POWER FLOW STUDIES OF AN HVDC TRANSMISSION SYSTEM

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Abstract: High Voltage Direct Current (HVDC) technology has characteristics that make it especially attractive for certain transmission applications. The same includes long-distance bulk power delivery, asynchronous interconnections, long submarine cable crossings and fast power controllability. Then, the HVDC transmission has proved its potential to be an interesting alternative or complement to the AC transmission. The thesis presents Newton - Raphson method for the load flow analysis modified to achieve compatibility for AC - DC systems with the integrated DC link in the AC network. The elements of the Jacobian for the AC network are modified to include DC real and reactive power at the AC - DC buses, and their dependency on the a.c system variables. The DC equations such as voltage expressions at rectifier and inverter, network configuration equation i.e., point-to-point, multi terminal series connection or multi terminal radial connection, real and reactive power demands at converters are represented in a per unit form which will be compatible with per unit a.c equations. For various control strategies, simulations are carried out for point-to-point DC link and multi terminal DC links. Simulations are also carried out for optimization of total power generation cost with the help of GAMS (General Algebraic Modeling System) and MATLAB for point-to-point and multi terminal HVDC transmission system. All equality and inequality constraints are considered in this optimization so that the entire power system can remain intact during the real-time operation.

1. INTRODUCTION

Alternating current (AC) is widely used in industries and residential areas, but for the long transmission line (more than 600 Km) AC transmission is more expensive than direct current (DC). Technically, AC transmission line control is more complicated because of the frequency and dependency of power transfer on angle difference between the voltage phasors at the two ends. DC transmission does not have these limitations, which has led to build long High Voltage Direct Current (HVDC) transmission lines [1], [2]. HVDC technology is a high power electronics technology used in electric power systems to transfer bulk power over long distances. The DC transmission requires conversion at two ends, from AC to DC at the sending end and DC to AC at the receiving end. This conversion is done at converter stations. By simple control action, converter can be switched from rectifier to inverter and vice-versa. Thus facilitating power reversal. The invention of the high voltage mercury valve shown the way towards the development of HVDC transmission. By 1954, the first commercial HVDC connecting two AC systems came in to operation in form of submarine cable link between the Swedish mainland and the island of Gotland [2]. Nowadays, the HVDC is being widely used all around the world. Until recently, HVDC based on thyristors uses the Current Source Converter (CSC) configuration. Now, a new type of HVDC transmission using more advanced 1 semiconductor technology instead of thyristors is available for power conversion. The semiconductors used are Insulated Gate Bipolar Transistors (IGBTs) and the converters are voltage source converters (VSCs) which operate with high switching frequencies (1-2kHz) utilizing pulse width modulation (PWM). The technology is commercially available as HVDC Light or HVDCPLUS. Currently, the demand for both massive renewable energy integration and passive network power supply is steadily rising. In addition, global energy interconnection has become increasingly popular. As an important solution, high voltage direct current (HVDC) transmission systems can provide favorable access to distributed renewable energy and passive networks. It can also easily achieve asynchronous grid interconnection. Hence, the requirements for HVDC transmission systems are increasing, prompting the need for multi-terminal HVDC (MTDC) transmission systems whose main task is to design corresponding control strategies for power distribution according to the requirements of each terminal. Thus, in recent years, an increasing number of studies have researched the control strategies of these systems, such as master-slave control, DC voltage droop control, etc. However, due to the topological complexity of HVDC transmission systems and the different requirements for AC systems at each terminal, the control strategies are more complex and diverse therefore, further research is required. The line requirements of the HVDC transmission system are likewise experiencing ongoing development. Because of this, the transmission power of each line is required to have independent controllability. Each DC line of a true bipolar DC transmission system can operate independently, as opposed to the conventional pseudo bipolar DC transmission system. In addition, the AC-DC converter has a more flexible control strategy. Due to the applications of bipolar and monopolar DC transmission systems, it is necessary to consider hybrid DC transmission systems in future development directions

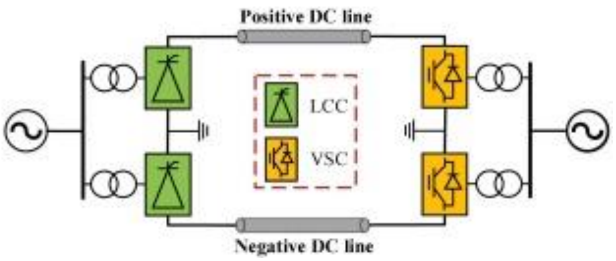


Figure: Schematic diagram of overall system with Hybrid HVDC system

COMPARISON BETWEEN HVAC AND HVDC

More power can be transmitted per conductor per circuit.

The capabilities of power transmission of an ac link and a dc link are different. For the same insulation, the direct voltage V_d is equal to the peak value (√2 x rms value) of the alternating voltage V_d.

$$V_d = \sqrt{2}\, V_a$$

For the same conductor size, the same current can transmitted with both dc and ac if skin effect is not considered.

$$I_d = I_a$$

Thus the corresponding power transmission using 2 conductors with dc and ac are as follows.

dc power per conductor $P_d = V_d I_d$

ac power per conductor $P_a = V_a I_a \cos\phi$

The greater power transmission with dc over ac is given by the ratio of powers.

$$\frac{Pd}{Pa} = \frac{\sqrt{2}}{cos\emptyset}$$

In practice, ac transmission is carried out using either single circuit or double circuit 3 phase transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by **2/3** or by **4/3**.

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission. Thus for the same power transmitted P, same losses P_L and same peak voltage V, we can determine the reduction of conductor cross-section Ad over Aa.

Let Rd and Ra be the corresponding values of conductor resistance for dc and ac respectively, neglecting skin resistance.

For dc current= $\frac{P}{\text{Vm}}$

Power loss P_L: $(P/Vm)^2\, R4 = (P/Vm)^2 . (\rho l/Ad)$

For ac current= $\frac{P}{(\frac{Vm}{\sqrt[2]{2}})\, cos\,\emptyset} == \frac{\sqrt[2]{2}\,P}{Vm\ cos\,\emptyset}$

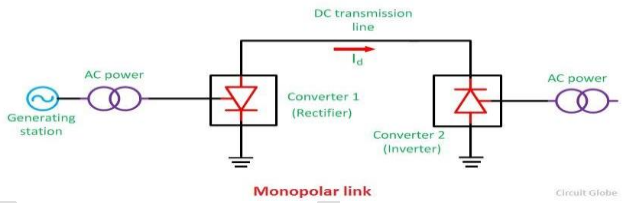
Power loss $P_L = 2(P/Vm)^2 . (\rho l/Aa\,(\cos\emptyset)^2$

The result has been calculated at unity power factor and at 0.8 lag to illustrate the effect of power factor on the ratio. It is seen that only one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag.

HVDC Transmission System

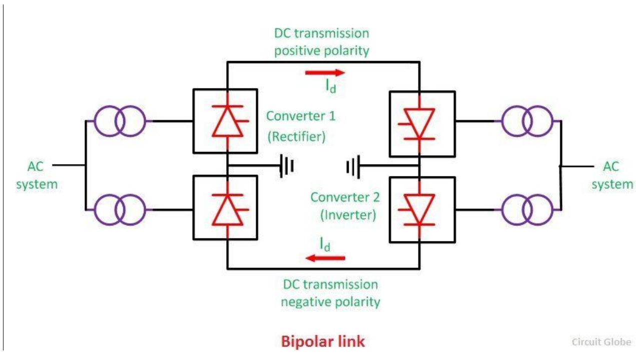
Monopolar HVDC system

In the monopolar configuration, two converters are connected by a single pole line and a positive or a negative DC voltage is used. In Fig. 2.1, there is only one insulated transmission conductor installed and the ground or sea provides the path for the return current. Alternatively, a metallic return conductor may be used as the return path where possible interference with underground/ underwater is objectionable.



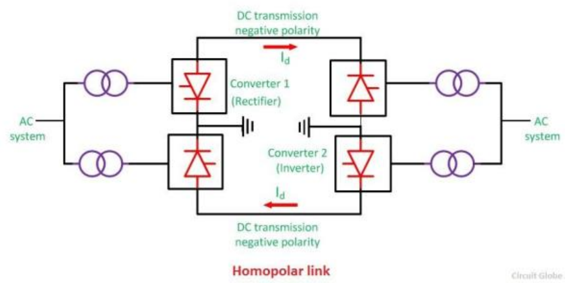
Bipolar HVDC system

This is the most commonly used configuration of HVDC transmission systems. The bipolar configuration is shown in Fig. 2.2. It uses two insulated conductors as positive and negative poles. The two poles can be operated independently if both neutrals are grounded. The bipolar configuration increases the power transfer capacity. Under normal operation, the currents flowing in both poles are identical and there is no ground current. In case of failure of one pole, power transmission can continue in the other pole which increases the reliability.



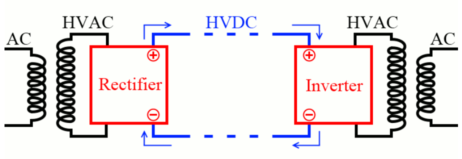
Homopolar HVDC system

In the homopolar configuration, Here, two or more conductors have the negative polarity can be operated with ground or a metallic return. With two poles operated in parallel, the homopolar configuration reduces the insulation costs. However, the large earth return current is the major disadvantage.



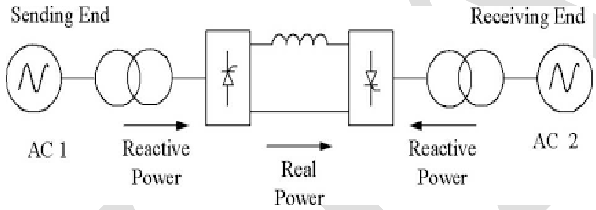
Back-to-back HVDC system

This is the common configuration for connecting two adjacent asynchronous AC systems. Two converter stations are located at the same site and transmission line or cable is not needed.. The two AC systems interconnected may have the same or different nominal frequencies.



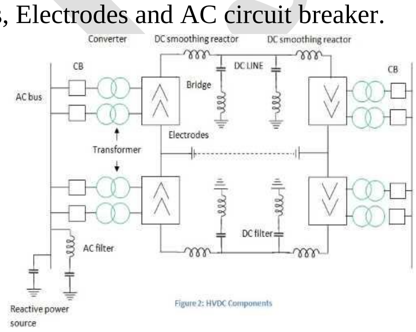
Multiterminal HVDC system

In the multiterminal configuration, three or more HVDC converter stations which are geographically separated are interconnected through transmission lines or cables. The system can be either parallel, where all converter stations are connected to the same 8 voltage as shown in Fig. 2.5. or series multiterminal system, where one or more converter stations are connected in series. A hybrid multiterminal system contains a combination of parallel and series connections of converter stations.



Components of HVDC System

A typical HVDC system comprises AC filters, transformers, converters, smoothing reactors, DC capacitors and DC lines/cables, Electrodes and AC circuit breaker.



Converters Perform AC/DC and DC/AC conversion. The valve bridges consists of high voltage valves connected in a 6-pulse or 12-pulse arrangements

Transformers Normally, the converters are connected to the AC system via transformers. The most important function of the transformers is to transform the voltage of the AC system to a level suitable for the converter **Smoothing reactors** These are large reactors having inductance as high as 1.0 H connected in series with each pole of each converter station which serves following purposes: 1) Decrease harmonic voltages and currents in the DC line. 2) Prevent current from being discontinuous at light load. 3) Limit the crest current in the rectifier during short-circuit on the DC line.

AC Filters The AC voltage output contains harmonic components, caused by the switching of the Thyristirs/IGBTs. The harmonics emitted into the AC system have to be limited to prevent them from causing malfunction of AC system equipment or radio and telecommunication disturbances.

Electrodes Most DC lines are designed to use earth as a neutral conductor for some time. The connection to the earth requires a large-surface-area conductor to minimize current densities and surface voltage gradients. This conductor is referred to as an electrode.

AC Circuit Breakers For clearing faults in the transformer and for taking the DC line out of service, circuitbreakers are used on the AC side.

DC Lines These may be overhead lines or cables.

Converter Performance Analysis HVDC converter also known as Graetz bridge. Normally two such six pulse converters, one connected Y-Y and the other Y-Δ transformers are used. This helps in eliminating multiples of sixth harmonics on the dc side which reduces harmonic filters significantly. The following assumptions are made during analysis.

a) All phases of the supply voltage are identical and are displaced by exactly 120o

b) The direct current (Id) is constant and ripple free

c) The transformer leakage reactance is unchanged

d) The valves are ideal switches

HVDC Transmission Advantages

Following are the main advantages of HVDC transmission compared to AC transmission system.

(1) A bipolar HVDC overhead line only requires two conductors with positive and negative polarities, thereby providing simple tower structure, low DC-line investment and less power loss. Compared to a double circuit HVAC line with six conductor bundles, one bipolar HVDC line with two conductor bundles takes much less the width of transmission routine. Under the effect of direct voltage, the capacitance of transmission line is never taken into account. Since capacitive current does not exist, direct voltage maintains the same along the transmission line.

(2) For the AC and DC cables with the same insulation thickness and cross section, the transmission capability for

DC cable is considerably higher than that for AC cable. DC cable lines only require one cable for monopolar link or two cables for bipolar link and AC cable lines need three cables, due to three phase AC transmission. Therefore, the price for DC cable lines is substantially lower than AC cable lines. Since there is no the cable capacitance in a DC cable transmission, the transmission distance for DC cable is unlimited theoretically.

(3) HVDC links can be used to interconnect asynchronous AC systems and the short circuit current level for each AC system interconnected will not increase. The intercon15 nected AC systems can be operated with different nominal frequencies and the exchange power between interconnected AC systems can be controlled rapidly and accurately.

(4) Due to the rapid and controllable features, HVDC systems can be used to improve the performance of AC system, e.g. the stability of frequency and voltage, the power quality and reliability of interconnected AC systems. For the DC/AC hybrid transmission system, the rapid and controllable features of HVDC system can also be used to dampen the power oscillations in AC systems, so as to increase AC lines transmission capacity.

(5) For an HVDC system, earth can be used as the return path with lower resistance, loss and operational cost. For a bipolar link, earth is normally used as a backup conductor. If faults occur on one pole, the bipolar link can be changed into the monopolar link automatically, thereby improving the reliability of HVDC system.

(6) An HVDC transmission system can also be used to link renewable energy sources, such as wind power, when it is located far away from the consumer.

HVDC Transmission Applications The first application for HVDC converters was to provide point-to-point electrical power interconnections between asynchronous AC power networks. There are other applications which can be met by HVDC converter transmission which include **Long Distance and Bulk Capacity Transmission** For the same transmission capacity, above a certain distance, an HVDC transmission offers more economic benefits than HVAC transmission. As the transmission distance increases, the transmission capacity for HVAC line is restricted by stability limitation, thereby necessarily increasing additional investment for short-circuit limitation, voltage support.

Power System Interconnection In order to optimize the resource utilization, several AC systems intend to be interconnected with the development of power industry, but it will give rise to the problems in the super system. For example, the interconnection for AC systems always increases the short-circuit levels, thereby exceeding the capacity of the existing circuit breakers. AC systems can also be interconnected by HVDC transmission and thereby, not only obtains the interconnection benefits but also avoids the serious consequences.

DC Cable Transmission For DC cable, without capacitance current, the transmission capacity is not restricted by transmission distance. Except for the purpose of long distance and bulk capacity, DC cables are also widely used across strait in the world. Due to environmental issue, large capacity power stations are not allowed to build in the vicinity of city. Moreover, it is very difficult to select appropriate the over headline routine, owing to high population and load density. Therefore, using HVDC underground/submarine cables is an attractive solution to deliver power from remote power station to urban load center.

Increasing the capacity of power transmission It is some what difficult for new transmission rights of way. But, if we upgrade the existing overhead AC transmission lines with DC transmission can substantially increase the power transfer capability on the existing right of way.

Lower short circuit fault levels

When an ac transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels. This problem can be overcome with HVDC as it does not contribute current to the ac short circuit beyond its rated current.

Economic Comparison

The HVDC system has a lower line cost per unit length as compared to an equally reliable ac system due to the lesser number of conductors and smaller tower size. However, the dc system needs two expensive convertor stations which may cost around two to three times the corresponding ac transformer stations. Thus HVDC transmission is not generally economical for short distances, unless other factors dictate otherwise. Economic considerations call for a certain minimum transmission distance (break-even distance) before HVDC can be considered competitive purely on cost.

Estimates for the break even distance of overhead lines are around 500 km with a wide variation about this value depending on the magnitude of power transfer and the range of costs of lines and equipment. The break- even distances are reducing with the progress made in the development of converting devices.

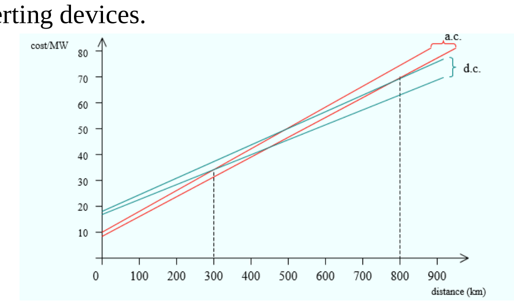


Figure. 1.1 Economic comparison of ac and dc

- **Power Flow Studies**
- Power flow analysis aims at determination of system parameters like voltage, current, power factor and power (real and reactive) flow at various points in the electric system under existing conditions of normal operation. This analysis helps in determining the scope of future expansion of the system. Power flows studies, commonly referred to as load flow, are the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities. In addition, power flow analysis is required for many other analyses such as transient stability and contingency studies
- **Operating principle of HVDC**
- The HVDC operating principle can be explained from the SLD shown in Fig. 2.4.1, where two AC networks are connected by a HVDC transmission system.

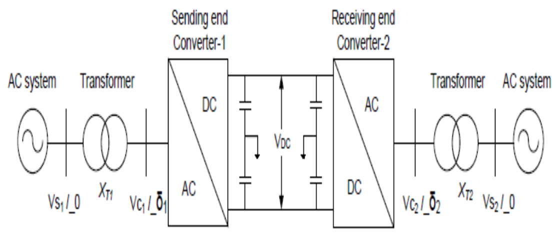


Figure. 2.4.1 Single line diagram for HVDC operating principle

- The converter transformer connecting AC network and converter can be modeled as an equivalent series resistance and reactance. The transformer resistance is very small compared to the transformer reactance so it can be neglected in power calculations. The phase shift between both sides' voltages due to transformer reactance is responsible for active power flow. At sending end, the voltage Vs1 at AC bus is considered as a reference so the converter output AC voltage Vc1 has phase shift δ1 with respect to the bus voltage Vs1. The magnitude and phase angle of converter output AC voltage Vc1 is controlled by the VSC control system. The active and reactive power flow between the AC system and the converter depends on the magnitude of the voltages at both sides of the transformer, the transformer reactance and the phase angle δ1 between them. The active and reactive power flow between AC bus and converter AC terminals can be expressed as follows:
- The active power at sending end and receiving end is given by,

$$P_S = \frac{|Vs_1|\times|Vc_1|\times sin\delta_1}{X_{T_1}}, \qquad P_R = \frac{|Vs_2|\times|Vc_2|\times sin\delta_2}{X_{T_2}}$$

- The reactive power at sending end and receiving end is given by,

$$Q_S = \frac{|Vs_1|^2}{X_{T_1}} - \frac{|Vs_1|\times|Vc_1|\times cos\delta_1}{X_{T_1}}, \qquad Q_R = \frac{|Vs_2|\times|Vc_2|\times cos\delta_2}{X_{T_2}} - \frac{|Vs_2|^2}{X_{T_2}}$$

- The amplitude, phase angle and frequency of fundamental component of converter output AC voltage Vc1 and Vc2 can be controlled using the SPWM technique. If the voltage at the DC side of the converter is Vdc which is assumed to be constant then the fundamental frequency component of converter output AC voltage can be derived from the following equation:

$$Vc(t) = \frac{1}{2}V_{DC}M_i\sin(\omega t + \delta)$$

- Where Vdc is the voltage on DC side, ω is the angular frequency, Mi is modulation index and δ is the phase angle between the converter output AC voltage and the AC bus voltage.
- Mi can be defined as the ratio of peak value of voltage of modulating waveform (fundamental frequency sinusoidal waveform) to the peak value of voltage of carrier waveform (switching frequency triangular waveform).
- In a HVDC, the polarity of DC voltage is constant so the power reversal is done by current reversal in the DC link. The current in DC link flows from higher to lower DC voltage level. For stable VSC operation and flow of active power, the DC link voltage is maintained at a desired reference value by using a feedback control loop.

Four quadrant operation of VSC

- Active power flow direction for rectifier or inverter operation and reactive power flow direction for inductive or capacitive operating mode of VSC can be explained by a PQ-circle diagram shown in the Fig. 2.4.2.
- In the first quadrant both the active and reactive power are positive which means that the converter injects both powers to AC system which shows the capacitive mode of inverter operation. The converter output AC voltage magnitude is higher than AC bus voltage and leads AC bus voltage by an angle δ.
- In the second quadrant, the active power is negative and the reactive power is positive which explains the capacitive mode of rectifier operation. In this

case, the converter output AC voltage amplitude is higher than AC bus voltage but it lags the AC bus voltage by an angle δ.

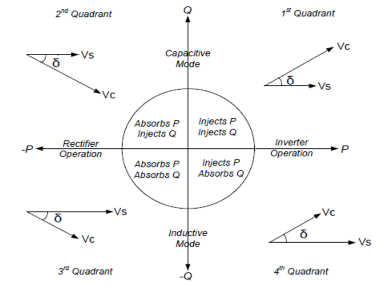


Figure. P-Q circle diagram for VSC operation

- Both the powers in the third quadrant are negative which means converter absorbs both powers from the AC system which explains the inductive mode of rectifier operation. In this case, the AC bus voltage magnitude is higher than the converter output AC voltage and it leads by an angle δ.
- In the fourth quadrant, the active power is positive and the reactive power is negative which explains the inductive mode of inverter operation. Here the converter output AC voltage leads the AC bus voltage but its magnitude is less than the AC bus voltage. According to the converter MVA capacity and system requirements, converter can operate in any mode (i.e. capacitive or inductive) of rectifier or inverter operation.
- **Rectifier- Inverter operation of VSC**

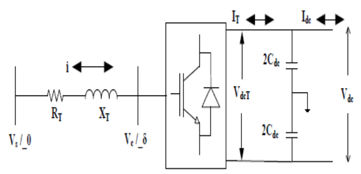


Figure. VSC Operation as Rectifier or Inverter

- The rectifier or inverter operation of VSC can be explained by considering Fig. 2.4.3. AC bus voltage Vs can be taken as a reference and Vc is the converter AC output voltage with phase shift δ. The converter transformer can be represented by an equivalent resistance R_T and reactance X_T. Two capacitors of same rating 2Cdc are connected in series across the DC terminals of the converter. The direction of current flow decides the operation of VSC as a rectifier or inverter.
- As shown in Fig 2.4.3(a), the AC system voltage Vs leads the converter AC output voltage Vc by an angle δ. The active power flows from the AC system to the converter so the converter operates as a rectifier. As shown in figure, ΔV is the voltage drop across the transformer impedance which is controlled in order to control the angle δ. In the rectifier mode of operation, the current Idc is considered positive and the capacitor Cdc is discharged through the DC transmission system. The error signal demands the control circuit for more power from the AC supply. The control circuit thereby generating the appropriate PWM signals for the switching devices and accordingly, more current flows from the AC to DC side and the capacitor voltage recovers its predefined value.

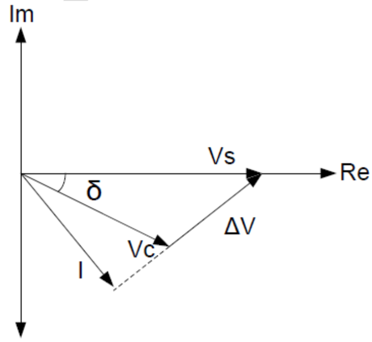


Figure. VSC Operation as a Rectifier

- As shown in Fig 2.4.3(b), the AC system voltage Vs lags the converter AC output voltage by an angle δ. In this case, the active power flows from the converter to AC system so the converter operates as an inverter. In the inverter mode of operation, Idc becomes negative and the capacitor Cdc is overcharged. The PWM can control both the active power and reactive power independently. Thus, this type of converter can be used for power factor correction also in addition to power transmission.

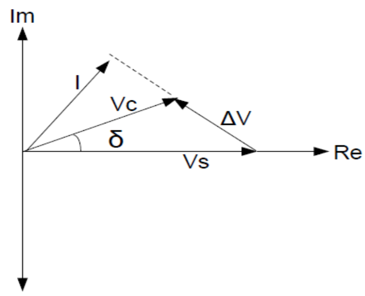


Figure. VSC Operation as a inverter

- Depending on the control strategy, VSC can be operated as either inverter or rectifier; therefore it is often referred to as a converter. Two such converters are often cascaded to control the power flow between two AC networks. The first converter converts AC voltage to variable DC link voltage and the second converter converts the DC voltage to variable AC voltage with fixed or variable frequency

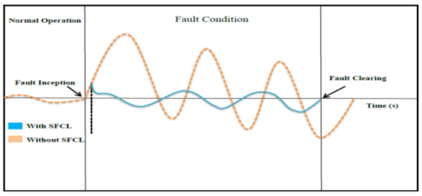


Figure. Current waveform with and without SCFCL during fault

OVERVIEW OF SIMULATION RESULTS

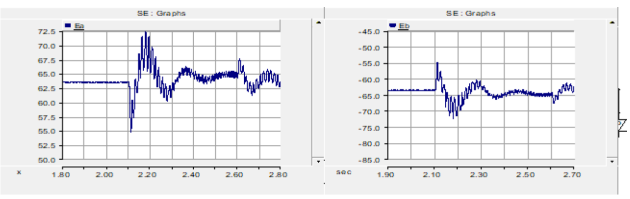
This section analyzes the performance and usefulness of resistive SCFCL to control the dc line fault current and CCR to overcome over-voltages in a higher rated VSC-HVDC system involving overhead dc transmission lines.

The resistive SCFCL model developed and CCR device is now integrated with VSC-HVDC system (125 kV, 1.2 kA, 75 MVA) involving dc overhead lines to overcome the effects of dc line fault, in PSCAD/EMTDC environment. The SCFCL is connected on the rectifier side, in series with the line and CCR is connected between dc lines across capacitor. The aim of this study is to investigate and evaluate the performance of the VSC-HVDC system with SCFCL and CCR devices for various dynamic ac/dc fault conditions. Of specific interest is the dc line fault. In all the cases presented here, the faults are created at 2.1 sec lasting for duration of 3 cycle.

CASE 1: WITH SCFCL AND WITHOUT CCR

In order to investigate the behavior of resistive SCFCL device alone in VSC-HVDC system, a three phase to ground fault at inverter ac bus is created at 2.1 sec lasting for 3 cycles. The variation of dc voltages, dc currents are compared for the cases with and without SCFCL are shown in Fig. 7.2(b) and (c).

Without SCFCL in the circuit, during the fault period, the dc voltage of positive pole reached the maximum value of about 71 kV from steady state value of 62.5 kV and this value for negative pole is about -72 kV from a steady state value of –62.5 kV. For the same case, the dc current in the positive pole increased rapidly and reached the maximum values of 2.3 kA from a steady state value of 0.60 kA. This also resulted in the variation of dc current of the negative pole in negative direction from steady state value of -0.60 kA to -2.4 kA.



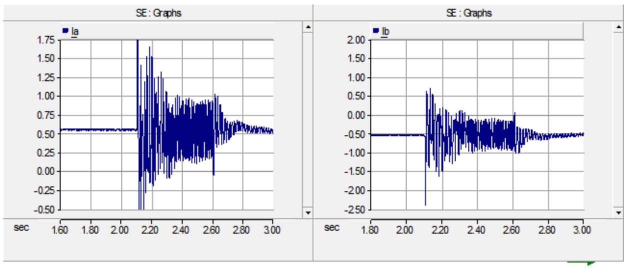


Figure.Voltage and Current waveform without SCFCL

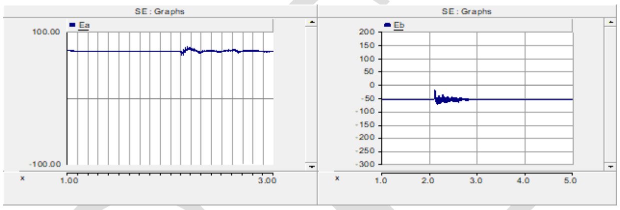


Figure. Voltage waveform with SCFCL

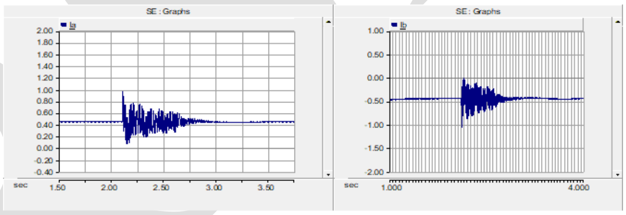


Figure. Current waveform with SCFCL

Conclusions and Future Scope of Research

Conclusions There has been a growing interest in HVDC technology since the first HVDC installation took place in Gotland, sweeden, in 1954. The high flexibility of control available with HVDC transmission results in a number of new advantages and applications which have been presented in Chapter 2. The main objective of the thesis is to perform load flow and optimal power flow analysis of an AC-DC system. Here, load flow analysis for different configurations of single and multiple DC transmission line are discussed. MATLAB simulations are carried out for point-to-point DC transmission for various operating modes. These modes are defined by considering any three out of the seven DC variables specified for a particular power transfer through the DC line. The respective modes of operation are discussed in detail in Section 3.4. Transition from one mode to another mode takes place if any unspecified variable exceeds its boundary limits. Then, HVDC operating mode shifts to a new mode. Under the transition between modes, the variable which exceeds its operating limit is fixed at that limit and any one of the fixed variables in the transiting mode is made free to be varied. The following results are observed from the case studies carried out.

(1) The reactive power consumed by converters is minimum when HVDC is operating in modes where αmin, γmin, Vdi/Vdr/t1/t2 are specified. Also, current flowing through the DC line depends on the specified value of tap position of the converter transformer.

(2) HVDC operation is practically not feasible for some modes.
(3) Simulations also involve the transition of operating modes under the case of priorities of them given as one of the inputs. The transition between operating modes took place successfully.

Simulations for series and radial configurations of multiterminal HVDC line are also carried out. In case of the series configuration, the range of transformer tap positions required is significantly greater than that in case of radial configuration. This directly affects the cost of transformer. In case of any converter failure, partial power can be transferred using a radial configuration, whereas it leads to complete interruption of power in case series configuration. Therefore, radial configuration is much superior and is preferred in practical systems. Apart from simple load flow studies, an optimal power flow study is also carried out for the AC-DC system. The OPF model is developed by using a generalized matrix representation of the HVDC link. The OPF calculation is performed by using GAMS. The input to the GAMS program is passed from a MATLAB program through the MATGAMS interface. Simulation results validated the satisfactory operation of an AC-DC system such as, maintaining voltages at all buses within 5 % tolerance level, transferring line power within acceptable limits. Moreover, it also ensures the correct direction of converter currents.

FUTURE SCOPE OF RESEARCH

In the present work, steady state analysis of AC-DC system is done. Based on the work done, it can be concluded that a number of applications and advancements in HVDC 58 transmission system are required, which are mentioned below.

1. Analysis of transient behavior of interconnected AC-DC system under switching and fault conditions can be done.
2. A generic concept of modeling of all types of HVDC systems considering all the possible configurations is needed. This can reduces the complexity involved in analyzing the power system.
3. Effective utilization of VSC in an interconnected AC-DC system can be sought for the integration of DC sources with the utility grid.

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