- Conversion of existing AC lines for use by HVDC transmission.
- Use of DC voltage higher than 600 KV.
- Converter control

In the figure 15 a single line diagram of monopolar HVDC power transmission system with capacitor commutated converter (CCC).
Capacitor Committed Converter (CCC) includes series capacitors which are placed between the converter transformer and the valves as shown in figure (15).

The advantages of CCC configuration are:

1. To ensure that the converter reactive power is lower than the line commutated converter.
2. The reactive power is constant over the full load range.
3. By connecting such HVDC system to the network, a much lower short-circuit capacity is allowed.
4. Capacitor Committed Conversion (CCC) gives more robust and stable dynamic performance of the inverter station, especially when it is connected to a weak AC system or to a long distance DC system.
5. Capacitor Commutated Conversion is the most economical methods of AC voltage control for HVDC converter stations according to a study has made by manitoba HVDC research center. [9].

First commercial application of the (CCC) configuration is the garabi 1100MW back-to-back connection between Argentina and Brazil.

6.2 Converter Control

Converter control has been developed by using the micro-computer as mean make it possible to design a complete redundant converter control using the automatic transfer between systems in the case of a malfunction and to be able to reduce the outage rate of the control equipment and also able to perform scheduled preventive maintenance on the stand-by system when the converter is in perform.
6.3 Conversion of exiting AC lines

Righ-of-way (WoR) can lead to use the option of converting the AC system into DC system in order to increase the power transfer limit and to avoid the electromagnetic induction problems induced from the AC system operation in the same RoW.

The ratio SCR

SCR is the ratio which define the strength of the AC system connected to the DC system if the result of the ratio is less than 3 the AC system is defined as weak.

\[
SCR = \frac{\text{short circuit level at the converter bus}}{\text{Rated DC power}}
\]

This can effect the recovery of inveter following the clearing of fault in the connected AC system and the extinction angle control can not be satisfactory with the weak AC system. To overcome these problems a constant reactive control or AC voltage control are applied.

6.4 DC breakers

One of the areas for development of the DC system is DC breakers suitable also for the new MTDC connected in parallel which allow flexibility in the planned growth of a system.

7. The applications of HVDC system

HVDC system point-to-point arrangement:
The first application for HVDC system was point-to-point electrical power interconnection between asynchronous AC power network there are other application as follow:

1) Interconnection between asynchronous systems such as the island loads,
island of gotland in the baltic sea, and east, west, texas and quebec networks in north of america.

2) Import electric energy into congested load areas where new generation is impossible to bring into service to meet the growth in the electricity consumption or replace old plant by using underground cable.

3) Import between the borders such as Finland-Russia, Fenno-Skan Monopolar link.

4) Increasing the capacity of existing AC transmission by conversion to DC transmission. New transmission right-of-way may be impossible to obtain. Existing overhead AC transmission lines if upgraded too or overbuilt with DC transmission can substantially increase the power transfer capability on the existing right-of-way.

5) Deliver energy from remote energy sources where the generation has developed at remote sites of the available energy, HVDC has the economical advances to bring the electricity to the load center.

6) Because the power flow control provided by the AC transmission do not meet the recommended power flow control, so HVDC transmission can achieve the power flow control.

7) A wide range of electric power networks operate at stability limits well below the thermal capacity of their transmission conductors, HVDC transmission can play an important role to increase the utility of the networks conductors and provide the stability of the electric networks.[6]

As the need for a new energy sources has been grow, such as wind or solar energy farms, and also to have an economical energy and to minimize the environment impact. The need for the new technology Of VSC based on PMW HVDC systems has grow too, and this very clear when needed to built wind farms out side the cities to be away from the communities for many reasons, such as minimizing the environment impact, building large plants which can be connected to the grid via the HVDC systems with VSC which leads to maximize of the resource available and reducing the cost of the
investment by cutting down the transmission costs. Previous example can be applied to other sources such as hydro energy, solar energy or other renewable energies.

7.1 Practical projects based on HVDC system applications

1) The Itaipu HVDC transmission project in Brazil is the impressive HVDC transmission in the world, it has a total power of 6300 MW and a world record voltage of ± 600 KV DC. Itaipu HVDC transmission line consists of two bipolar DC transmission lines bringing power generated at 50 HZ in the 6300 MW (3150+3150) MW. Itaipu hydropower plant owned by itaipu Binacional, is connected to the 60 HZ network in saopaulo, in the industrial center of Brazil. The main reasons for choosing the HVDC are the long distances and 50/60 HZ conversion, the length of itaipu overhead DC line is 785 KM+805 KM.

2) Leyte-Luzon HVDC power transmission project in Philippines
National power corporation has constructed a 440 MW, 350 KV monopolar HVDC link to transfer power from the geothermal power plant on the island of Leyte to the southern part of the main island of Luzon to feed the existing AC grid in the Manila region. The HVDC interconnection will be beneficial both to industry and inhabitants of Manila area. The length of the overhead line is 430 KM, the length of submarine is 21 KM, the link has been in commercial operation since August 10, 1998.

3) Rihand-Delhi HVDC Transmission in India
National thermal power corporation limited built a 3000 MW coal-based thermal power station in the sonebbadrea district of uttar pradesh state. Part of the power from the Rihand complex is carried by the Rihand-Delhi HVDC bipolar transmission link which has a rarefied capacity of 1500 MW at ± 500 KV DC. Some of the power transmitted via the existing parallel 400 KV AC lines, the reasons why choosing HVDC instead of 400 KV AC were better economics, halved right-of-way requirements, lower transmission losses and better stability and controllability. Rihand-Delhi HVDC has a total overhead length 814 KM, and the mean reasons for choosing are long distance and better
stability. The link has been in operation since 1990.

4) Gotland-Wind power Evacuation

In recent years the push for renewable forms of energy has brought wind power farms into focus on the swedish island of Gotland in the baltic sea. Today the island needs additional transmission capacity and a better means of maintaining good power quality because wind power quality has been greatly expanded on the southern tip of the island. Moreover, sensitive wildlife environments and the fact that many holiday resorted on Goyland demand low visual impact on the surroundings, so VSC’s combination with underground DC cables was the obvious choice for this project. Accordingly, in 1997, GEAB the local electric supplier agreed to install the world first VSC based HVDC transmission system on Gotland. GEAB is a subsidiary to Vattenfall AB, which has financed the project together with the Swedish National Energy Administration. Rated as 50 MW, the transmission has linked the wind power park on the southern tip of Gotland (NÄS) to the city of Visby (BÄCKS), some 70 KM away. It will run in parallel with the exiting AC connection. The main reasons for choosing HVDC system are Environmental aspects and power quality, the voltage rated is ±80 KV DC, the commissioning year is 1999.

5) Direct Link

TransEnergic Australia, a subsidiary of Hydro Quebec and the New South Wales distributor North power, awarded the 21 of December 1998 the supply of the equipment for the directlink interconnection. Directlink will emply VSC with DC cablest connect the queensland and New South Wales electricity grids between Terranora and Mullumbimy, a distance of 65 KM, the ultimat size of the interconnection will be approximately 180 MVA, (3x 50 MW) the DC voltage is ± 80 KV, the interconnection has designed to supply the energy needs of about 100,000 homes, and has choosen as
8 Control of HVDC system

8.1 Introduction

One of the major advantages of HVDC system is the rapid controllability of the transmitted power. The control of the power in the HVDC system is based on the control of the current or the voltage, while for minimizing the losses in the DC line, it is important to maintain a constant voltage and establish the desired current in the line from the rectifier to the inverter to obtain the desired power flowing in the DC line by varying the voltage at the converters. This method is important for the voltage regulation in HVDC system to meet the consideration of the optimal utilization of the insulation and as we have noticed that the voltage drop in the DC line is smaller compared to the AC line because of the absence of the reactive voltage drop.

8.2 Principles of HVDC transmission system control

![Steady state equivalent circuit](image)

Figure (16) Steady state equivalent circuit of two terminal DC line and converter.[5]

We can develop for this process a steady state equivalent circuit of two terminal DC line which include rectifier, inverter, and transformer tap changing. On both converter stations, the commutating resistances are separated into rectifier and inverter resistances. See the figure (16). The equivalent circuit represent the steady state condition of the DC link, the voltage drop in the DC link is very small compared with the AC lines because of the absence of the reactive voltage drop, based on the
assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angles and the same number of the series connected bridges in both stations the rectifier and the inverter.

The steady state current is:

\[ I_d = V_{do} \cos \alpha - V_{di} \cos(\beta - \gamma) / (R_{cr} + R_{ci}) \] ...................................................(9)

- \( V_{do} \) : ideal rectifier voltage
- \( V_{di} \) : ideal inverter voltage
- \( R_{cr} \) : rectifier resistance
- \( R_{ci} \) : inverter resistance

\( \alpha \) : is the delay angle which means the time expressed in electrical angular measure from the zero crossing of the idealized sinusoidal commutating voltage to the starting instant of forward current conduction, the delay angle (\(\alpha\)) is controlled by the gate firing pulse, and if it is less than 90º degrees the converter bridge operate as rectifier, and in case its value exceeds 90º degrees the converter bridge operate as inverter. so that the delay angle (\(\alpha\)) often referred to as ignition angle.

\( \beta \) or the advanced angle (\(\beta\)) is the time expressed in electrical measure from starting instant of forward current conduction to the next crossing of the idealized sinusoidal commutating voltage. The angle (\(\beta\)) is related in degrees to the angle of delay (\(\alpha\)) by the \(\beta = 180 - \alpha\)

\( \gamma \) : it is the extinction angle described as the time expressed in electrical measure from the end of current conduction to the next idealized sinusoidal crossing voltage, the extinction angle (\(\gamma\)) depends on the angle of advanced (\(\beta\)) and angle of overlap (\(u\)) from the end of current conduction where overlap (\(u\)) is the duration of commutation between the converter valve arms expressed in electrical angular measure.

*It is to be noted that*

+ \( R_{ci} \) in the denominator is used with \(\cos \beta\) in the numerator.

− \( R_{ci} \) in the denominator is used with \(\cos \gamma\) in the numerator.

We assume that (\(\beta\)) is controlled angle at the inverter since this angle can directly be
controlled whereas $\alpha$ indirectly controlled through the control of ($\beta$). the following relation express the determination of ($\alpha$) through ($\beta$) and ($u$).

$$\alpha = \beta - u$$

the current flowing in the line depends only on the terminal voltage because of the total circuit resistance is constant for any given mode of operation. so that The current and the power transmitted are controlled by varying the terminal voltages by changing the the transformer taps on both sides changer .[2]&[5]

The current control and the voltage regulation have to be done simultaneously in the DC line. In normal condition the current control will be maintained at the rectifier station and the voltage regulation on the inverter station.

### 8.3 The control characteristics of a typical rectifier and inverter stations

Figure (17) illustrate HVDC control system characteristics of both stations, each station characteristic has three parts which represented by solid lines through the normal operating characteristics, while the existence of the dotted lines represent the changes in the operation modes and condition. The solid line (a b c d) represent the normal operating characteristics of the station I which operating as rectifier and the solid line (h g f e) represent the normal operation of the station II, which operate as inverter, we have to mention that the upper half of the converter controller characteristic plane represent the positive direct voltage DC, while the bottom of the plane represent the negative direct voltage DC. The intersection of the two normal operating characteristics represented by the solid lines (a b c d) and (h g f e) at point (A) determines the mode of operation of the station I which operate as rectifier with the constant current control CC and the station II which operate as inverter at constant extinction angle CEA, in the normal operating condition the power flow from station I (the rectifier) to the station II (the inverter). There can be three point (modes) of operation for the same direction of the power flow. The point (C) on the control characteristic plane represent the shifting of the intersection point of the rectifier and inverter characteristics because of the changing in the mode of the operation as a result of slight dip in the AC side voltage. in this case we have to maintain a minimum alfa (}
α) at the rectifier and minimum gamma (γi) at the inverter, the maintaining of both minimum α and γ can be done by using tap transformer position (tap changer control) at both rectifier and inverter by varying the number of turns on the primary side in order to obtain the suitable voltage. With lower AC voltage at the rectifier the mode of operation will shift to point (B) which will result in the inverter will operate in the constant current control mode (CC) and the rectifier will operate in the constant extinction angle mode (CEA) with minimum α at the rectifier. The three operation points (A, C, B) for the DC link converter control can be illustrated in the figure below.[2]&[5]

Figure (17) Converter controller characteristics[2]

We can notice from the figure that the characteristic (ab) has negative slope than (fe) for similar values of the rectifier and inverter resistances Rcr and Rci respectively, because the slope (ab) is results from the combined resistances (Rcr = Rci), but the slope (fe) is results from only the resistance Rci, the slope (fe) will become more negative than (ab) in case of the Short Circuit level / Rated inverter (SCR) is low. If Im is the negative current margin where the current reference for the inverter (station II) is larger than the
current reference of the rectifier (station I), the operating point shifts to (D) in the lower part of the control characteristics plane as illustrated in the figure (17) which will imply the power reversal, which will flow from the (station I) operating with minimum (CEA) acting as inverter to (station II) operating with CC control acting as rectifier. The power reversal can cause a huge disturbances to the power system if occurred at two different places at the same time, to avoid such cases, the current order at the two stations must move together, the power reversal can be eliminated by maintained a minimum delay angle ($\alpha_i$) in range of ($100^\circ - 110^\circ$) at the inverter station.[2] &[5] (it is to noted that for increasing the transmitted power in the link and for minimizing reactive power consumption we have to reduce alfa ($\alpha_r$) at the rectifier which will also lead to improving the power factor and minimizing the reactive power consumption at the rectifier, and also reducing gamma for minimizing the reactive power consumption at the inverter.)

8.3.1 Modification of the control characteristics

As we have noticed from the last section that to avoid the power reversal we have to locate the control region within the first quadrant of the $V_d$-$I_d$ plane, as we need other two requirements to ensure the modification of the control characteristics.[2]

1) mode stabilization

In normal operation the characteristic AB is more negative than the characteristic FE for the similar values of the resistances $R_{cr}$ and $R_{ci}$, because the slope AB is due to the sum of the two resistances $R_{cr} + R_{ci}$, while the slope FE is only due to the resistance $R_{ci}$. But in case the of low SCR at the inverter, the slope FE could be more negative than the slope of AB.

Figure 18 Illustration of three point instability.[2]

If the slope (fe) exceeds the slope (ab) in this case will lead to three operating points
Figure (18) Three points of the instability control.[2]

(A, A', A'') as illustrated in figure (18) which will lead to system control instability causing hunting between different mode of operation, to avoid this problem the inverter characteristics should modified through two methods.[2]

1) By providing a positive slope when the current is between \( I_{d1} \) and \( I_{d2} \).
2) By modifying the inverter control to maintain a constant DC voltage with back-up control of minimum constant extinction angle (CEA). This requires the normal operating value of the extinction angle to be greater than the minimum value.
2) Voltage dependent current order limit (VDCOL)

The faults in AC system on both inverter and rectifier sides results in low DC voltage in the line, if the low AC voltage is due to the faults on the inverter side will cause persistent commutation failure because of the increase of the overlap angle, in this case it is important to reduce the DC current in the line until the reasons which cause the reduction in the DC voltage eliminated. On the other hand if the low DC voltage due to the faults on the rectifier side AC system, the inverter will operate at very low power factor which will lead to huge consumption of reactive power, this also undesirable case. for these reasons we need to modify the control characteristics to include voltage dependent current order limits (VDCOL), see the figure 19.[2]
Figure 20 shows the current error characteristics to stabilize the mode during DC current operation between the currents $I_{d1}$ and $I_{d2}$, the characteristics $C'$ and $C''$ which show the limitation of current due to the reduction in the voltage. The DC current is reduced from $I_{d1}$ to $I'_{d1}$ linearly and maintained at $I'_{d1}$ below the voltage $V_{d2}$. The inverter characteristics follow the rectifier characteristics to maintain the current margin except for $hd''$ which is due to the lower limit imposed on the delay angle of the inverter.

### 8.3.2 Hierarchical control structure of HVDC system

Using hierarchical control structure allow to perform the control functions of the system where the master controller of the bipole is located at one of the terminals provided by power order ($P_{ref}$) from the energy control center in addition to the necessary information such as the AC voltage at the converter bus, DC voltage and else. Master controller transmits the current order ($I_{ref}$) to the pole control units which in turn provide a firing angle order to the individual valve groups which form the converter, converter control oversees valve monitoring and firing logic by using optical interface.
A control signal $V_c$ which generated by the current or the extinction angle controller is related to the firing angle controller which in turn generates gate pulses in response to the signal $V_c$, as illustrated in figure (22) the selector picks up the smaller of \( \alpha \) value which is determined by both the current and constant extinction angle (CEA) controllers.[2]
Firing Angle Controller

As we have noticed from the pole and converter controller the importance of the firing angle for generates gate pulses required for the valve control in the converter and how it dependent on the operation of the current and the CEA controllers. There are two basic requirements for the firing pulse generation of HVDC valves.

1) For all the valves, the firing instant are determined at ground potential and the firing signals sent to each individual thyristors by light signal through fiber optic cables the desired gate power is made available at the potential of individual thyristor.
2) the gate pulse generator must be available in any time to send a pulse required for turning on the thyristors, (a single pulse is adequate for turning on the thyristors). The gate pulse generator must be available in any time to send the pulse to turn on the thyristors when it is required for keeping any particular valve in a conducting state, this process is very important when operating at low DC current and a transient might reduce the current below the holding current. There are two firing types.

1) Individual phase control (IPC)
2) Equidistant pulse control (EPC)

In the latest method (EPC) the firing pulses are generated in a steady state at equal intervals of $1/p_f$, through a ring converter, in this scheme using a phase locked oscillator to generate the firing pulses which is divided into three types.
a) Pulse frequency control (PFC)
b) Pulse period control
c) Pulse phase control (PPC)

9. Principles of HVDC system protection

9.1. Introduction

The fault in the DC system are caused by malfunctioning of the equipment and controllers in addition to the failures caused by external sources such as lightning, pollution, etc. The fault must be detected and the system has to be protected by switching and control action such that the disruption in the power system minimizing. The figure below illustrate the protection system for one pole [2].

Figure (23) HVDC protective systems for one pole [5]
9.2 The types of HVDC protection system

9.2.1 AC side protection

Figure (24) explain the AC side protection associated with only one of the two poles, the other pole will have identical protective system.

Figure (24) illustrate one line protection of the AC side for one pole. [5]

9.2.2 AC line protection

The AC supply by the pole may be provided by a short circuit AC line, which will protect such a feeder line would be on the left in the figure (23) the type of the line protection is high-speed line protection for both phase and ground faults. In many cases this protection will form of pilot relaying, the AC line breakers must be tripped for all major pole and line faults. May be sometimes a short length of line on the AC source side in which case the breaker separates the bus protective zone from the harmonic filter and capacitor zone. Input to the protection are from (CT’s) located at the converter terminal boundary, with current and voltage polarization for zero-sequence ground faults from the converter transformer neutral and the bus voltage transformers.[5][4]
9.2.3 AC bus protection

A rigid bus will normally be used to tie the supply breaker to the converter transformer. This bus also supplies the harmonic filters and the reactive support for this pole of the converter. The breaker must be tripped for all bus faults, we can notice from the figure (24) that the protected zone of the AC bus lies between the current transformers on the source side of the breaker to the converter transformer high-voltage winding. This zone include the harmonic filter and reactive support, by using the neutral end (Ct’s) of each shunt connection. Bus differential relays are recommended to be used in this protection.[4]&[5]

9.3 Converter transformer protection

The converter transformer is supplied in the form of single-phase units. Each transformer has two secondary windings. They are connected in delta for one valve group and connected in wye for the other valve group. The fourth transform is considered as a spare transformer which not in use unless the in-service units should fail. A transformer differential relay will provide the transformer protection which is connected as show in the figure (24) Second harmonic restraint is commonly provided to suppress tripping when he transformer is energized. It is useful to use high -speed ground fault protection across the high-voltage bushing to the ground. Over current protection provided as backup for the transformer differential protection. On the line side of the transformer we can measure the phase currents.[4]&[5]

9.4 Protection of the filters and the reactive support

On the bus supporting each pole of the converter, harmonic filters and shunt capacitors for reactive support are installed. The use of the harmonic filters is for the 11th and 13th harmonics. Using also the reactive support for the reactive power which absorbed by the converter station in proportional to the active power load on the pole, so that a large capacitor banks are used for the reactive support. The filters are largely capacitive in
nature at the power system fundamental frequency and supply about half of the needed reactive support. Over voltage protection can be used for both harmonics filters and shunt banks, so, both shunt devices can use the same protection. The fundamental and harmonic currents are measured in the filter branches by using the inverse-time over current protection. [5]

9.5 DC side protection

DC side protection includes equipments at the bipole, pole, and converter levels. That mean there are many different equipments, and so, many different failure cases which required detection and protective action, which can block the pole or the bipole, depending on the nature of the disturbances. Because the protection is an integral part of the control system, the control system itself must be redundant to guard against the failure of the controller. Can be accomplished, by means of providing two identical controllers which require both controllers agree that a given control action is required. We can have this result by designing one of the controller as active controller and the other as backup. For security matter, some disturbances are predefined that require conformation by the two controllers before ordering any protection action. The procedure will be as the following:

The active controlled will monitor the usual control quantities, and having a defined situation that requires protective action but does not require fast tripping action, and the control will be transferred to the redundant controller.

The redundant controller will takes the required action based on its independent measurement of the system. This procedure will prevent the error or the failure in the first controller from creating a false trip, or failing to trip in a fault condition. To have more secure method, three controllers can be used. It is common to require redundant controllers at the bipole, but it is not necessary at the pole level. Dc side protections for the redundant control system are divided into two or more protection blocks, with block having its own power supply. The blocks parentally independent with a minimum of equipment in a common. And any fault does need fast tripping will be transferred to the redundant control system.[5]
9.6 Valve protection

In modern converter designs, the converter valves are solid-state thyristor valves. The thyristor valves are considered to be the heart of the converter system, which have physical limits that must not be exceeded, otherwise the valve will be damaged and has to be avoided.

9.6.1 The protection of the valve short circuit

The protection zone for valve short circuit is the twelve-pulse bridge circuit, which begin from the wall bushings on the ac side to the DC wall bushings at the neutral bus and at the smoothing reactor terminal. Each pole can be provided by the same protections. Blocking the converter valves and tripping the ac side circuit breakers are used to clear the short circuit event. Differential current protection is the method used for the detection, which is a form of comparing the amplitude of the currents of both sides at AC wall bushings and DC wall bushings. Based on the differential current protection type, under normal operation condition the magnitudes of the currents in both AC and DC sides are equals, a short circuit will cause unbalance in the system, which results in excess a current in ac side which flows in the operating coil of the relay, this will results in the tripping on the AC side circuit breaker. The short circuit will cause phase-to-phase fault. The maximum fault currents are occur on the rectifier sides.[5]

Other benefit of using the differential protection method:

The protection system should not operate for AC ground faults between the converter transformer and the valve bridge, to ensure that we use the differential protection method, which compare the maximum AC current with the DC current at both high voltage and low voltage sides of the converter pole, this results in avoid the protection operation for the ground faults on the AC conductors in the converter. But the protection will operate to block the faulted pole and will tip the AC circuit breaker at the AC supply bus.[4]&[5]

The protection operation must meet the following conditions
\[ I_{ac} > [0.5 + 0.2(I_d/I_{dn})] * I_{dn} \]  

\( I_{ac} \) = current on the ac side of the pole 
\( I_d \) = dc current at the dc high voltage line bushing 
\( I_{dn} \) = dc current at the dc neutral bushing

### 9.6.2 Converter protection against overcurrents

The converter overcurrent protection zone is mainly in the twelve pulse bridge of each pole to detect the overcurrents which can cause a stress in the thyristor valves of the converter.

![Fig. (25) overcurrent protection in the pole](image)

Overcurrent protection in the converter can be operated as follow:

At first, detecting the DC overcurrents and gives a transfer trip after a preset delay, or in the case of high overcurrents, an instantaneous trip. If the overcurrents are high, then will be an instantaneous trip.

Secondary, the thermal overload protection, which is provided by a computer model of the valve heating and cooling.
The valve losses can be determined as follow:

\[ P_{th} = K_1 I_d * I_d + K_2 I_d \]  \hspace{1cm} (11)

After determined the losses, the result will transfer to the network representing the thyristor cooling properties. Depending on the results of the losses determination, the thyristor temperature rise will be detected, and will be added to the cooling water temperature. The resulted temperature value will be compared to the temperature threshold value, if the resulted temperature value exceed the threshold temperature, then the overcurrent protection will act as follow:

1) Transfer converter control
2) A trip order to the AC circuit breakers.
3) Block the pole and simultaneous fire bypass pair.
4) Isolate the pole and the line at both ends
5) Out of range alarm for cooling water temperature.[5]

### 9.7 The Commutation Failure Protection

Commutation failure is identified as the inability to transfer the current to the valve next in the line to conduct. so there is need to maintain the extinction angle which can be determined from the following relation:

\[ \gamma = 180 - \alpha - u \]  \hspace{1cm} (12)

The reasons for commutation failure are the low voltage or a distortion in the voltage waveform or an increase in the current or all of these factors which will result in increasing in the overlap angle \( u \) which result in \( \gamma < \gamma_{\text{min}} \), this will lead to raise to The commutation failures. The commutation failures are temporary and cause no damage to the equipments. In the case of repeating the commutation failure, this will require temporary or permanent pole blocking. The commutation Failures will not be considered as a fault, but it is considered as indicator of the failure of the valve control pulses, or a fault but in the AC side. The commutation failures protection zone is the twelve-pulse bridge and classified into two types, single commutation failure and double
commutation failure which is more severe than the single commutation failure.[5][2]

The commutation failure protection is based on the following:

Instantaneous advancing of the firing angle in the converter under its failure case to improve recovery.

- The transferring to the redundant control system.
- Blocking and simultaneous by pass of the faulty converter for the slow part of the protection and tripping of the ac breakers feeding the converter.
- Blocking of the converter when the commutation failure is detected in only one of the six pulse group.[5]

The commutation failures protection must be organized with other three system protections, they are:

1) DC harmonic protection.
2) Valve misfire protection.
3) AC protection, where the delays must coordinate with the longest clearing time for ac side fault.

Note that, backup protection is provided by valve misfire protection and DC harmonic protection.

9.8 Missfire and Arc Through valve protection:

Arc Trough is caused by the presence of an unwanted gate pulse, misfire occurs when the required gate pulse is missing and the incoming valve is unable to fire. In modern valve stations the occurrence of the missfire is limited because the duplication converter control, the monitoring and the protection firing of the valves, the protection zone is the thyristor valve. The basic of the valve misfire protection is:

Detecting the valve failure and conduct when a control pulse is applied.
To prevent the valve that fails to conduct from being selected into a bypass pair.
To select into a bypass pair a valve that is firing unintentionally.
To detect unintentional valve firing.
Supervising the system operation.[2]&[5]

9.8.1 Overvoltage protection in the converter station

Overvoltage in the converter station is caused by

1) Disturbances in the AC side.
2) Disturbances in the DC side.
3) Internal fault in the converter.

This kind of protection includes both of the thyristor valves and the converter transformer, in other words, the protection zone for the voltage stress protection it is all the equipment which located in face to the AC side.

9.8.2 DC Surge Arrestor

With the development of metal oxide resistors with high nonlinearity, the present DC arrestors are gabless arrestors, the metal oxide elements were first applied in AC system in 1976 comprising primarily of zinc oxide and containing a number of other metal oxides such as Bi2o3, Sb2o3, Mno2, Cr2o3, as additives elements. these materials has extremly nonlinear voltage-current characteristics, a typical disc that conducts less than a milliamper of current at normal operating voltage can carry currents of thousands of ampers at twice the normal voltage, this property makes it possible to eliminate series connected spark gaps and treduce the voltage margins the cinstancy of protective levels. the figure below shows a typical arrangement of surge arresters in a converter station for a pole, the system with 12-pulse converters per pole, there are about 40 arresters per pole.[2]
Fig. (26) Typical arrangement of surge arrestors for a converter pole.[2]

9.8.3 DC harmonics protection

The converter is the concerned area for this type of protection. DC harmonics protection is passed on the detection of the abnormal harmonics in the converter current. The abnormal harmonics can be caused by:
1) Valve disturbances.
2) AC network disturbances.
3) Control equipment malfunction.

10. The application of control and protection in HVDC system

10.1 Fenno-Skan DC link

The Finnish and Swedish power transmission networks are part of the Nordic Nordial joint operation grid. The generation and consumption of the electricity in Finland and
Sweden are concentrated in the southern parts of both countries, while the hydro-
power generation of the electricity is concentrated in the north, because of the AC
interconnections transmission between Finland and Sweden in the north, so the
transmission distances in power exchange between the two countries are long and by
interconnecting the two grids by HVDC link in the south, the capacity for power
transmission between the two countries is significantly increased. HVDC link will also
allow the power flow between Finland and Sweden to be redistributed which results in
reducing the losses in the nordic grid.[21]

10.2 Monopolar Configuration (Fenno-Skan)

Fenno-Skan monopolar DC link is the world’s first 400 KV, 500 MW HVDC
submarine link, the sea is used as the current return bath, where we can not use the
ground because of the corrosion problems, the cathode is located at finland side and the
anode is located at Sweden side to allow the magnetic field caused by the monopolar
link to reinforce the natural magnetic field of the earth thereby minimizing the magnetic
disturbances caused by the link. A loop of 300 mm² copper conductor serves as the
cathode. The size of the loop connected to the electrode line with two 630mm² plastic-
insulated copper cables. Wire netting of titanium serves as sea cathode. The link is
designed for the future extension to form with a second cable a bipolar arrangement
(Fenno-Skan 2). Fenno-skan DC link designed by Imatra Voima oy and Swedish State
Power Board.[13][20]
The stability of the electric power system is the tendency of the power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium. Stability is divided into two main categories

a) Steady-state stability.

Steady-state stability refers to the ability of the power system to regain the synchronism after small disturbances, an extension of steady state stability is known as dynamic stability which concerned with small disturbances lasting for long time with the inclusion of automatic control devices.

b) Transient stability

Deal with the effect of large and sudden disturbances, such as occurrence of fault, the sudden outage of a line or sudden add or remove loads.
HVDC System provided with suitable auxiliary controllers is an important tool to balance the power flow and maintain stability if one of the AC tie lines trips. It is preferred to use Fenno-Skan DC link in parallel (synchronous link) with the two ± 400 KV AC ties, through the Finnish power transmission and Swedish power transmission networks, to damp the low frequency interarea oscillations in the AC tie, the rate of change of the AC tie link power (or current) or even the phase angle difference across the AC tie can be used as control signal. Fenno-Skan DC link can also provide the frequency control for one of the ends of the AC tie if the AC tie becomes disconnected, thus DC link can provide resynchronization of the AC tie. The ideal control signal should have only the components of mode of oscillation to be damped, sometimes there are extra components that should be eliminated by suitable filters design such as bandwidth or notch filters.[2]

Fig. 28 DC link in parallel with AC links [14]

### 10.4 principles control of Fenno-Skan DC link

The control of power in Fenno-Skan DC link is achieved by controlling the current while maintaining a constant voltage as preferred strategy for minimizing the losses in the link and its useful for voltage regulating in the system from optimal utilization of the suitable insulation point of view, the losses can be evaluated from the relation (P_loss = \( I_d R_d^2 \)). The figure below illustrate the equivalent circuit of the modelling of the fenno-skan DC link, the modelling has been based on the assumption that Fenno-skan DC link is in the steady-state and all the series connected bridges in both poles of a converter station are identical to ensure the same delay angles, also the number of series
connected bridges (nb) in both stations rectifier and inverter in both terminals are the same. [2]

Fig. (29, a) steady state equivalent circuit of two terminal DC link

Fig. (29, b) Schematic of a DC link showing the transformers ratio

$E_{dr} = (\frac{3\sqrt{2}}{\pi}) \cdot nb \cdot E_{vr} \cos \alpha_r$  \hspace{1cm} (13)  
$E_{di} = (\frac{3\sqrt{2}}{\pi}) \cdot nb \cdot E_{vi} \cos \gamma_i$  \hspace{1cm} (14)

where $E_{dr}$ and $E_{di}$ are the voltage sources of both rectifier and inverter respectively.

$E_{vr} = N_{sr} \cdot E_r / N_{pr} \cdot T_r$  \hspace{1cm} (15)
$E_{vi} = N_{si} \cdot E_i / N_{pi} \cdot T_i$  \hspace{1cm} (16)

$E_{vr}$ and $E_{vi}$ are the AC line to line voltages in the valve side windings of the rectifier and inverter transformer respectively. $N_{pr}$ and $N_{pi}$ are the converter transformers ratio in both rectifier and inverter sides. $T_r$ and $T_i$ are the off-nominal tap ratios on the rectifier and inverter sides. By combining the last three equations $E_{dr}$ $E_{di}$ can be redetermined as

$E = (A_r \cdot E_r / T_r) \cdot \cos \alpha_r$  \hspace{1cm} (17)
$E = (A_i \cdot E_i / T_i) \cdot \cos \gamma_i$  \hspace{1cm} (18)
Ar and Ai are constant \( \alpha_r \) is the delay angle on the rectifier side and \( \gamma_i \) is the constant extinction angle on the inverter side. The steady-state current \( I_d \) in the DC link is obtained as

\[
I_d = \left( \frac{A_r E_r}{T_r} \cos \alpha_r - \frac{A_i E_i}{T_i} \cos \gamma_i \right) \div \left( R_{cr} + R_d - R_{ci} \right) \]

where \( R_{cr} \) is the rectifier resistance and can be calculated as

\[
R_{cr} = \left( \frac{3nb}{\pi} \right) x_{cr} \]

\( x_{cr} \) is the leakage reactance of the rectifier transformer in the rectifier.

\( R_{ci} \) is the inverter resistance which can be calculated as

\[
R_{ci} = \left( \frac{3nb}{\pi} \right) x_{ci} \]

\( x_{ci} \) is the leakage reactance of the inverter transformer.

where r and i are subscripts refer to the rectifier and the inverter respectively.

10.4.1 Power control in Fenno-Skan DC link

It is important to select the suitable control signal locally from economical and reliability considerations, there are several of thoses local control signals, the power or current control signal has been selected as the most suitable control signal for power modulation in Fenno-Skan DC link which is a parallel tie with the two AC networks for damping the oscillation and the stablization of the AC ties (The Finnish and Swedish power transmission networks). The figure below (30,a) shows a block diigram which represent the power and auxiliary power controller at any converter station in which consisting of several inputs such as a power control, auxiliary control, and (VDCOL) voltage dependent current order limiter and the output is the desired current order.
We can also notice from the block diagram that includes a direct voltage divider V\textsubscript{d}, its object to divide the power order Pref. The voltage dependent current order limiter (VDCOL) has been used to limit the current order I\textsubscript{ref} to prevent the individual thyristors from carrying full current for long periods during commutation failures. By providing both converter stations with dividing circuits and transmitting the power order from the leading station (which either rectifier or inverter) where the power order is set to the trial station, the faster response to the DC line voltages is obtained without undue communication requirements. The master controller which located at one of the stations (rectifier or inverter) sends a current order I\textsubscript{order} to the pole controls of the two ends of the link which are the rectifier and the inverter stations, as illustrated in the figure (30,b) below.
The power is monitored by multiplying the voltage and the current which collected from both poles. The lower limit of the power range is determined by the direct current discontinuity, the power control range of Fenno-Skan is 0.05-1.0 pu. In the second stage of overall control structure of Fenno-Skan DC link, the pole control units will provide firing angles order ($\alpha_r$ & $\alpha_i$) at both stations because of the constant current CC and constant extinction angle CEA controllers at the rectifier and inverter respectively, while the input for the two controllers is the current order which generated locally or at the remote station, the output of these controllers is a control voltage $V_c$ which is related to the firing angle ($\alpha$) controller required for determining the instant of the gate pulse generation, the control voltage $V_c$ is the output of the selector (or limiter) unit in which its object is to pick up the smaller of ($\alpha$) provided by the current constant CC and CEA controllers, In the third stage of overall control structure of Fenno-Skan link the gate pulse generator which has input from CC and CEA controllers and determines the instant of gate pulse generation which required for the individuale valve group, the valve group overseas valve monitoring and firing logic through optical interface. There are two types of firing control schemes.
1) Individual phase control (IPC)
2) Equidistant pulse control (EPC)
The latter one can of pulse frequency control (PFC) or pulse phase control (PPC)
From the typical controller block diagram which does not give all the details it is important introduce and define some units to follow the control steps.
S1 is a switch at the inverter station, is closed in case of Equidistant pulse control (EPC)
S2 is a switch at the rectifier station, is closed in case the synchronous circuit is provided
\( \Delta \delta_v \) is the change in the phase of converter bus voltage and the transfer function of the synchronous circuit, which is determined as
\[
\text{SYN}(s) = \frac{1}{1 + sT_{ss}}, \text{ where } T_{ss} = \frac{1}{2\pi Bw} 
\]
(23)
\( T_{ss} \) is the time delay at steady state case
\( Bw \) is the bandwidth of the synchronous circuit in hertz, if the band width increased the characteristics of (EPC) will tend to individual phase control (IPC)
\( T_d \) is the time delay which is introduced if continuous time model of the converter is used
\[
T_d = \frac{1}{2p f_0} 
\]
(24)
where \( p \) is the pulse number and \( f_0 = \frac{W_0}{2\pi} \)
(25)
\( f_0 \) is the nominal frequency and \( W_0 \) is the synchronous speed
The rectifier and inverter controller scheme block diagram includes two limiters at each station, the limiter is treated as a separate block with the input variable unrestricted while the output is limited within specified range.[2]&[14]

10.5 Additional Control Modes

10.5.1 Power Emergency Control (EPC)

In case of AC tie link where the control activated based on the criteria obtained from the AC networks, if one of the interconnected systems experience disturbances, the line will trip to avoid the disturbances affecting the other line. In case of the DC tie link even with simple control, shields one system from disturbances on the other, Although the specified power flow can continue, the option is available to vary the power setting
to assist the system in difficulty to extent which the healthy system can allow, without being itself in difficulty and subject to the rating on the link. With suitable control the disturbances in either system can be shared by the predetermined parameters and the oscillation occurring in the two systems can be damped simultaneously, a very small amount of DC power modulation can be used to achieve the necessary damping. In case of the DC link operated at full capacity or close, a large degree of modulation can be needed for the necessary damping by reduction of DC power at the appropriate instants. In Fenno-Skan monopolar DC link the EPC will be activated automatically with a maximum ramp of 990 MW/s. Fig.31 illustrate the emergency power control in Fenno-Skan DC link.[2][14][18]

When large systems are connected by long relatively weak interties this will result in low frequency swing modes. The factors which responsible for the low frequency swing modes are:
1) high gain automatic voltage regulators (AVR)  
2) fast exciters  

DC links in the system can provide with auxiliary controllers to modulate the power flow in the link which in turn helps the system to be stable. The power system controls can respond to synchronising swings associated with the low frequency modes and produce sufficient negative damping to cancel the natural positive damping of the system which lead to occurring of oscillation of increasing amplitude. The power modulation can be classified as small signal modulation and large signal modulation which depends on the level of power changes ordered by the modulation controllers.\[2\] & [12]

10.5.2 Reactive Power Control

The reactive power change in the load has the most effect on the voltage regulation, since the internal impedance of the AC system is mainly inductive, as result of the transmission distribution lines, transformers and generators, a great amount of the reactive power required by the converters in the rectifier and in the inverter mode is provided by the filters. Because of the converter station is line commutated, so that the initiation current in the valve will be delayed with reference to the zero crossing of the converter bus AC voltage, which will lead to the lagging of the power factor of the converter operation, then reactive power sources are required which have to be connected at both rectifier and inverter sides for better voltage control.\[2\]

10.5.2.1 Reactive power drawn by the rectifier

As we assume latently, \( L_s = 0 \), as illustrated in figure 6, which show the phase-to-neutral-voltage \( V_{as1n1} \) and the current \( i_{as1} \) which corresponding to converter 1, and \( i_d(t) \approx i_d \) at a delay angle \( \alpha \), we can notice that the fundamental frequency current component (\( i_{as1} \)) is drawn as a dotted curve lags behind the phase voltage \( V_{as1n1} \) by the displacement power factor angle \( \phi_1 \) where
\[ \phi_1 = \alpha \] \hspace{1cm} (26)

The three-phase reactive power for the 6-pulse converter can be calculated as;
\[ Q_1 = \sqrt{3} V_{LL} \times (I_{as1})_1 \sin \alpha \] \hspace{1cm} (27)

Where, \( I_{as1} \) is the fundamental frequency current component which lags its respective phase voltage by 90°.
\( V_{LL} \) is the line-to-line rms voltage applied to each 6-pulse converter on the AC-side.
\( \alpha \) is the delay angle, which equals the displacement power factor angle \( \phi_1 \).
Through the Fourier analysis of the \( i_{as1} \), rms value of its fundamental frequency component calculate by
\[ (I_{as1})_1 = \sqrt{6/\pi} \times I_d \cong 0.78 \times I_d \] \hspace{1cm} (28)

The value of reactive power \( Q_1 \) is calculated by substituting equation (27) into equation (28).
\[ Q_1 = \sqrt{3} V_{LL} (\sqrt{6/\pi} \times I_d ) \sin \alpha = 1.35 V_{LL} \times I_d \sin \alpha \] \hspace{1cm} (29)

With \( L_s = 0 \), the real power transfer for each 6-pulse converter can be calculated as:
\[ P_{d1} = V_{d1} I_{d1} = 1.35 V_{LL} \times I_d \cos \alpha \] \hspace{1cm} (30)

A small delay angle \( \alpha \) is desired

A delay angle \( \alpha \) has a great role to produce a high quality of power transfer \( P_{d1} \), and to reduce the losses through the DC transmission line. As result of the minimizing the reactive power \( Q_1 \), And \( I_d \) respectively. To minimize \( I_d \) and \( Q_1 \), the delay angle \( \alpha \) should be kept small as possible, practically \( \alpha \) must be chosen in the range of 10° to 20° [3] & [11]
10.5.2.2 Reactive power drawn by the inverter

In the inverter mode of operation the DC voltage is defined to positive as illustrated in figure (13)

and the extinction angle $\gamma$ for the inverter is written as

$$\gamma = 180-(\alpha + u)$$  \hspace{1cm} (31)

Where $\alpha$ is the delay angle and $u$ is the commutation or the overlap angle. The inverter voltages can be calculated as

$$V_{d1} = V_{d2} = V_d/2 \cdot 1.35 \cdot V_{LL} \cos \gamma - 3\omega L_d/\pi* I_d$$  \hspace{1cm} (32)

Using the assumption $L_s = 0$ for simplicity, we can see through the figure (14) that the waveforms of the voltage $V_{as1n1}$ and the current $i_{as1}$ at an angle $\alpha > 90$ in the inverter mode of operation, we notice the fundamental frequency component $(i_{as1})_1$ of the phase current is a dotted curve.

![Waveforms of the phase to neutral voltage and fundamental frequency current.](image)

The figure 32 shows that the fundamental frequency reactive current component lags the phase-to-neutral voltage.
which gives the fact that, in the inverter mode of operation where the direction of the power flow has reserved, the converter needs a reactive power, which is “lagging” from the AC-side.

With $L_s = 0$ and $u = 0$

$\gamma = 180^\circ - \alpha$  .................................................................(33)

According on the inverter mode of operation and in terms of $\gamma$, the reactive power and the power transfer can be calculated respectively as:

$Q_1 = 1.35 V_{LL} I_d \sin \gamma$  .................................................................(34)

$P_{d1} = 1.35 V_{LL} I_d \cos \gamma$  .................................................................(35)

small $\gamma$ is desired

It is desirable to make the angle $\gamma$ small as possible, to minimize the losses $I^2R$ in the DC transmission line due to $I_d$, and to minimize the reactive power $Q_1$ to a better quality of the power transfer $P_{d1}$. That minimum value of $\gamma$ which could be obtained to do so, is called the extinction angle $\gamma_{\text{min}}$, which based on allowed sufficient turn-off time to the thyristor. As result of the 12-pulse converter arrangement, the reactive power is the sum of the reactive powers for both 6-pulse converters. The reactive power demand of the converters is provided by both, AC-side filter banks and the power factor correction capacitors. [3]

Converter stations required reactive power supply dependent on the active power loading it is about (50 to 60)% of all the active power in the DC link. This can provided
by in addition to the AC filter there are several compensators such as synchronous condensers, shunt capacitors banks, static var system, these means can be used depending on the speed of the control desired. Link during a light load, extra reactive power can be taken from the network to the converter.

10.5.3 Frequency Control

When a DC link is used as a tie between two power systems a frequency feedback loop will act on the DC link control to adjust the power flow over the tie and sustain the system. Providing the frequency control, frequency control can be used in either two cases.

(a) Isolating an load.
(b) Isolating an generator.

The control signal applied to the current controller is a power as long as the frequency remain within the predetermined limits, once interrupted and faces difficulties the frequency control will sustain the system. when the system operate at its maximum transmission power frequency controller will stop acting.[2][12]

Special Control modes in Fenno-Skan link provide the following advantages:

1) Greater power transmission capacity from Finland to Sweden on the interconnection in the north due to increased damping of electromechanical oscillations.
2) Positive damping contribution for subsynchronous oscillations at selected frequencies.
3) A higher transient stability limit for power transmission from Sweden to Finland on the northern interconnections and improved network reliability.
4) Increased power transmission capacity for network sections in the Swedish grid, where the voltage collapse is a limiting factor. [18 ]
10.6 Protection of Fenno-Skan DC link

A typical protection of the DC transmissions has made for the components of monopolar HVDC link, the faults in monopolar DC link could caused by malfunctioning of the equipments and controllers in addition to the failures caused by the external sources such as lighting, pollution, etc, then the fault must be detected and the system has to be protected by switching and control action such that the disturbance in the power transmission is minimized, there is a faults could occure and stress the Fenno-Skan DC link equipments and disturb its normal operation which are caused due to the overcurrents and overvoltages.

10.6.1 Protection in the AC side of Fenno-Skan DC link

Typical AC side protection is used for Fenno-Skan DC link which include AC line protection, AC bus protection, converter transformer protection and the protection of AC filters and shunt capacitors.

10.6.1.1 Converter transformer protections

The converter transformers of Fenno-Skann monopolar link are of the single-phase, three winding type. Three units of 194.6 MVA are required, the weight of each one unit is 311 tones, including the oil, A typical conveter transformer protection is applied.[19]

10.6.1.2 AC filters and shunt capacitors protections

Fenno-Skann monopolar DC link converters introduce both AC and DC harmonics which are injected into the AC and DC line respectively causing a lot of problems such as, extra power losses resulting from the heating in the machines and capacitors connected in the system, instability of converter control primarily with individual phase
control (IPC) scheme of firing pulse generation and overvoltages due to resonance. On the Fenno-Skan DC link AC side two AC filters each 80 Mvar and one shunt capacitor 80 Mvar too, to filter out the AC current harmonics and to supply the reactive power. They are provided with breakers, in addition to a power line carrier (PLC) filter which is located between the converter transformers and the AC filters to prevent carrier frequency disturbance to the AC network. The two AC filters, each one has double-tuned branches, tuned to the 11/13 and 24/36 harmonic the latter branch is of high pass type. One of the main function of the two filters and the capacitor bank is the compensation of the reactive power which is consumed by the HVDC link, so a large capacitive banks are usually required for reactive support. The filters are largely capacitive in nature at the power system fundamental frequency and may supply about half of the needed reactive power. At full active power there is no reactive power unbalance between the link and the 400 KV network. In Fenno-Skan DC link, overvoltage protection has been used for protection of both filter banks and the harmonic filters, which requires a voltage measurements on the converter bus and an overvoltage relay, the capacitor banks have a voltage distribution that is dependent on the number and location of failed individual capacitor units which is detected and an alarm signal generated to warn of serious unbalances in the structure.[5]&[19]

10.6.2 Protection of the DC side of Fenno-Skan DC link

The DC side protection include the thyristor valves in the valves hall in addition to the outdoor DC switchyard which includes two smoothing reactors $L_s$, 225 mH and 112,5 mH and one DC filter, a typical protection is required to remove the short-circuit on the DC line by driving the rectifier momentarily to AC range (the supply of the fault is switched-off).[14]&[19]

10.6.2.1 Thyristor valve protection

The thyristor valves in Fenno-Skan DC link are air-insulated and water-cooled. The water-cooled system transfers the heat from the valves to coolers, which are outside the
valve hall. A single valve consists of eleven thyristor modules, a thyristor module includes six thyristors, one valve consists of 66 series-connected thyristors. So the 12-pulse converter bridges include 792 thyristors altogether for one pole. A typical thyristor valves protection has been made for Fenno-Skan DC link. The thyristor valves protection in Fenno-Skan is provided by microprocessor control, the firing information transmitted to the thyristors valve through a light guide in order to avoid electromagnetic disturbances, the first target of the valves protection is to remove the short-circuit which occurred on the valves where the protection zone for the valves short circuit is the 12-pulse bridge from the wall bushings on the AC side to the wall bushings at the neutral bus and at the smoothing reactors terminals, similar protection is provided for each pole, the short circuit are cleared by blocking the converter and tripping the AC side breakers, the rest of the protection targets for the thyristor valves still under consideration as mentioned earlier in the protection section. [14] & [18]
10.6.2.2  **DC Filter protection**

The protection zone of the DC filter is the filter itself and the objective is to detect the overload on the DC filter components and to relieve the filter from being overstressed by blocking the pole, also interlocks the operation of the DC filter switches if the filter current becomes too high. The detection principles of the DC filter in Fenno-Skan DC link is based on the measuring of the current through the filter bank and compare this magnitude against a preset reference.
11. The conclusion

HVDC is electricity has taken from AC power network and converted at a converter station acting as rectifier located at the sending point, to DC power and transmitted to the other converter station which act as inverter located at the receiving point, using a cable in case of a distance between the two converter stations, where to be converted back to AC power. The benefits of using HVDC technology to interconnect between two HVAC systems are its ability to transmit more power through distances and geological barriers, using fewer and economical towers, lowering both environmental impacts and investment costs than the traditional HVAC systems in addition to its rapid controllability, accurately and its improving the performance and the efficiency of the connected networks.
References


[20] www.fingrid.fi Fenno-Skan DC link