UNIT I
INTRODUCTION TO HIGH VOLTAGE TRANSMISSION SYSTEMS

Introduction - Historical sketch - Comparison between AC and DC transmission - kinds of DC links – Planning and modern.

Two Marks

1. Define Energy availability and Transient Reliability?

$$\text{Energy availability} = 100\left(1 - \frac{\text{Equivalent Outage Time}}{\text{Total Time}}\right)\%$$

Where equivalent outage time is the product of the actual outage time and fraction of system capacity lost due to outage .

$$\text{Transient Reliability} = 100 * \frac{\text{No. of times HVDC system performed as designed}}{\text{No. of Recordable AC faults}}$$

This is a factor of specifying the performance of HVDC systems during recordable faults on the associated AC systems.

2. What are the applications of DC transmission?

a) Long distance bulk power transmission.
b) Underground (or) underwater cables
c) Asynchronous interconnection of AC systems operating at different frequencies
d) Control and stabilization of power flow in AC ties in an integrated power system.

3. What is DC switch Gear?

It is usually modified AC equipment used to interrupt small DC currents (employed as disconnecting switches). DC breakers (or) metallic return transfer Breakers (MRTB) are used. If required for interruption of rated loaded currents.

AC switch gears and associated equipments for protection and measurement are also part of the converter station.

4. What are types of filters used in HVDC transmission line ?

a) AC filters – used to provide low impedance path for In
b) DC filters- Filtering of DC harmonics
c) High frequency (RF/PLC) filters- These are connected between converter transformer station AC bus, to suppress any high frequency currents.

5. Define smoothing Reactor?

It is a sufficiently large series reactor which is used on DC side to smooth DC current and also for protection.

The Reactor is designed as a linear reactor and is connected on the line side neutral side (or) at intermediate location.

6. What are all the possible configurations for HVDC Transmissions?

a) A two terminal transmission where each terminal located at suitable place somewhere within the network and connected by a DC overhead line (or) cable.
b) A back to back HVDC station located somewhere within one of the network and an AC line from the other network to the common station.
c) A back to back station located close to the border between the two systems.

7. What are all the aspects required for system interaction?

a) Var requirements of converter stations
b) Dynamic over voltages
c) Harmonic generation and design of filters
d) Damping low frequency and sub-synchronous torsional oscillations.
e) Carrier frequency interference caused by spike currents in values due to discharge of stray capacitances and snubber circuits.

8. What are all the considerations required for DC interconnection?

a) Small fluctuations in the voltage and frequency do not affect the power flow which can be set at any desired value.
b) The system security can be enhanced by fast control of DC power

9. Define SCR?

The strength of AC systems connected to the terminals of a DC link is measured in terms of short circuit Ratio (SCR)

$$\text{SCR} = \frac{\text{Short circuit level at the converter bus}}{\text{Rated DC Power}}$$

10. Define HVDC Transmissions?

As generation and utilization of power remain at AC, whereas DC transmission requires conversion at two ends, from AC to DC at the sending end and back to AC at the receiving end.

This conversion is done at converter station at sending end and inverter station at the receiving end. The converters are static using these high power thyristors connected in series, to give the required voltage ratings.

11. What are the types of HVDC lines (Types of HVDC, HAVC & HVDC Tr)?

a) **Monopolar link** – It has one conductor with negative polarity and uses ground or sea as return.
b) **Bipolar link** – It has two conductors, one positive and other negative.
c) **Homopolar link-** It has two or more conductors, all are having some polarity (usually –ve).

12. What are the disadvantages of DC transmission and how it can be overcome using modern trends?

Disadvantage:

a) The difficulty of breaking DC currents which results in high cost of DC breakers.
b) Inability to use transformers to change voltage levels.
c) High cost conversion equipment.
d) Generation of harmonics which require AC & DC filters, adding to the cost of converter stations.
e) Complexity of Control.

Remedies:

a) Development of DC breakers
b) Modular construction of thyristor values.
c) Increase in the rating of thyristor cells that make up a value.
d) Twelve pulse operation of converters
e) Use of metal oxide, gapless arresters.
f) Application of digital electronics and fiber optics in control of converters.

13. What are the power semiconductors devices used in DC transmission?

a) GTO [2000A, 250v]- gate Turn OFF thyristor
b) MLT – Metal oxide semiconductor controlled thyristor

14. Draw the converter station unit in HVDC Transmission?

See K.R padiyar – Pg.No- 12 , Pg. No- 15

15. Name the new modern trends in DC transmission?
a) Power semiconductor and values
b) Converter control
c) DC breakers
d) Conversion of existing AC lines
e) Operation with weak AC system

16. Advantages of DC Transmission?
a) Full control over power transmitted
b) The ability to enhance transient and dynamic stability in associated AC networks
c) Fast control to limit fault current in DC lines. This makes it feasible to avoid DC breakers in two terminal DC links

17. Compare AC and DC Transmission?

AC	DC
1. AC tends to move economical than DC for distances less than breakeven distance	1. DC tends to move economical than AC for distance more than breakeven distance.
2. Power buses are high due to more than conductors	2. Power losses are reduced due to only two conductors
3. Skin effect increases power losses	3. No skin effect
4. It requires line compensation ,so cost increased	4. It requires as terminal equipment such as converters and filters

11 Marks

1. Explain the History of HVDC Transmission.

History

At the beginning of the electricity supply industry there was a great battle between the proponents of Alternating Current (AC) and Direct Current (DC) alternatives for electricity distribution. This eventually played out as a win for AC, which has maintained its dominance for almost all domestic, industrial and commercial supplies of electricity to customer.

As the size of electricity supply systems increased several major challenges for AC systems emerged. There were major difficulties in increasing the voltage (and hence capacity) and the range of under-sea cables. Also the development of very large hydro-electric projects in areas quite remote from their load centres became an increasing challenge for AC systems to transport vast quantities of electricity over very great distances. For very large transmission schemes High

Voltage Direct Current (HVDC) is both more efficient and has a greater capability than AC systems. It was recognized as early as the 1920's that there were advantages in the use of DC transmission systems for these more challenging applications. Hence the concept of HVDC emerged, however development was held back by the lack of a suitable technology for the valves to convert AC to DC and vice versa.

In the late 1920's the mercury arc rectifier emerged as a potential converter technology, however it was not until 1954 that the mercury arc valve technology had matured enough for it to be used in a commercial project. This pioneering development led to a number of successful projects. However at the same time a new technology, the silicon semi-conductor thyristors, began to emerge as a viable technology for the valves of HVDC systems.

The thyristors valve first came into use in HVDC applications in 1970 and from that time forward the limitations of HVDC were largely eliminated. The technology is now mature and experiencing rapid increases in the voltage, power carrying capacity and length of transmission lines. This has occurred at a time when the efficiency of electricity supply systems is under great pressure due to Greenhouse Gas considerations whilst the development of large hydro- electric schemes is an imperative to decrease the reliance on fossil fuel power generation which produces a large proportion of the planet's Greenhouse gases.

Lamm's efforts were finally realized in 1954 when the island of Gotland off the east coast of Sweden was connected to the mainland by a HVDC scheme. The Gotland 1 project operated at 100kV and consisted of 98km of under-sea cable between Västervik on the mainland and Ygne on the island. The valves were of the mercury arc type which Lamm and his team had spent 25 years developing. The initial scheme had a rating of 20MW.

The Gotland scheme, generally considered to be the first truly commercial scheme in the world, also became the test site for a series of new technology breakthroughs in the development of HVDC. This site is therefore the most significant heritage site in the development of HVDC for several reasons.

From the commissioning of the Gotland scheme ASEA (later to become ABB) pursued commercial success with the HVDC technology, and have remained the leaders in the field ever since. After the success of the Gotland 1 scheme HVDC did not immediately become an unreserved commercial success for ASEA. Many potential customers were concerned about the possible fragility of the mercury arc valves although history showed that the complex technology was remarkably robust. ASEA implemented six projects from Gotland 1 in 1954 to the Pacific DC Intertie in 1970 using mercury arc valves.

In 1970 the Gotland scheme was re-engineered to 30MW and 150kV using the first thyristor valves to be used in a HVDC application. The original mercury arc valves remained in service alongside the new thyristor valves proving, not for the last time, that the two technologies could work harmoniously together. The arrival of the thyristor valve was the key to large- scale commercial development of HVDC schemes throughout the world.

DISADVANTAGES OF HVAC TRANSMISSION

The following are the disadvantages in HVAC transmission lines:

- Thermal limit
- Corona loss
- Skin effect

- Ferranti effect
- Economics of transmission
- Technical performance
- Reliability

THERMAL LIMIT

Thermal limits usually determine the maximum power flow for lines. Thermal power flow limits on overhead lines are intended to limit the temperature attained by the energized conductors and the resulting sag and loss of tensile strength.

The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. The increase in thermal limit of the transmission system increases the cost of insulation and also it increases the cost of Transformers, Switch gear and other terminal apparatus.

CORONA LOSS

A corona is a process by which a current, perhaps sustained, develops from an electrode with a high potential in a neutral fluid, usually air, by ionizing that fluid so as to create a plasma around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules.

SKIN EFFECT

The skin effect is the tendency of an alternating electric current (AC) to distribute itself within a conductor so that the current density near the surface of the conductor is greater than that at its core. That is, the electric current tends to flow at the "skin" of the conductor. The skin effect causes the effective resistance of the conductor to increase with the frequency of the current. Skin effect is due to eddy currents set up by the AC current.

The skin effect has practical consequences in the design of radio-frequency and microwave circuits and to some extent in AC electrical power transmission and distribution systems. Also, it is of considerable importance when designing discharge tube circuits.

This effect can be minimized by using ACSR (Aluminum conductor steelreinforce) conductors which has the property to minimize the skin effect. But it increase the cost compare to normal conductors.

FERRANTI EFFECT

The Ferranti Effect is a rise in voltage occurring at the receiving end of a long transmission line, relative to the voltage at the sending end, which occurs when the line is charged but there is a very light load or the load is disconnected.

This effect is due to the voltage drop across the line inductance (due to charging current) being in phase with the sending end voltages. Therefore both capacitance and inductance are responsible for producing this phenomenon.

The Ferranti Effect will be more pronounced the longer the line and the higher the voltage applied. The relative voltage rise is proportional to the square of the line length.

Due to high capacitance, the Ferranti Effect is much more pronounced in underground cables, even in short lengths

HVDC TRANSMISSION

Modern DC power transmission is relatively a new technology which made a modest beginning in the year 1954. The advent of thyristor valve and relater technological improvements over the last 18 years has been responsible for the acceleration of the growth of HVDC technology is still undergoing many changes due to continuing innovations directed at improving reliability and reducing cost of converter stations. The latest development of multi-terminal system operation has increased the scope of application of HVDC systems. However, the growth in the knowledge on HVDC technology remains limited.

When the number and size of dc system are small, it was common to consider HVDC power transmission as too specialized and fit only to be taken up by the manufacturers and consultants. With the growth of HVDC systems there is now a greater awareness among engineers from utilities, regarding the potential of dc transmission from the point of view of interaction with ac systems. Some of these interactions are beneficial, while others may pose problems unless investigated thoroughly during the design stage and solutions incorporated to overcome the adverse effects. While it is true that the HVDC systems are quite reliable and converter control allows flexibility in the system operation.

2. Compare AC and DC transmission and mention the application of DC transmission.

COMPARISION OF AC & DC TRANSMISSION

The relative merits of two modes of transmission (ac & dc) which need to be considered by a system planner are based on the following factors:

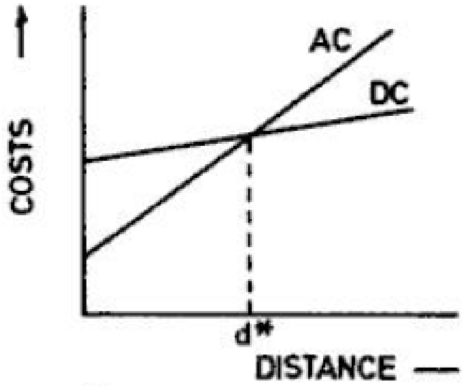
- Economics of transmission
- Technical performance
- Reliability

ECONOMICS OF POWER TRANSMISSION

The cost of transmission line includes the investment and operational costs. The investment includes costs of Right of Way (ROW), transmission towers, conductors, insulators and terminal equipment. The operational costs include mainly the cost of losses.

The characteristics of the insulators vary the type of voltage applied. For simplicity, if it is assumed that the insulator characteristics are similar for ac & dc and depend on the peak level of the voltage applied with the respect to the ground. Then it can be shown that for lines designed with the same insulation level, a dc line carry as much power with two conductors (with positive and negative polarities with respect to ground) as an ac line with three conductors for the same size. This implies that for a given power level dc line requires less ROW, simpler and cheaper towers and reduced conductor and insulation costs. The power losses are also reduced with dc as there are only two conductors. The absence of skin effect with dc is also beneficial in reducing power losses marginally. The dielectric losses in case of power cables is also very less for dc transmission.

The corona effects tend to be less significant on dc conductors than for ac and this also leads to the choice of economic size of the conductors with dc transmission. The other factors that influence the line cost are the cost of compensation and terminal equipment. Dc lines do not require compensation but the terminal equipment costs are increased due to the presence of the converter and filters.



d* = break-even distance

Ac tends to be more economical than dc for distance less than break even distance and costlier for longer distances. The break even distance can vary from 500 to 800 km in overhead lines depending on the per unit line costs.

TECHNICAL PERFORMANCE

The DC transmission has some positive feature which are lacking in AC transmission. These are mainly due to the fast controllability of power in DC lines through converter control.

The following are the advantages:

- Full control over power transmitted.
- The ability to enhance transient and dynamic stability in association AC networks.
- Fast control to limit fault currents in DC lines. These make it feasible to avoid DC breakers in two terminal DC links.

In addition, the DC transmission overcomes some of the problems of AC transmission. These are described further:

STABILITY LIMITS

The power transfer in AC lines is dependent on the angle difference between the voltage phasors at the two ends. For a given power level, these angle increases with distance. The maximum power transfer is limited by the considerations of steady state and transient stability.

The power carrying capability of AC lines as a function of distance is shown in the figure. The same figure also shows the power capability of the DC lines which is unaffected by the distance of transmission.

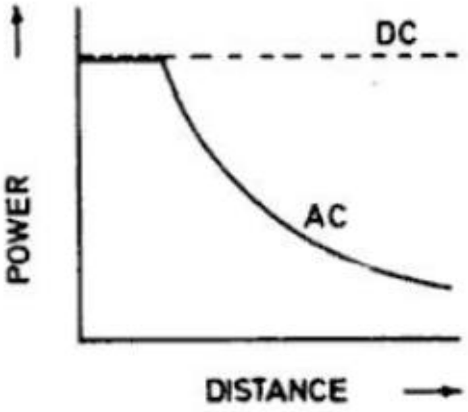


Fig: Power Transfer capability Vs Distance

VOLTAGE CONTROL

The voltage control in AC lines is complicated by the line charging and inductive voltage drops. The voltage profile in an AC line is relatively flat only for the fixed level of power transfer corresponding to surge impedance loading (SIL). The voltage profile varies with the line loading. For the constant voltage at the line terminals, the mid point voltages reduced for the line loading higher then SIL and increase for loading less than SIL.

The maintenance of constant voltages at the two ends requires reactive power control from inductive to capacitive as the line loading is increased. The reactive power requirements increase with the increase in the line lengths.

Although dc converter stations require reactive power related to the line loadings, the line itself does not require reactive power. The steady state charging currents in ac lines pose serious problems in cables this puts the break even distance for the cable transmission around 40 km.

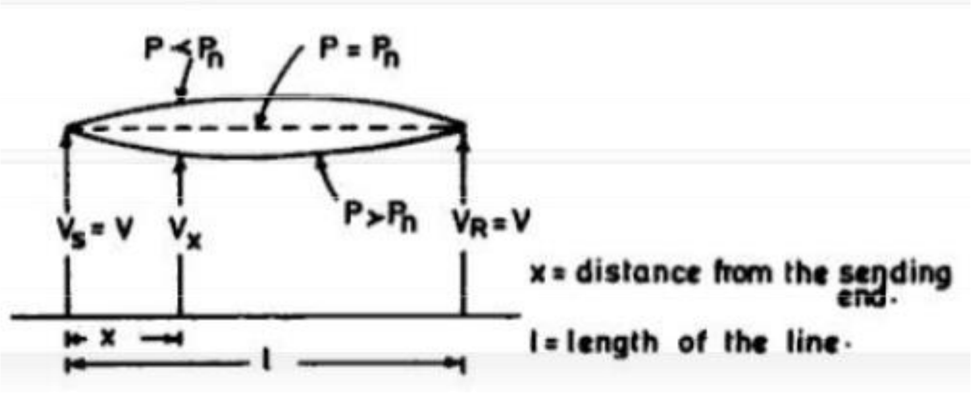


Fig: Voltage control

RELIABILITY

The reliability of dc transmission systems is quite good and comparable to that of Ac systems. An exhaustive record of existing HVDC links in the world is available from which the reliability statistics can be computed. It must be remembered that the performance of the thyristor valves is much more reliable than mercury arc valves and further development in devices control and protection is likely to improve the reliability level for example the development of direct light triggered (LTT) is expected to improve reliability because of the elimination of the high voltage pulse transformers and auxiliary supplies for turning on the device.

Both energy availability and transient reliability of existing dc systems with thyristor valves is 95% or more.

Reliability:

- DC system reliable
- Performance of thyristor valve is more reliable than memory arc valve
- Direct Light Triggered Thyristors (LTT) is expected to improve reliability because of elimination of high voltage pulse transformers and auxiliary supplies for turning on the devices

2 measures of overall system reliability are energy availability and transient reliability

Energy reliability:

$$\text{Energy availability} = 100\left(1-\frac{\text{Equivalent Outage Time}}{\text{Total Time}}\right)\%$$

Equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to Outage.

Transient reliability:

$$\text{Transient Reliability} = 100^{*}\,\frac{\text{No. of times HVDC system performed as designed}}{\text{No. of Recordable AC faults}}$$

Recordable AC fault at which cause in one or AC bus phase where voltage drops to 90%

APPLICATIONS OF DC TRANSMISSION

The detailed comparison of ac & dc transmission in terms of economics and technical performance leads to the following areas of application for dc transmission.

- Long distance bulk power transmission.
- Underground or underwater cables.
- Asynchronous interconnections of ac systems operating at different frequencies or where independent control of systems is desired.
- Control and stabilization of power flows in ac ties in an integrated power system.

DISADVANTAGES OF DC TRANSMISSION

The scope of application of DC transmission is limited by the following factors:

- The difficulty of breaking dc currents which results in high cost of dc breakers.
- Inability to use transformers to change the voltage levels.
- High cost of conversion equipment.
- Generation of harmonics which require ac & dc filters, adding to the cost of converter stations.
- Complexity of control.

3. What are the types of commutated converters used in converter Station?

There are three ways of achieving conversion:

1. Natural commutated converters
2. Capacitor Commutated Converters
3. Forced Commutated Converters

Natural Commutated Converters (NCC):

NCC is most used in the HVDC systems as of today. The component that enables this conversion process is the **thyristor,** which is a controllable semiconductor that can carry very high currents **(4000 A)** and is able to block very high voltages **(up to 10 kV)** . By means of connecting the thyristors in series it is possible to build up a **thyristor valve,** which is able to operate at very high voltages (**several hundred of kV**).Thethyristor valve is operated at net frequency (50 hz or 60 hz) and by meansof a control angle it is possible to change the DC voltage level of the bridge..

Capacitor Commutated Converters (CCC):

An improvement in the thyristor-based Commutation, the CCC conceptis characterized by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves . The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.

Forced Commutated Converters

This type of converters introduces a spectrum of advantages, e.g. feed of passive networks (without generation), independent control of active and reactive power, power quality. The valves of these converters are built up with semiconductors with the ability not only to **turn-on but also to turn-off**. They are known as VSC (Voltage Source Converters).A new type of HVDC has become available. It makes use of the more advanced semiconductor technology instead of thyristors for power conversion between AC and DC. The semiconductors used are insulated gate bipolar transistors (IGBTs), and the converters are voltage source converters (VSCs) which operate with high switching frequencies (1-2 kHz) utilizing pulse width modulation (PWM)

4. Explain Various Kinds of DC link.

Types of DC Link:

There are different types of HVDC systems which are as follows:

MONO-POLAR HVDC SYSTEM:

In the mono-polar configuration, two converters are connected by a single pole line and a positive or a negative DC voltage is used. In Fig. There is only one Insulated transmission conductor installed and the ground or sea provides the path for the return current.

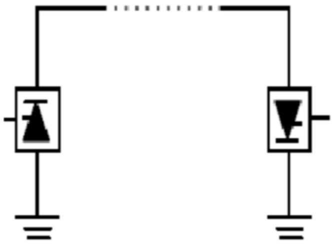


Figure: Mono polar HVDC system

BIPOLAR HVDC SYSTEM:

This is the most commonly used configuration of HVDC transmission systems. The bipolar configuration, shown in Fig. below 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. Most overhead line HVDC transmission systems use the bipolar configuration.

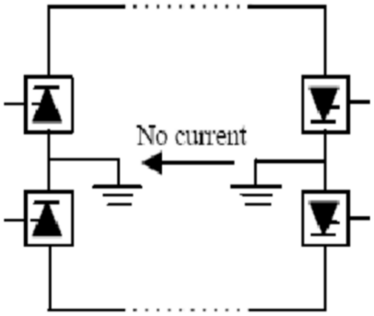


Figure: Bipolar HVDC system

HOMO-POLAR HVDC SYSTEM:

In homo polar configuration, shown in Fig. Two or more conductors have the negative polarity and 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.

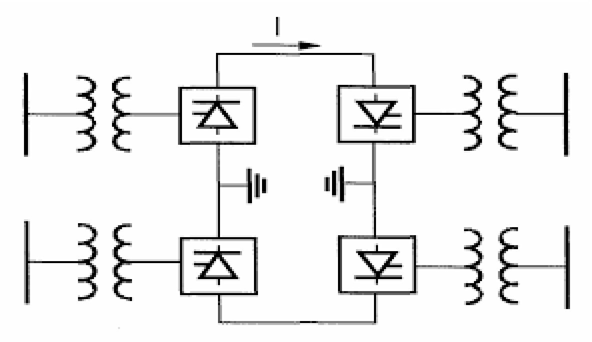


Figure: Homopolar HVDC system

5. List out modern trends and Planning in DC transmission system.

PLANNING FOR HVDC TRANSMISSION:

Factors to be considered are:

i. Cost
ii. Technical performance
iii. Reliability

- Last two factors are considered as constraints to be met and minimum cost option is selected
- For submarine, cable transmission and interconnecting 2 systems of different nominal frequencies, the choice of DC is obvious
- Other cases, the choice is to be based on detailed techno-economic comparison
- Planning depends on the application and they are:
  i. Long distance bulk power transmission
  ii. Interconnection between 2 adjacent systems
- In I application, DC and AC alternatives for same level of system security and reliability and have same power carrying capability
- Cost - major role in DC or AC
- In II application, AC interconnection poses several in certain cases
- Choice of DC is based on certain considerations
  i. Small fluctuations in the voltage and frequency do not affect the power flow which can be set at any desired value
  ii. System security can be enhanced by fast control of DC power

- Three possible configuration of DC link for interconnection and these are:
  i. 2 terminal transmission
  ii. Back to back HVDC (HVDC coupling station) located somewhere within one of the network and AC line from other network to the common station
  iii. Back to back station located closed to the border between 2 systems
- For I and II, converters costs are less for comm. Coupling station and the AC line costs are > DC line costs
- Distance < 200 Km, II configuration is to be preferred
- If SCR is acceptable III is alternative and most economical
- The interruption (or deduction) of power can occur due to
  i. DC line faults
  ii. AC system faults
- Recovery of DC link from AC system faults is more complex
- Depression of AC voltage at inverter leads to commutation failure and loss of DC
- power
- DC power - ramped up to clear fault
- Increase in DC power output leads to decrease in AC voltage
- Rate of Increase in DC power can be determined from stability study
- Influenced by control strategy and system characteristics
- Following aspects of system interaction are:
  i. Var requirements of converter station
  ii. Dynamic over voltages
  iii. Harmonic generation and design of filters
  iv. Damping of low frequency and subsystem torsional oscillations
  v. Carrier frequency interference caused by spiky current in valves

Choice of voltage level:

- For long distance bulk power transmission, the voltage level is chosen to minimize the total costs for a given power level (P)
- Total cost = investment (C1) and Cost of losses (C2)
  C1 = A0 + A1nV + A2nq
  V - Voltage level with respect to ground
  n - no of conductors
  q - Total cross section of each conductor
  A0 , A1 ,A2 – constants

$$C_2 = [n(P/nV)^2 \rho TLp]/q$$

where

ρ – Conductor resistivity
T – Total operation time in a year
L – Loss load factor
p – Cost per unit energy
C_2 can be simplified as
$C_2 = (A_3(P/V)^2\rho) / nq$

By minimizing the sum of C_2 and the third term in C_1, we have,

$$nq = \sqrt{(A_3/A_2)\rho} \quad (P/V)$$

$$J = P/(nqV) = \sqrt{A_2/(A_3 \rho)}$$

where J is the current density. The total costs, using (1.5) can be written as

$$C = C_1 + C_2 = A_0 + A_1 nV + 2\sqrt{A_2 A_3 \rho}\left(\frac{P}{V}\right)$$

MODERN TRENDS IN DC TRANSMISSION:

- DC protection equipment have increase in application if DC transmission
- Major contribution is to reduce the cost of converter while increasing the reliability and performance

Power semiconductor and valves:

- Cost of converters decreases if no of devices to be connected in series and parallel
- Size of devices have gone upto 100mm in dia, there is no need of parallel connection
- Increase in current rating has made it possible to provide higher overload capability at reasonable costs and decrease in lower limit on T/F leakage Z thereby improving PF
- Voltage ratings are also high
- Development of LTT, improve the reliability of converter operation
- Cost of value is also reduced by the application of zinc oxide gapless arresters and protective firing methods
- GTO available at 2500V, and 2000A
- Disadvantage of GTO' –Large gate I is needed to turn them off
- MOS and MCT– MOS IC on top surface of high power thyristor
- Very large I_L can be switched off by a small I_g
- Turn-off time is < 1/3 that of GTO
- IGBT – less power (to turn off) and has high switching speeds and available at ±150KV and 350 MVA rating

Converter control:

- Micro computer based control

- Redundant converter control with automatic T/F between system in case of malfunction
- Preventive maintenance on the stand-by system when the converter is in operation
- Flexible– adaptive control algorithms
- Expert system for fault diagnosis and protection
- Control and protection requires– measurement of DC – using transducers of zero
- flux type
- Recent development – hybrid optical measurement – uses ohmic shunt– voltage
- drop is measured and digitized by an cc located at high voltage potential

DC breakers:

- Development and testing of breakers, it is possible to go in for tapping an existing Dc
- link or development of new MTDC system
- Parallel operation preferred due to certain flexibility in planned growth of system
- DC breaker rating does not exceed full load rating i.e to limit the fault current

Conversion of existing AC lines:

- Constraints on ROW – converting existing AC to DC in order to increase power
- transfer limit
- Some operational problems due to electro-magnetic induction from AC operating in
- the same ROW
- Converting single circuit of a double circuit 220KV was commissioned in 1989-90 in
- India between Sileru and Barsoor
- Double circuit AC bipolar HVDC with substantial power rating (i.e about 3.5
- times)

Operation with weak AC system:

- Strength of AC system connected to DC is measured using SCR

  SCR = short circuit level at the converter bus/ Rated DC power
- SCR<3 – AC system weak
- Conventional constant extinction control may not be satisfactory
- Clearing of fault using inverter is also problematic
- Const. Reactive I control or AC voltage control is used to overcome some problems
- Use of fast reactive power control
- Limiting dynamic over voltage through converter during load injection
- PM technique used to increase dynamic stability

UNIT II

HVDC CONVERTERS

Three phase bridge converter - Simplified analysis, waveforms with and without overlap - Current and voltage relations - Input power factor - principles of control – Control characteristics – Constant ignition angle control – Constant current and extinction angle control.
HVDC converters – twelve - higher pulse operation - introduction to modern converters.

Two Marks

1. **Define Pulse Number?**

   The pulse number of a converter is defined as the number of pulsations(cycles of ripple) of direct voltage per cycle of Alternating Voltage.

2. **What are the Assumptions are made in analyzing the conversions?**

a) DC current is constant.
b) The values can be modeled as ideal switches with zero impedance when ON and with infinite impedance when OFF.
c) The AC voltages at the converter bus are sinusoidal and remain constant.

3. **What is the principle behind DC link control?**

a) The control of power in a DC link can be achieved through the control of current or voltage.
b) From minimization of loss considerations, it is important to maintain constant voltage in the link and adjust the current to meet the power.
c) This strategy is also helpful for voltage regulation in the system from the considerations of the optimum utilization of insulation.

4. **Write the Equation of AC current of DC voltage harmonics?**

AC current:

Rms value of fundamental component of I,

$$I_1=\frac{\sqrt{b}}{\pi}I_d$$

Where harmonic order h=np±1
Rms value of I,

$$I=\sqrt{2/3}\,I_d$$

The RMS value of h^th^ harmonic

$$I_h=\frac{I_1}{h}$$

DC voltage:

RMS value of the h^{th} order harmonic h=np in DC voltage,

$$V_h=V_{do}\frac{\sqrt{2}}{h^2-1}[1+(h^2-1)sin^2\alpha]^{1/2}$$

5. **Define Commutation Group?**

   It is the group of values in which only one conducts at a time (Neglecting overlap).

6. **What is the choice of converter configuration?**

a) The configuration of a given pulse no. is selected in such a way that both the value and transformer utilization are minimized.
b) The converter configuration can be defined by basic commutation group and no. of such groups connected in series of parallel.
c) If there are ‘q’ values in a basic communication group and ‘r’ of these are connected in parallel and ‘S’ of them connected in series, then **P=qrs**

7. **Define Peak Inverse Voltage [PIV]?**

   It is the term, which is used for specifying the value voltage rating.

   The ratio of PIV to average DC voltage is called index of value utilization.

   It q is odd, maximum inverse voltage occurs when the value with a phase shift of

   If q is even PIV occurs at (π) radians.

   PIV=2Em

8. **Why feedback control of power in a DC link is not desirable?**

a) At low DC voltages, the current required is excessive to maintain the required level of power. This can be counterproductive because of the excessive requirements on the reactive power, which depresses the voltage further.
b) The constant power characteristics contribute to Negative damping and degrade dynamic stability.

9. **What is meant by Neglecting overlap in great Z circuit?**

   At any instant, two valves are conducting in the bridge, one from the upper group and second from lower group. The Firing of the next valve that is in a particular group results in the timing off of the valve that is already conducting the assumption that there is no overlap between two valves in the same group is called Neglecting overlap.

10. **What are the types of firing or Ignition angle control?**

i. Individual phase control [IPC]
   a) Constant α Control
   b) Inverse cosine control
ii. Equidistant pulse control[EPC]
   a. Pulse frequency control [PFC]
   b. Pulse period control[PPC]
   c. Pulse phase control[PPC]

11. **What are the advantages of pulse phase control over PFC?**

a) Easy inclusion of α limits of limiting Vc as in IPC.
b) Linearization of control character by including an inverse cosine function block after current controller.

12. What are the drawbacks of EDC scheme?

a) Under unbalanced voltage conditions EPC results in less DC voltage compared to IPC.
b) It also results in higher negative clamping contribution to torsional oscillations when HVDC is the major transmission link from a thermal station.

11 Marks

1. Discuss the operation of 6 pulse HVDC converter with and without overlap condition and derive the voltage and current equation. (Graetz circuit).

Convertor arrangements and operation

The three-phase six-valve bridge rectifier is almost exclusively used in high voltage direct current applications. This is shown in figure 11.2.

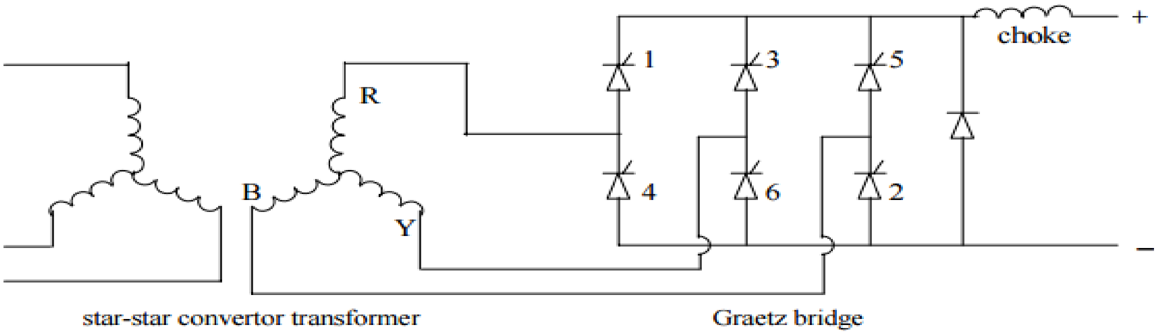


Fig: Hexa – Valve Bridge Converter Arrangement

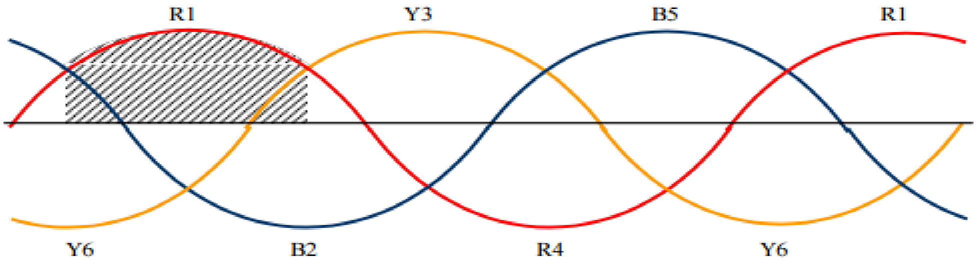


Figure 11.3 - Thyristor voltage waveforms (α = 0)

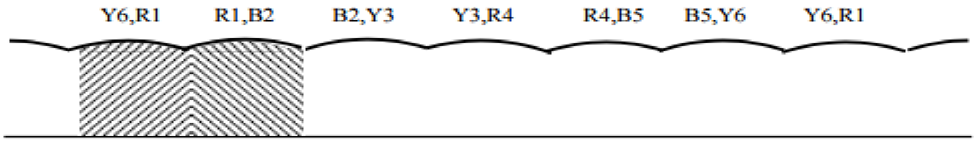


Fig : dc Output waveforms (α=0)

The 6-valve bridge connection gives double the direct voltage as output compared to the simple 3-phase rectifier. The convertor transformer may either be wound star-star as shown, or as star-delta (or even as deltastar or delta-delta). The ripple of each of these connections is the same, but are phase shifted by 300 in output with respect to each other. To obtain a smoother output, two bridges (one star-star and the other star-delta) may be connected together to give the twelve pulse connection. For the 6-valve bridge, with zero firing delay, the voltage waveforms across the thyristors are shown in figure 11.3. At any given instant, one thyristor valve on either side is conducting. The conducting period for the thyristor valve R1 is shown on the diagram.

It can be shown that for the 6-valve bridge, the total r.m.s. ripple is of the order of 4.2% of the d.c. value (for zero delay α=0 and zero commutation γ=0). The ripple of course increases with the delay angle and has a value of about 30% α=π/2.

With the 12 pulse bridge, the r.m.s. ripple is of the order of 1.03% of the d.c. value (for α =0 and γ=0), and increases to about 15% at α = π/2.

The use of a choke reduces the ripple appearing in the direct current transmitted.

If E is the r.m.s. line-to-line voltage, then if α = 0, γ=0, then the direct voltga eoutput is given by equation

$$V_{do} = 2\,x\,\frac{E}{\sqrt{3}}\,x\,\sqrt{2}\,x\,\frac{3}{2\pi}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} \cos\theta \;\; d\theta$$

$$= E\,.\,\frac{3\sqrt{2}}{\pi}\,.\,\frac{1}{\sqrt{3}}\left[\,2\,x\sin\frac{\pi}{3}\,\right]$$

$$V_{do} = \frac{3\sqrt{2}}{\pi}\,.\,E = 1.350\,E$$

Control angle (Delay angle)

The control angle for rectification (also known as the ignition angle) is the angle by which firing is delayed beyond the natural take over for the next thyristor. The transition could be delayed using grid control. Grid control is obtained by superposing a positive pulse on a permanent negative bias to make the grid positive. Once the thyristor fires, the grid loses control. Assuming no commutation (2 thyristors on same side conducting simultaneously during transfer), the voltage waveforms across the thyristors as shown in figure

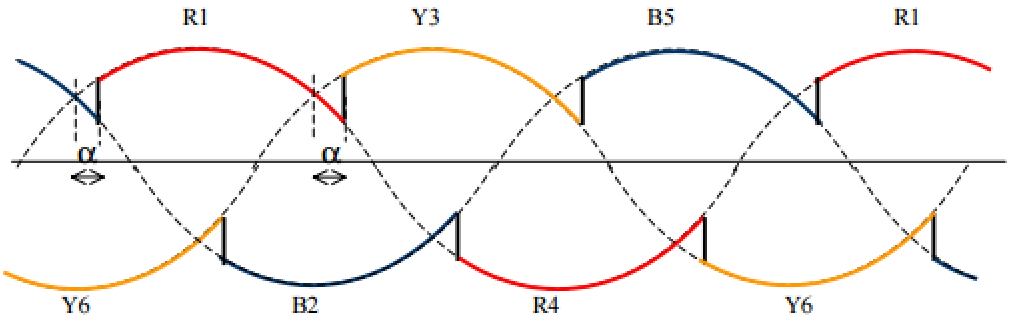


Fig: Thyristor voltage waveforms (with delay α)

In this case, the magnitude of the direct voltage output is given by the equation

$$V_d = 2 \, x \, \frac{E}{\sqrt{3}} \, x \, \sqrt{2} \, x \, \frac{3}{2\pi} \int_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha} \cos\theta \; d\theta$$

$$= E \, . \, \frac{3\sqrt{2}}{\pi} \, . \, \frac{1}{\sqrt{3}} \left[\sin\left(\frac{\pi}{3}+\alpha\right) + \sin\left(\frac{\pi}{3}-\alpha\right) \right]$$

$$V_d = \frac{3\sqrt{2}}{\pi} E \cos\alpha = V_{do} \cos\alpha$$

Commutation angle (overlap angle) The commutation period between two thyristors on the same side of the bridge is the angle by which one thyristor commutates to the next. During this period γ, the voltage follows the mean voltage of 2 conducting thyristors on the same side.

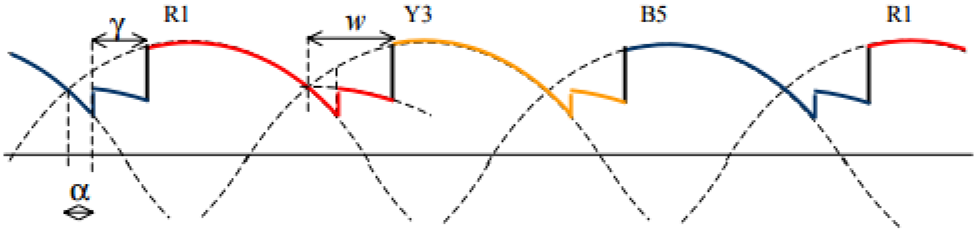


Fig: Commutation between 2 Thyristros

With both the delay angle and commutation being present, the magnitude of the direct voltage may be determined from equation (11.3) as follows.

$$V_d = 2\frac{E}{\sqrt{3}}\sqrt{2}\ \frac{3}{2\pi}\int_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha} f(\theta)\,d\theta$$

$$= \frac{3\sqrt{2}\,E}{\sqrt{3}\,\pi}\left[\int_{-\frac{\pi}{3}+\alpha}^{-\frac{\pi}{3}+\alpha+\gamma}\tfrac{1}{2}\left(\cos\left(\theta+\tfrac{2\pi}{3}\right)+\cos\theta\right).d\theta+\int_{-\frac{\pi}{3}+\alpha+\gamma}^{\frac{\pi}{3}+\alpha}\cos\theta\,.d\theta\right]$$

$$V_d = \frac{V_{do}}{2}\left[\cos\alpha+\cos(\alpha+\gamma)\right]$$

An alternate method of derivation of the result is based on comparison of similar areas on the waveform. Figure 11.7 gives the necessary information

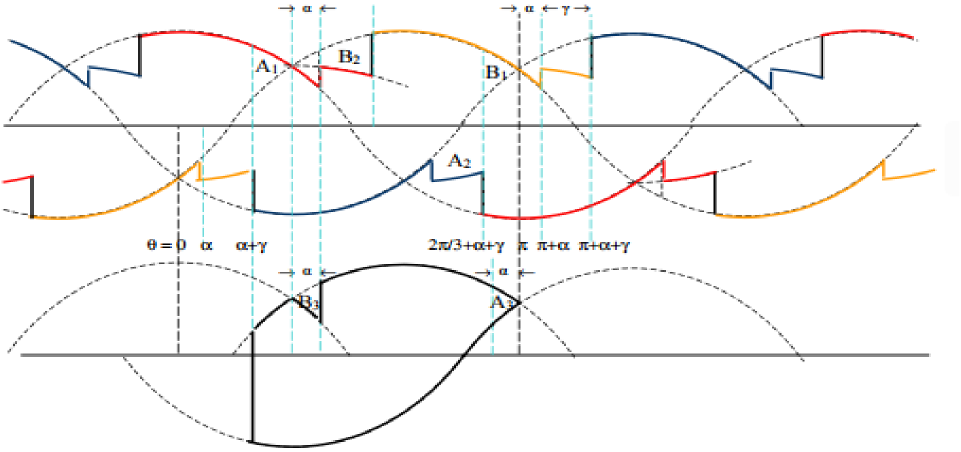


Fig Graphical analysis of waveform

d.c. output = average value of waveform

$$V_d = \frac{1}{2\pi/3}\int_{\alpha+\gamma}^{\alpha+\gamma+\frac{2\pi}{3}} V(\theta).d\theta$$

In this integral, in graphical form, area A1 can be replaced by area B1. Similarly, area A2 can be replaced by area B2 and area A3 by area B3. The integral equation then reduces to the form shown below.

$$V_d = \frac{3\sqrt{2}\,E}{2\pi}\int_{\alpha+\gamma}^{\pi-\alpha}\sin\theta\,d\theta$$

$$= \frac{3\sqrt{2}\,E}{2\pi}\left[\cos(\alpha+\gamma) - \cos(\pi-\alpha)\right]$$

where √2 E is the peak value of the line voltage. Simplification gives the desired result as in equation.

$$V_d = \frac{3\sqrt{2}\,E}{2\pi}\left[\cos\alpha+\cos(\alpha+\gamma)\right]$$

$$= \frac{V_0}{2}\left[\cos\alpha+\cos(\alpha+\gamma)\right]$$

Power factor cosϕ

Since the convertor consumes reactive power, there will be a power factor associated with the convertor on the a.c. side. This can be calculated as follows.

Active power supplied to d.c. link = $V_d I_d$

Active power supplied from a.c. system = $\sqrt{3}$ E I cosϕ

Since the convertor does not consume any active power, there must be power balance.

$$V_d I_d = \sqrt{3} \text{ E I } \cos\phi$$

From this the power factor can be calculated as follows.

$$\cos\phi = \frac{V_d I_d}{\sqrt{3} E I}$$

$$\cos\phi = \frac{\frac{I}{2} V_0 (\cos\alpha + \cos w) \frac{\pi}{\sqrt{6}} I}{\sqrt{3} \frac{\pi}{3\sqrt{2}} V_0 I}$$

This gives the result as in equation

$$\cos\varphi = ½ (\cos\alpha + \cos w) = ½ [\cos\alpha + \cos(\alpha+\gamma)]$$

In the absence of commutation, this reduces to the simple relationship

Cosϕ **=cos α**

Which means that α is the power factor angle in the absence of commutation. The presence of commutation reduces the effective power factor by increasing the effective angle.

With γ=0, the active power transmitted is $\sqrt{3}$ E I cosϕ and is zero in value when α=90.

Thus if a high inductance is connected with the load, the limit of power transfer under rectification is α=90. However, if no inductance were present with the load (i.e. Ld=0) then the voltage and the current waveforms would become identical in shape (since the load is purely resistive). Under these conditions, the voltage cannot go negative at any instant of time, since the current cannot flow in the opposite direction through the thyristors. The power transmitted would then become zero only at α=120. Figure 11.13 shows typical output current and voltage waveforms.

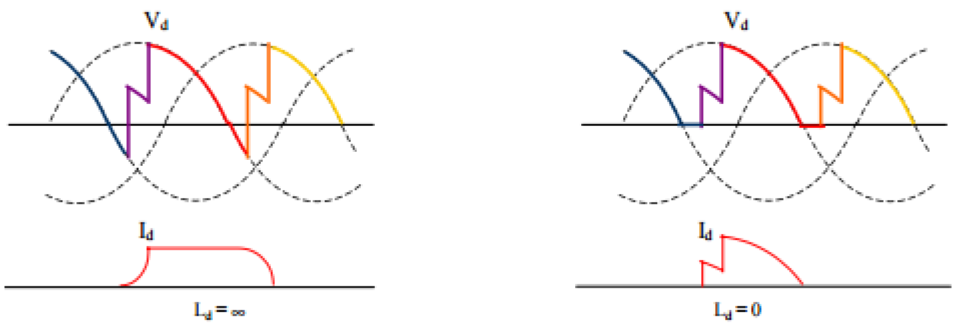


Fig: Typical DC output waveforms

2. Explain the principle of DC link power control and derive the necessary expression

Principles of DC link control:

- Two terminal DC link is assumed
- Control of power in DC link is achieved through the control of current or voltage
- From minimization of loss considerations, it is important to maintain constant voltage in the link and adjust the current to meet the required power
- Also helpful for voltage regulation in the system
- Voltage drop along a DC line is small compared to the AC line, mainly because of the absence of the reactive voltage drop
- Consider steady state eqn. of circuit of a 2 terminal DC link

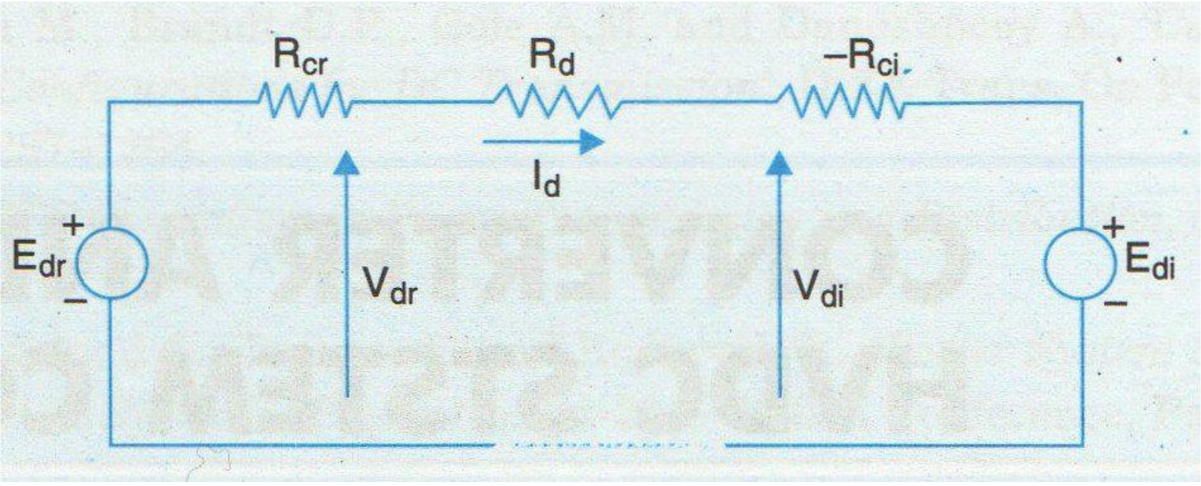


Fig: Principle of Dc link Control

- Based on the assumptions that all series connected bridges in both poles of a converter station are identical and have same delay angle
- The no of series connected bridges n_b in both stations (rectifier and inverter) are the same
- E_{dr} and E_{di} are voltage sources and are defined by

$$E_{dr} = \left(3\sqrt{2}/\pi\right) n_b E_{vr} \cos\alpha_r$$

$$E_{di} = \left(3\sqrt{2}/\pi\right) n_b E_{vi} \cos\alpha_i$$

Where E_{vr} and E_{vi} are line to line voltages in the valve side windings of the rectifier and inverter transformer respectively

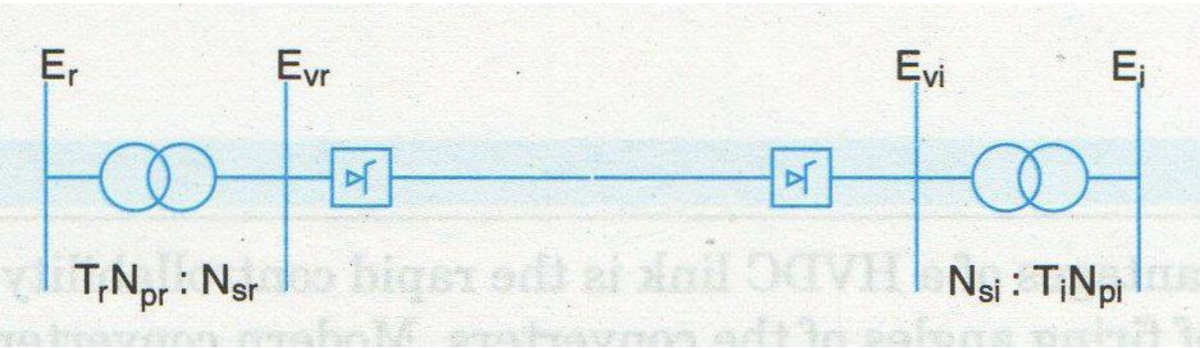


Fig: Rectifier & Inverter Transformer

$$E_{vr} = \frac{N_{sr}E_r}{N_{pr}T_r} E_{vi} = \frac{N_{si}E_i}{N_{pi}T_i}$$

$$E_{dr} = (A_rE_r/T_r)\cos\alpha_r$$

$$E_{di} = (A_iE_i/T_i)\cos\alpha_i$$

E_{di} is defined in terms of extinction angle γ_i rather than β_i (angles of advance in the inverter).

E_{di} can also be written as:

$$E_{di} = \left(\frac{A_iE_i}{T_i}\right) co\ s\,\beta_i + 2R_{ci}I_d$$

$$R_{ci} = (3n_b/\pi)X_{ci}. R_{cr} = (3n_b/\pi)X_{cr}$$

X_{cr} and X_{ci} are leakage reactance of the conv. transformers in the rectifier and inverter station respectively.

The steady state current I_d in the DC link is obtained as:

$$I_d = \frac{(E_{dr} - E_{di})}{R_{cr} + R_d - R_{ci}}$$

$$I_d = \frac{((A_rE_r/T_r)\cos\alpha_r - (A_iE_i/T_i)\cos\alpha_i)}{R_{cr} + R_d - R_{ci}}$$

- Control variables are Tr, Ti , αr and βi
- For maintaining safe commutation margin it is convenient to consider γi as control variable instead of βi

- Denominator in equation is small, even small change in voltage margin Er or Ei can result in large changes in DC current, if control variables are held constant
- Increase Voltage change is sudden, manual control of converter angles is not feasible

- Therefore, direct and fast control of current by varying αr and γi in response to a feedback
- signal is essential
- Also limits over current in thyristors valve – limited over load capability
- Although current and power can be controlled by changing transformer taps Tr and Ti , this can be achieved only by slow control of mechanical switches
- It is desirable to control the current and regulate the voltage simultaneously in the link
- It is desirable to have current control at the rectifier station under normal conditions

  1. Increase of power in link is achieved by increase in αr which increases power factor at the rectifier, for higher loadings and minimises the reactive power consumption
  2. Inverter operated at the minimum γ thereby minimizing the reactive power consumption at the inverter also

     Current control worsens Pf at higher loadings as γ has to be high
  3. Operation at minimum extinction angle at the inverter and I control at the rectifier results in better voltage regulation
- I during line faults are automatically limited with rectifier station in I control
- Need to maintain extinction angle to avoid commutation failure, it is economical to operate the inverter at CEA> above the absolute minimum required for the comm. margin
- Less cost, converter loss and power consumption
- Main drawback of CEA is the –ve resist characteristics of conv. which makes it difficult to operate stably when AC system is weak
- Constant DC voltage or constant AC voltage control are alternatives that could be used at the inverter
- Under normal conditions, the rectifier operates at constant current control (CC) and inverter at CEA control
- Under condition of reduced AC voltage at the rectifier it is necessary to shift the I control
- to the inverter to avoid run down of the DC link when the rectifier control hits the minimum and limit
- I controller provided at inverter in addition to CEA controller
- Smooth transition from CEA to CC takes place whenever link I starts falling
- Avoid clash of 2 I controllers, the I reference at the inverter is kept below that at the rectifier by an amount called the ‘current margin’ is 10% of rated
- Power reversal can take place by reversal of DC voltage and done easily by increase in delay angle at the station initially operating as the rectifier, while decrease in delay angle at the station operating as the inverter

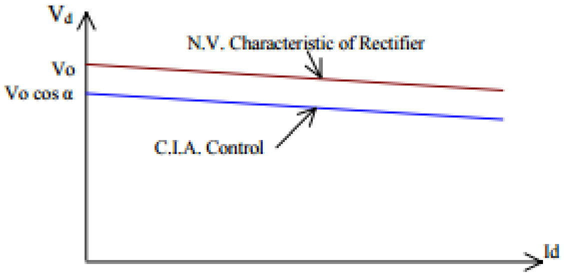
- It is necessary to provide both CEA and CC controllers at both terminals
- OLTC at inverter is used to maintain a constant DC voltage
- Tap changer control at rectifier □ to maintain delay angle within certain limits, maintain voltage margin for purpose of I control
- Feedback control of power in a DC link is not durable for following reason:
- Cons. Power characteristics contributes to –ve damping and degrades dynamic stability
- At low DC voltages, I required is excessive to maintain the required level of power

3. Explain about the different firing angle control techniques

Control Characteristics

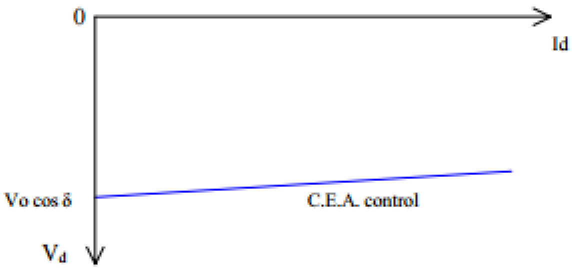
The control characteristics of the convertor are the plots of the variation of the direct voltage against the direct current. These are described in the following sections.

The Natural Voltage Characteristic corresponds to zero delay angle $\alpha=0$. This has the characteristics equation given by $V_d = V_o - (3\omega Lc/\pi) I_d$. The Constant Ignition Angle control is a similar characteristic which is parallel to the NV characteristic with a controllable intercept Vo cosα. These are shown in figure



Constant Extinction Angle (CEA) control

The Invertor is usually operated at constant extinction angle. This has the characteristic equation given by $V_d = V_o - (3\omega Lc/\pi) I_{d+}$. This is shown in figure



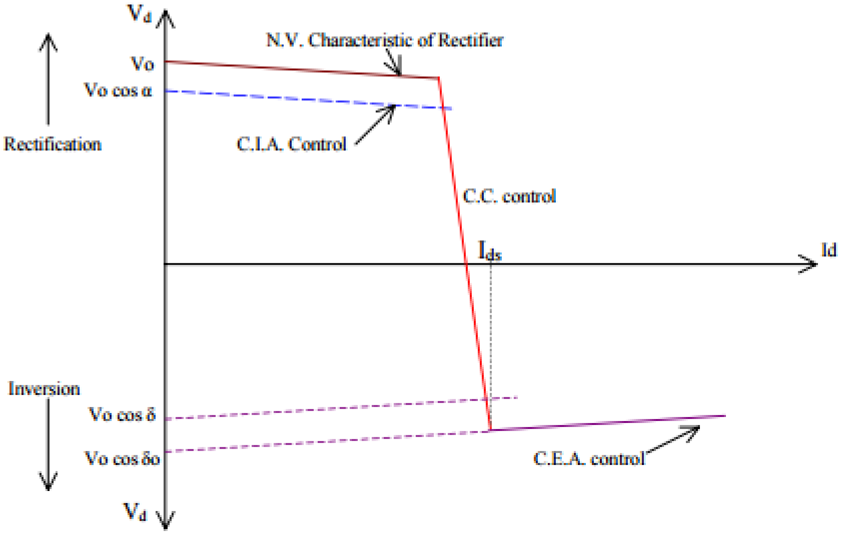
Constant Current Control (CC)

In a d.c. link it is common practice to operate the link at constant current rather than at constant voltage. [Of course, constant current means that current is held nearly constant and not exactly constant].

In constant current control, the power is varied by varying the voltage. There is an allowed range of current settings within which the current varies.

Full Characteristic of Convertor

The complete characteristic of each convertor has the N.V. characteristic and equipped with C.C. control and the C.E.A. control. This is shown in figure for a single convertor.



Note: The constant current controller adjusts the firing angle α so that the current is maintained at a set value, even for short-circuits on the d.c. line. The C.C. control is present in the invertors too, although the invertors are not usually operated in that region. The rectifier is normally operated in the C.C. region while the invertors are operated in the C.E.A. region.

Constant ignition angle control:

The operation of CC and CEA controllers is closely linked with the method of generation of gate pulses for the valves in a converter.

The following are the two basic requirements for the firing pulse generation of HVDC valves.

- The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signal through fibre –optic cables. The required power is made available at the potential of individual thyristors.

- While a single pulse is adequate to turn on a thyristors, the gate pulse generator must send a pulse whenever required, if the particular valve is to be kept in a conducting state.

There is of important when operating at low DC currents and a transient may reduce the current below holding current.

There are two basic firing schemes:

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

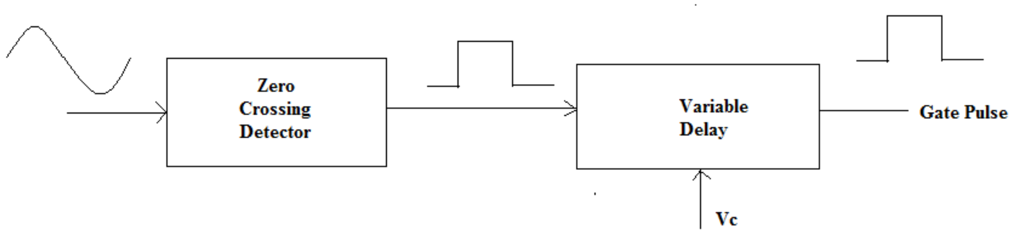
IPC was used in past and now it is replaced by EPC.

Individual phase control

The main feature of this scheme is that the firing pulse generation for each phase is independent of each other and the firing pulses are rigidily synchronized with the commutation voltage.

Constant α control

- In this control, six timing voltages are derived from converter AC bus via voltage transformer.
- Six gate pulses are generated at nominally identical delay times subsequent to the respective voltages zero crossings.



- The instant of zero crossing of a particular commutation voltage corresponds to α=0 for that value.
- The delays are produced by independent delay circuits and controlled by a common control voltage and derived from the current controllers.

Equidistant pulse control (EPC):

- In this scheme the firing pulses are generated in steady state at equal intervals of 1/pf, through a ring counter.

- This control scheme was first suggested by Ainsworth using a phase load oscillator to generate the firing pulses.

3 variations are there in EPC scheme

1. Pulse frequency control (PFC)
2. Pulse period control
3. Pulse phase control

4. With neat diagram explain the operation of twelve pulse converter.

Almost all thyristor-based converters developed recently have been 12-pulse. A 12-pulse converter, which fires a thyristor every 30°, is at left in Fig. 4. Its shorthand circuit symbol is at right. The basic building block for the 12-pulse converter is the 6-pulse converter.

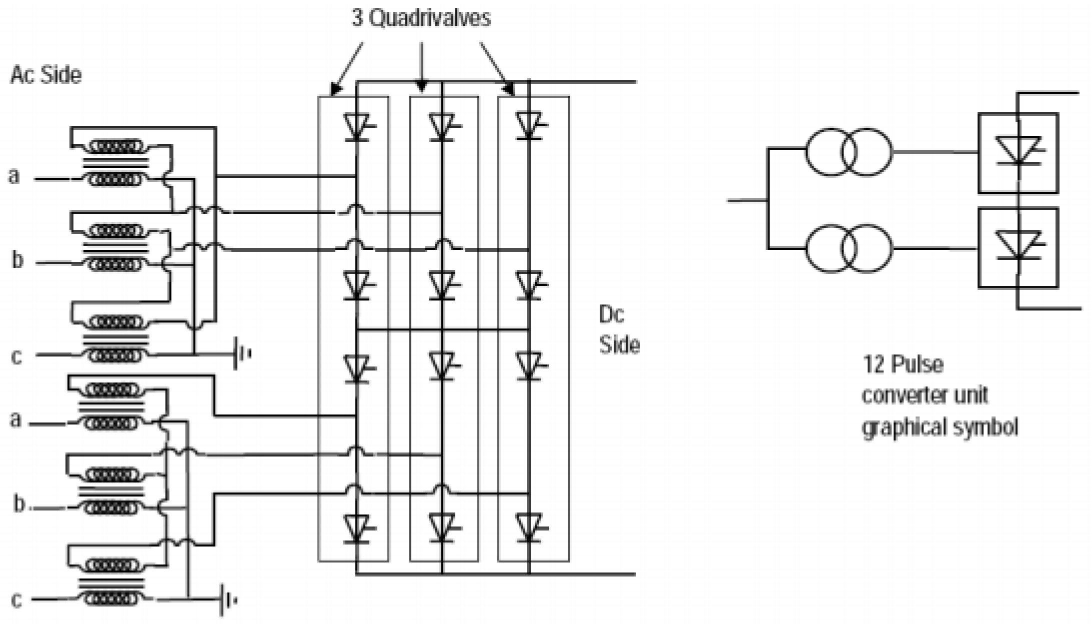


Fig 1: Twelve pulse Converter

We make three observations regarding Fig.1.

The two 6-pulse bridges are connected in series to increase the DC voltage. Because each thyristor may have a rating of only a few kV, handling voltages on the AC side may require stacking several valves in series. In the case of Fig. 4, each group of four valves shown as a single vertical stack are assembled as once valve structure by stacking four valves in series, referred to as a “quadivalve.” A ±500kV quadrivalve may have hundreds of thyristors stacked in series . The two transformers on the AC side are both fed from the same three-phase AC source;

however, to obtain 12 pulses that are symmetrically phase displaced by 30° , one transformer (the bottom one) is connected Y-Y and the other Y-Δ, so that the line to line voltages of the Δ-connected secondary (which are in-phase with the line to neutral voltages of the primary side) are 30° behind the line to line voltages of the Y-connected secondary. By taking appropriate polarities, one can obtain voltages that are phase displaced from one another by consecutive 30°, as shown in Fig.2 (dotted lines are polarity reversals). Winding ratios can be adjusted to achieve equal amplitudes.

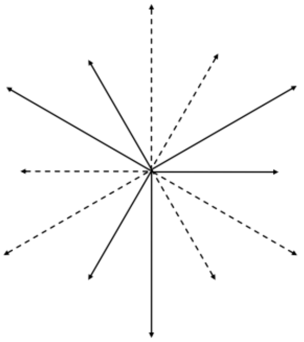


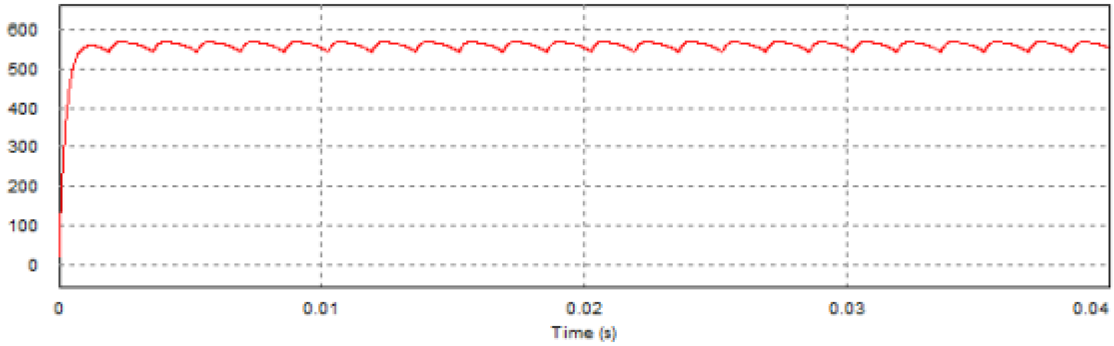
Fig2: Phasor Diagram

Possible methods of DC voltage control can be observed from inspection of equation (1), repeated here for convenience:)

$$V_{\mathrm{dc}} = \frac{3}{\pi}\int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} v_o(\omega t)d(\omega t) = \frac{3}{\pi}\int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} v_{ab}(\omega t)d(\omega t)$$

$$= \frac{3}{\pi}\int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} V_M \sin(\omega t)d(\omega t) = \frac{3V_M}{\pi}\cos\alpha$$

Here we see that we may control the DC voltage by controlling either the magnitude of the applied AC voltage Vm or the firing angle α.



DC output voltage

UNIT III

HVDC FAULTS AND PROTECTION

Converter faults, commutation failure, axis fire – Disturbance caused by over current and over voltage – Protection against over current and over voltage – Surge arrestors smoothing reactors – Corona effects of DC line – Transient over voltages for DC line – Protection of DC links.

Two Marks

1. What are the faults in converters?

- I. Faults due to malfunction of valves and controllers.
  - a) Arc backs in mercury arc valves
  - b) Arc through
  - c) Misfire
  - d) Quenching or current extinction
- II. Communication failure in inverters
- III. Short circuits in a converter stations.

2. Define Arc back (back fire)?

- a) The arc back is the failure of the valve to block in the reverse direction and results in the temporary destruction of rectifying property of the valve due to conduction in the reverse direction.
- b) It is a major fault in mercury are valves and it is not self clearing fault.

3. Define commutation failure?

Because of the turn off time requirement of thyristors there is need to maintain a minimum value of extinction angle.

$$\gamma=180-\alpha-\mu$$

The overlap angle(u) is a function of the commutation voltage and DC current. The reduction in the voltage or increase in the current of both can result in an increase in overlap angle which can result in . It leads to communication failure.

4. Define double commutation failure?

The failure of two successive commutations in the same cycle is called double commutation failure.

5. What are the effects of single commutation failure?

- a) The bridge voltage remains zero for a period exceeding 1/3 of a cycle, during which the DC current tends to increase.

b) There is no AC current for the period in which the two valves in an arm are left conducting.

6. **What are the factors needed to recover from commutation failure?**
   a) The response of gamma controller at the inverter.
   b) The current control in the line.
   c) The magnitude of AC voltage.
7. **Arc through:**
   a) It is a malfunction in the gate pulse generator or the arrival of specious pulse can fire a valve which is not supposed to conduct but it is forward biased.
   b) It is likely to occur in inverter station where the valve voltages are positive most of the time.
8. **Define Misfire.**

It occurs when the required gate pulse is missing and incoming valve is unable to fire. The probability of the occurrence of misfire is small in modern converter stations because of duplicated converter controls monitoring and protective firing of valves.

9. **Define current Extinction?**
   a) The excitation of current can occur in a valve, if the current through it falls below the holding current. This can arise at low values of bridge currents.
   b) Current extinction leads to over voltages across the valve due to current chopping in an oscillating circuit formed by smoothing reactor DC line capacitance.
10. **What are the factors must be considered in designing a protection system?**
    a) Selectivity
    b) Sensitivity
    c) Reliability
    d) Backup
11. **What are the types of faults produced due to over current? Write the remedies for these faults?**
    a) Internal faults- It cause high over currents, but are very infrequent. The thyristor surge current ratings must be chosen to withstand these over currents.
    b) Line faults- It causes over currents in the range of 2 to 3 Pu. These are limited by current control
    c) Commutation failure at increases may be quite frequent. It is also limited by current control
12. **What are the causes for over voltages in converter station?**
    a) Disturbances originating on AC side
    b) Disturbances originating on DC side
    c) Internal faults in the converter.
13. **What are the types of over voltages in AC system?**
    a) The switching over voltages (with wave front times >100ms)
    b) Temporary over voltages [lasting few sec]
    c) Steep front over voltages[with front times in the range of 0.3 to 3ms]
14. **What is meant by surge arresters?**

a) Surge arresters are a active spark gaps. It is used to extinguish the arrester current without exceeding the protective level and DC arresters were made up of non-linear resistors in series with spark gap
b) Now days with the development of metal oxide (Bi_2O_3, Zn_2O_3, Sb_2O_3) arresters, the need of a series gap has disappeared.

15. Define Corona.

Luminous discharge due to ionization of air surrounding a conductor caused by a voltage gradient exceeding a certain value.

16. What are the effects of corona?

a) Corona loss
b) Audible Noise
c) Radio and Television interference
d) Space charge field

17. What is the function of smoothing reactor?

a) They reduce the incidence of commutation failure in inverters and caused by dips in the AC voltage at the converter bus.
b) They reduce harmonic voltage of currents in the DC line.
c) They limit the crest current in the rectifier due to short circuit on the DC line.

They smooth the ripple in the DC in order to prevent the current becoming discontinuous at light loads

11 Marks

1. Brief notes on various types and causes of converter faults.

CONVERTER FAULTS:

There are three basic types of faults occur in converters as given below:

1. Faults due to malfunctions of valves and controllers

   i) Arc backs in mercury arc valves

   ii) Arc through (fire through)

   iii) Misfire

   iv) Quenching or current extinction

2. Commutation failure in inverters

3. Short circuits in a converter station

The arc back is the failure of the valve to block in the reverse direction and results in the temporary destruction of the rectifying property of the valve due to conduction I the reverse direction. This is a major fault in mercury arc valves and is of random nature. This is a non self clearing faults and results in severe stresses on transformer windings as the incidents of arc backs are common.

Fortunately, thyristors don't suffer from arc backs which have led to the exclusion of mercury arc valves from modern converter station. Hence this fault will not be considered in further discussion.

Some of the converter faults such as commutation failure, arc through and misfire are self clearing if the causes that led to these faults are of transient nature. However, they can still cause a major disturbance unless the system including the controllers is properly designed.

COMMUTATION FAILURE:

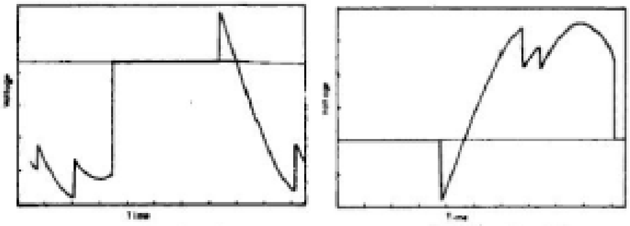
Because of turn-off time requirements of thyristors, there is need to maintain a minimum value of extinction angle defined by

$= 180-\alpha-u$

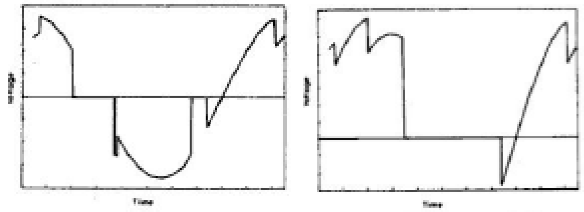
The overlap angle (u) is a function of the commutation voltage and the DC current.

The reduction in the voltage or increase in the current or both can result in an increase in the overlap angle which can result in < min. This gives rise to commutation failure. The current in the incoming valve (say valve 3) will diminish to zero and the outgoing valve (valve 1) will be left carrying full link current.

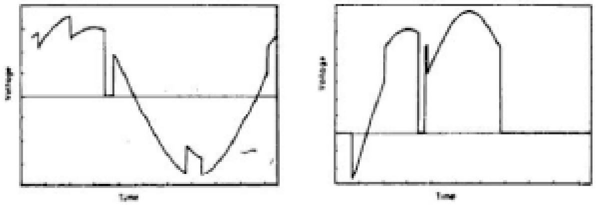
The firing of the next valve in sequence (valve 4) will result in the short circuit of the bridge as both valves in the same arm will conduct. If the commutation from valve 2 to valve 4 is successful, only valves 1 and 4 are left conducting and this state continues until the valve 6 is fired. The firing of valve 5 prior to the firing of valve 6 is unsuccessful of the valve 5 is reverse biased at the time of firing.



(a) Bridge voltage (b) Voltage across valve 2



(c) Voltage across valve 3 (d) Voltage across valve 4



(e) Voltage across valve 5 (f) Voltage across valve 6

Fig: Commutation Failure

If the commutation from valve 4 to valve 6 is successful, the conduction pattern returns to normal except that the bridge voltage is negative at the instant where valve 4 ceases conduction. If the causes which led to commutation failure in valve 1 in the first instance have disappeared, the bridge operation returns to the normal state. Thus, a single commutation failure is said to be self-clearing. The waveforms of the bridge voltage and valve voltages are shown.

The failure of two successive commutations in the same cycle, is called ‘double commutation failure’. If the commutation failure occurs when valve 4 is fired also the valves 1 and 2 are left in the conducting state until the instant in the next cycle when valve 3 will be fired. The bridge voltage for this case is shown in fig and it can be seen that the double commutation failure is more severe than the single commutation failure.

The following are the effects of a single commutation failure

1. The bridge voltage remains zero for a period exceeding 1/3 of a cycle, during which the dc current tends to increase.

2. There is no ac current for the period in which the two valves in an arm are left conducting.

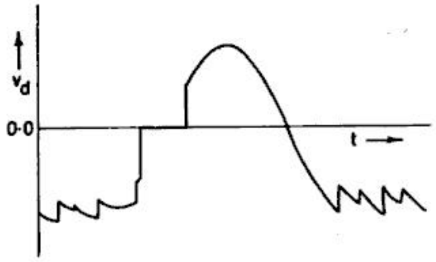


Fig Bridge voltage waveform for a Double commutation failure

The recovery from a commutation failure depends on the following factors

1. The response of the gamma controller at the inverter

2. The current control in the link and

3. The magnitude of the ac voltage

If, on detection of a commutation failure, the angle of advance (β) is increased, there is a good chance that subsequent commutation failures may be averted. However, this also depends upon the control of dc current and magnitude of ac voltage. The initial rate of rise of current in the inverter is limited by the smoothing reactor and the current controller at rectifier helps to limit the current in the case of persistent commutation failure. It may be even necessary to reduce the current reference to limit the overlap angle in the case of low voltages caused by faults in the ac system.

While in most cases commutation failures are self-clearing, in the case of persistent commutation failures, the converter differential protection helps to take the converter out of service. This protection is based on the comparison of dc and the valve side ac currents. During commutation failures when the two valves in an arm of bridge are left conducting, ac current goes to zero while the dc current continues to flow. The commutation failure in the bridge can lead to consequential commutation failures in the series connected bridges unless the rate of rise of current is sufficiently limited by the series connected smoothing reactors.

2. Discuss about the causes for overvoltage.

DISTURBANCE CAUSED BY OVER VOLTAGE

The over voltage in a converter station are caused by

(i) Disturbance originating on the ac side

(ii) Disturbance originating on the dc side

(iii) Internal fault in the converter

The type of over voltages as in the ac system, can be classified into three types

1. The switching over voltages (with wave front times of more than 100msec.)

2. Temporary over voltages (lasting few seconds)

3. Steep front over voltages (with front times in the range of 0.3 to 3 msec.)

1. DISTURBANCES ON THE AC SIDE:

The lightning strokes in the AC network cause steep-fronted high over voltages which are, however, reduced in magnitude and steepness by AC filters. After they pass through the converter transformer, they appear only as highly damped switching surges across the converter.

The initiation and clearing (by switching action) of the faults in the ac system result in switching surges and temporary over voltages. The energization of a converter transformer can cause high (upto1.6 p.u) overvoltage due to the inrush magnetizing currents and last upto 100 cycles. The voltage is also distorted due to even harmonics (typically 4th harmonic). This type of temporary overvoltage can cause severe stresses on the metal oxide surge arrestors due to excessive energy dissipation. Pre-insertion resistors in circuit breakers energizing the converter transformer are very effective in controlling these over voltages.

The temporary over voltages due to load rejection can be quite serious for converter stations connected to weak AC systems. The load rejection may be caused by blocking of the converter in response to the action of the protection system. During the load rejection, there is a possibility of self excitation in case of the isolated generating plant supplying the converters. This arises from the ac filters which appear as capacitive at fundamental frequency and result in self excitation of synchronous generators which cannot be controlled by AVR (automatic voltage regulator) action. The only solution is to switch off capacitor and filter banks.

2. DISTURBANCES ON THE DC SIDE:

The steep waveform surges in DC overhead lines are produced by lightning strokes. However, when they reach the converter through the smoothing reactor they appear as switching surges.

The switching surges at the converter are also caused by ground faults on a pole of bipolar dc link. Owing to capacitive and inductive coupling between the conductors, the surges also occur at the healthy pole. The magnitude and the wave shape of these surges arriving at the terminal are dependent on the type of termination – inductive, capacitive or resistive. The rate of decrease of voltage at the terminal is a variable that is usually utilized in line fault detection and the setting of the threshold value is based on the knowledge of the voltage waveforms.

The over voltages can also arise from the oscillation of current and voltage in the line caused by sudden jumps in the converter voltage (due to commutation failure and other converter faults) or injection of ac voltage of fundamental frequency and second harmonics. The switching of dc filter branches, parallel connection of poles can cause transient currents ad over voltages which will mainly stress the neutral bus and filter reactors.

3. OVERVOLTAGE CAUSED BY INTERNAL CONVERTER DISTURBANCES:

The series connection of thyristors and the spread in the delay times of the thyristors turn-on result in overvoltage across the device during turn-on. However, there are repetitive and have to be taken into account in the valve design and the choice of grading circuit (snubber circuit) parameters. The spread in the reverse recovery charges and the commutation overshoot also result in repetitive over voltages. Transient over voltages of very steep front may result from internal converter faults, such as a ground fault at the valve side of the smoothing reactor. The ground faults can also produce switching surge type over voltages, for example, a fault between the valve bridge and the converter transformer. The firing of bypass pairs or closing of the bypass switch across one converter generates over voltages across the remaining converters.

The energizing of the DC line from the rectifier side with the remote terminal blocked can cause high over voltages at the inverter which is open ended. Such events must be avoided by deblocking the inverter first and limiting the rate of decrease of the delay angle.

3. Discuss about protection against over current and over voltage with neat diagram.

PROTECTION AGAINST OVERVOLTAGES:

The basic principles of over voltages protection is the same in DC systems as in AC systems. These are given below:

1. The overvoltage stresses in equipment with non self-restoring insulation must be limited at all times by providing surge arresters. The protection level of the arresters must be lower than the breakdown voltage of the insulation.

2. Self restoring insulation such as air may be allowed to breakdown where there is o danger to the safety of the personnel.

3. The operation of surge arresters or flashover of air insulation must not be frequent. Frequent discharges of arresters may damage them. This implies that the protective level of arresters must be higher than the maximum operating voltage in the system.

4. There must be proper coordination of the insulation and overvoltage protection in different parts of the system, taking into account the characteristics of insulation, the nature of over voltages, etc.

The over voltages generated on the ac side should, as far as possible, be limited by arresters o the ac side. The over voltages generated on the dc side should be limited by dc line, dc bus and neutral bus arresters. The critical components such as valves are directly protected by arresters connected close to the components.

OVERVOLTAGE PROTECTION IN A CONVERTER STATION:

The typical arrangement of surge arresters in a converter station is shown. For a system with two 12-pulse converters per pole, there are about 40 arresters per pole. The arresters are selected with adequate energy dissipation capabilities which vary with the location of the arresters. For example, the valve arrester protecting the commutation group at the highest potential can be subjected to higher energies than other arresters when a ground fault occurs between the valve and the converter transformer in the upper bridge. This is due to the discharge of the lie and the DC filter.

The closing of a bypass switch across a converter results in increasing the DC voltage across the remaining converter. The converter unit arrester is stressed in such cases. The protective firing of a valve is the backup protection that is available for over voltages in the forward directions.

PROTECTION AGAINST OVERCURRENTS:

The over current protection in converters is based on principles similar to those used in AC systems. The factors that must be considered in designing a protection system are i) selectivity ii) sensitivity iii) reliability and iv) back up.

The main feature of converter protection is that it is possible to clear faults by fast controller action (in less than 20 msec) by blocking gate pulses or current regulation and control. The selectivity is also enhanced by high impedances of the smoothing reactor and the converter transformer. Further, the converters are divided into independent valve groups such that the protection system must be able to switch off only the affected valve group (or bridge).

Consider a converter station with a 12 pulse converter per pole (2 valve groups per pole). The protection system used for a pole is shown. This does not show protection against DC line faults, under voltages or transformer protection.

The basic protection against converter fault (considered in the previous section) is provided by valve group differential protection, which compares the rectified current on the valve side of converter transformer to the DC current measured on the line side of the smoothing reactor. The differential protection is employed because of its selectivity and fast detection. The over current protection circuit is used as back-up. The level of over current required to trip must be set higher than that of the valve group differential protection to avoid tripping with faults outside the station (that can be cleared by the control action).

The pole differential protection is used to detect ground faults which may not be otherwise detected, such as faults at the neutral bus.

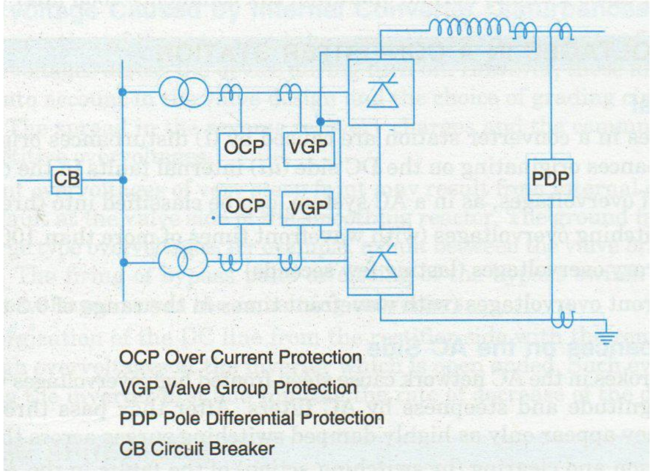


Fig: Protection against over current

The fault clearing action of these protection circuits is to block the valves and at the same time trip the AC breaker of the affected group or pole. The fast tripping sequence is used for internal faults where there is a danger of valve damage. This involves forced retard (Increasing the delay angle of the rectifier to about 150°) combined with the signal to trip the ac breaker. The pulses are blocked after 20ms this allows the inverter action (by forced retard) at the rectifier station to try to reduce the current before the converter is blocked.

The faults producing over current are classified into 3 categories:

1. Internal faults which causes high over currents but are very infrequent. The thyristors surge current ratings must be chosen to withstand the over currents.
2. Line faults which cause over currents in the range of 2 to 3 p.u. These are limited by current control.

3. Commutation failures at inverters may be quite frequent. However, the over currents are small and limited by current control. However, because of continuous conduction during commutation failures, the current reference has to be reduced.

In case 1, normal operation may commence only after the inspection of the valves to check for damage. In cases 2 and 3, normal operation can commence soon after fault clearing.

SURGE ARRESTER

In the initial stages of application of DC technology, dc surge arresters were not available; the valves were protected by the spark gaps connected across them. Later, with the development of active spark gaps, it was possible to extinguish the arrester current without exceeding the protective level and DC arresters were made of nonlinear resistors in series with the active spark gaps.

With the development of metal oxide resistors with high nonlinearity, the need for a series gap has disappeared and the present DC arresters are gapless arresters. The metal oxide elements were first applied in AC arresters in 1976. Comprising primarily of zinc oxide, but containing a number of other metal oxides (such as Bi_2O_3, Sb_2O_3, MnO_2, Cr_2O_3), as additives, the material has extremely nonlinear voltage current characteristics.

A typical disc that conducts less than a mill ampere of current at normal operating voltage carry currents of thousands of amperes as twice the normal voltage. This properly makes it possible to eliminate series connected spark gap and reduce the voltage margins due to the constancy of protective levels. The volt ampere curve for typical zinc-oxide disc is shown for different levels of operating temperature.

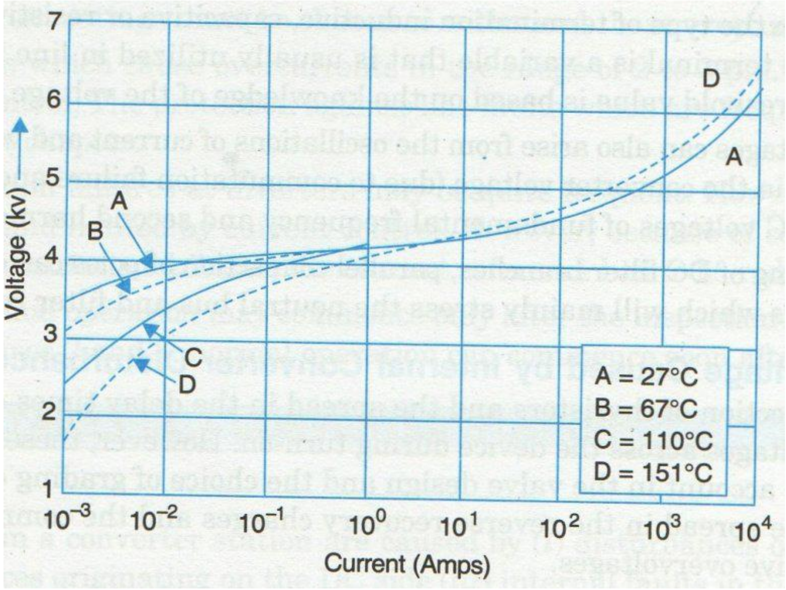


Fig. Voltage & Current waveform

It is seen that the temperature coefficient of the material is slightly negative at low currents, but becomes positive at current above a few amperes. This makes it possible to operate the zinc-oxide elements in parallel to discharge high energy surge. The long term stability of the material is satisfactory although it is influenced considerably by disc composition and processing.

The properties of the material are such that it is possible to design arresters to control dynamic over voltages in addition to switching surges. This results in economic insulation coordination. However, proper design of the arrester based on the evaluation of the energy losses is essential. The ultimate limit of the energy dissipation capability of a disc is imposed by the cracking of the disc under the thermal shock. A single column arrester is capable of absorbing around 7 KJ/KV of the maximum continuous operating voltage (MCOV).

In many DC applications the energy capability of a single column of discs is inadequate and multiple columns are used. A parallel column arrester is made up by selecting discs such that the voltage for each column is the same at a predetermined current. The maximum difference in the currents of parallel columns can be made less than 0.5%.

SMOOTHING REACTORS:

The smoothing reactors have many functions as given below:

1. They reduce the incidence of commutation failure in inverters caused by dips in the AC voltage at the inverter bus**.**
2. They prevent consequent commutation failures in inverters by reducing the rate of rise of current in the bridge when the direct voltage of another series connected bridge collapses.
3. They smooth the ripple in the direct current in order to prevent the current becoming discontinuous at light loads.
4. They decrease harmonic voltages and current I the DC line.
5. They limit the crest current in the rectifier due to a short circuit on the DC line.
6. They limit the current in the valves during the converter bypass pair operation, due to the discharge of shunt capacitances of the DC line.

It is to be noted that in back to back HVDC systems; the last three functions are not relevant. For systems with DC transmission lines, the inductors of value from 0.27H to 1.5H have been used. For back to back HVDC systems, the value ranges from 12mH to 200mH.

The sizing of the reactor is done not only from the considerations mentioned above, but also from the point of view of minimizing the effect of low order harmonic resonances in the AC/DC system. It is necessary to avoid series resonance of the DC system at fundamental frequency and also at the second harmonic. The effect of the inductive value on the resonant frequency (corresponding to the first peak of the admittance as seen by the converter) as a function of the DC filter capacitance is shown.

This shows that the resonant frequency is reduced by increasing the inductance.

The inductance value must remain practically constant with variation in the direct current. This requires air core construction. The smoothing reactor helps to limit the fault current in the dc line as mentioned above this is feasible only if the reactor does not get saturated by the fault current. By the way, it is to be noted that saturable reactors used for the limitation of di/dt in thyristor valves, cannot replace the smoothing reactor as smoothing reactors unaffected by saturation reduce commutation failures.

The location of the smoothing reactor can be either at the high voltage terminal or at the ground terminal as shown in fig. in the latter case, it is also necessary to have a small reactor of the order of 5 to 10 mH on the line side, to protect the converter station from the consequences of lightning strokes to the line. The advantage of having the reactor at the ground side is that it allows the converter ground faults to be cleared by converter control (of increasing the delay angle to its maximum limit to control the current). The insulation level of the reactor also is reduced for this location of the reactor.

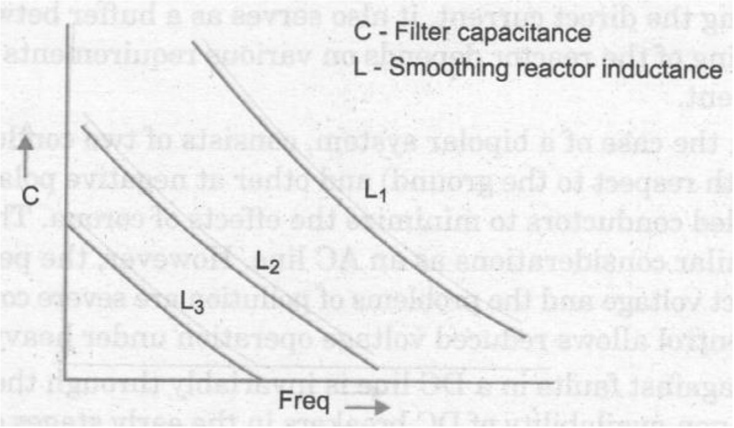


Fig: series resonance frequency as a function of smoothing inductor and filter capacitance

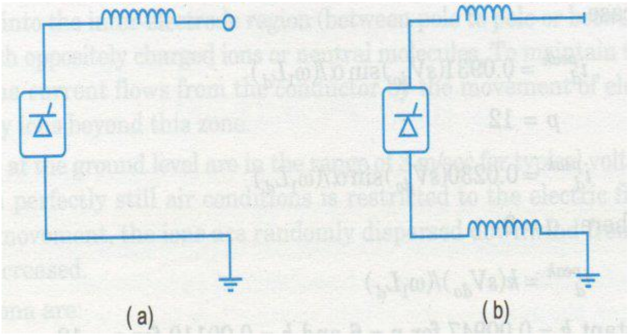


Fig: Location of Smoothing Reactor

There is little information available on the choice of the smoothing reactor. One criterion used is the Si factor defined below.

$$S_i = V_{dn} / (LI_{dn})$$

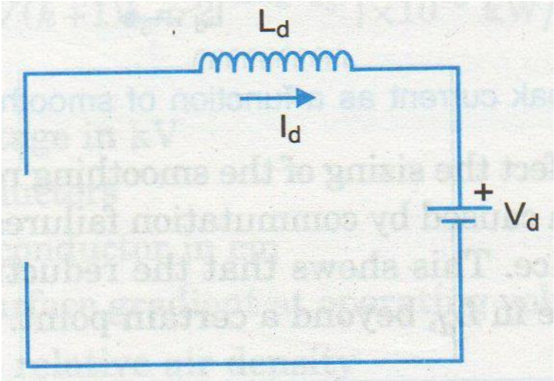


Fig Equivalent circuit for calculation of Ripple

Where and are the rated direct voltage (in kv) and direct current (in kA) respectively. L is the DC circuit inductance in mH which includes the transformer leakage inductance. This Si factor for back to back HVDC links varies from 0.24 to1.3 ms^-1. Higher the factor, lower is the rate of rise of the fault current.

Alternate criterion for the sizing of the reactor is the ripple in the direct current. For a converter feeding a constant voltage source through a constant inductor, the peak value of the ripple is given by

Where V_{do} is the no load DC voltage of a converter, S is the number of converters connected in series, is the pulse number, L_d is the inductance of the reactor,w_1 is the fundamental frequency. In deriving, the leakage reactance of the converter transformer is neglected. A major assumption used in deriving is that the delay angle α exceeds α where

$$\tan \bar{\alpha} = (p/\pi) - \cot(\pi/p)$$

$$p = 6,\ \bar{\alpha} = 10^\circ \text{ and for } p = 12, \bar{\alpha} \simeq 5^\circ$$

Where the constant k=0.00947 for p=6 and k=0.00119 for p=12.

It is necessary to avoid discontinuous conduction of current in the converter valves during the system operation. This is because of the possibility of over voltage across the valve that is transmitted from the line side.

Another factor that could affect the sizing of the smoothing reactors is the peak direct current during the bypass pair operation caused by commutation failures the effect of the smoothing reactor inductance. This shows that the reduction in the surge current is not commensurate with the increase in L_d, beyond a certain point.

4. Discuss elaborately the effects of corona.

CORONA EFFECTS OF DC LINE

The corona is defined as a 'luminous discharge due to ionization of air surrounding a conductor caused by a voltage gradient exceeding a certain value'. The ionization takes place in a zone which is a very thin circumference layer (not more than 2cm) surrounding the conductor surface. Within this zone, the high field strength caused high velocity particles to collide with the air molecules. Electrons are removed from the atoms of the air molecules and are accelerated towards the positive conductors or away from the negative conductor.

These high velocity electrons collide with other air molecules releasing additional electron in a avalanche process. The ions carrying the same charge as the adjacent conductor are repelled from the ionization zone at initial velocities of about 1.4 cm/sec for positive ions and 1.6 cm/sec for negative ions for every v/cm of the field strength.

The ions moving into the inter electrode region (between pole to pole or between pole to the ground) recombine with oppositely charged ions or neutral molecules. To maintain the net charge in this region, a corona current flows from the conductor by the movement of electrons in the ionization zone and by ions beyond this zone.

The ion velocities at the ground level are in the range of 3m/sec for typical voltage gradient. The ion movement in perfectly still air conditions is restricted to the electric field direction. However, with wind movement, the ions are randomly dispersed downwind from the DC line. The losses are also increased.

The effects of the corona are

1. Corona loss
2. Radio and television interference
3. Audible noise
4. Space charge field

While the first three effects occur on AC lines also, the last one is peculiar to DC lines. It involves the effect of movement of ions which results in the increase in the voltage gradient at the ground level. The 'electrostatic field' is defined as the field resulting from the charges on or near the conductor surface. The total 'electric field' results from the superposition of the electrostatic and space charge fields.

Corona Loss

The power losses due to corona can be expressed as

$$P_{\text{loss}} = [2V(k+1)k_c n r 2^{0.25(g-g_0)}] \times 10^{-3}\ \text{kW/circuit} - \text{km}$$

The relative air density δ is given by

$$\delta = 2.94p/(273+T)$$

$$g = \frac{[1+(n-1)(r/R)]V}{nr \cdot \ln\left[\dfrac{2H}{(nrR^{n-1})^{1/2}[(2H/S)^2+1]^{1/2}}\right]}$$

The other quantities are as defined earlier. In refers to the natural logarithm. The power loss predicted by eq gives correctly the mean fair-weather corona loss levels. With rain, the DC losses may increase by a factor of 10 to 1 while AC losses may increase by 50 to 1.

However, the average ratio of rain weather loss to fair-weather loss varies from 2 to 4, with higher ratios application to operation at lower gradients.

The bipolar corona loss per pole is higher than the mono polar corona loss by a factor of 1.5 to 2.5. However, for a given voltage, the positive and negative polarity losses are approximately equal. DC corona losses usually increase with wind velocity in the range of 0

to 10 m/sec.

5. Explain how transient voltages are produced in DC line with neat waveforms

TRANSIENT OVERVOLTAGES IN DC LINE:

Pole to ground faults in bipolar DC lines can result in transient overvoltages in the healthy pole of magnitudes exceeding 2.0 p.u(although typically they are 1.7 p.u). The maximum overvoltage occurs at midpoint in a pole when the fault is also at the midpoint of the other pole. For off-centre faults, the maximum overvoltage occurs at a location which is a mirror image of the fault location (with respect to the midpoint). For example, if a fault occurs at a point of one third distance from the receiving end.

There are two modes of travelling waves on a bipolar dc line. One is termed as the pole to pole mode (analogous to positive sequence) while the other is termed as the pole to ground mode (analogous to zero sequence). If the prefault voltage is V at a given location, it can be shown that immediately after the fault, the voltage at the other pole rises by an amount

ΔV, given by

$$\Delta V = [(Z_0 - Z_1)/(Z_0 + Z_1)]V$$

Where z0 and z1 are the surge impedances of the first and second mode respectively,

Generally z0>z1 . For typical values of z0 and z1 ,ΔV=0.3V. The travelling waves originating at the fault location travel in both directions and arc reflected by the terminals. The kind of termination at the converter station-inductive, capacitive or resistive has a bearing on the voltage waveform at the converter and the line.

The typical voltage waveforms at the midpoint and the terminal are shown for i) inductive, ii) capacitive and iii) resistive terminations. The following conclusions can be drawn from a digital computer study of the transient over voltages.

1. With capacitive termination to the wave front, overvoltage in the un faulted pole is caused by pole to pole mode. The attenuation and distortion of this mode is slight.

2. The surge capacitor, while helping in reducing the overvoltage at the terminal, does this at the expense of the DC line. It is desirable to use a surge arrester to protect the terminal against over voltages.

3. The resistive termination of the wave front with R=Z, is the best and can be achieved by putting R=Z1 in the high pass DC line and not having a surge capacitor.

4. With inductive termination to the wave front, over voltages are caused by the pole to ground mode for which the attenuation is sustainable. But the over voltages at the terminal are high.

5. It is desirable to provide extra insulation around the middle portion of the DC line to take care of the highest over voltages that may occur in that zone.

6. With the capacitive termination, the lowest limit o the dv/dt setting of the line fault protection is determined by the maximum fault resistance above which the fault will not be detected.

It is also necessary to provide a time delay in the operation of the protection (using dv/dt) to prevent the healthy pole. Typically, a time delay of about 3 milliseconds may be adequate.

The tests carried out on Pacific intertie and subsequent simulation using digital computer have shown that the modeling of frequency dependent characteristics of the line for both modes is essential for accurate prediction of the over voltages.

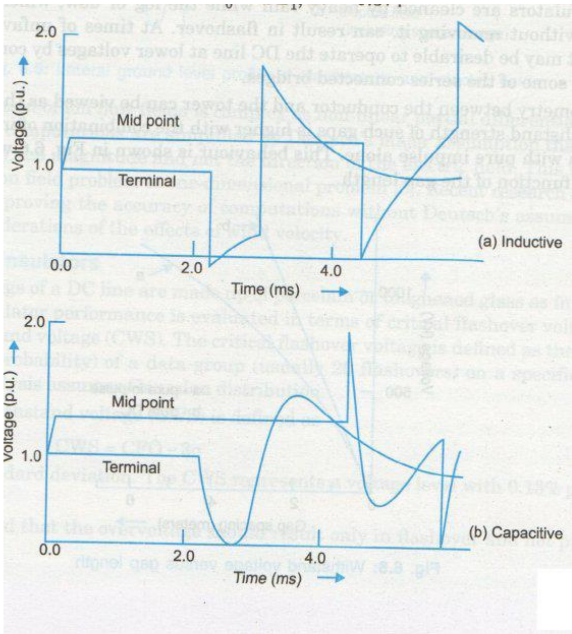


Fig Overvoltage waveform for a) Inductive, b) Capacitive

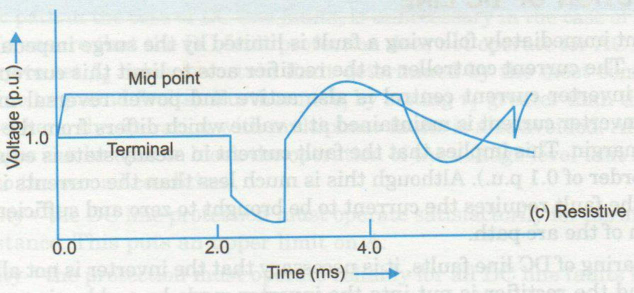


Fig:Transient Voltage Waveform

PROTECTION OF DC LINE:

The fault current immediately following a fault is limited by the surge impedance and is of the order of 2.0 p.u. The current controller at the rectifier acts to limit this current to the pre fault current. If the inverter current control is also active and power reversal in the inverter is permitted, the inverter current is maintained at a value which differs from the rectifier current by the current margin. This implies that the fault current in steady state is equal to the current margin (of the order of 0.1p.u.). Although this is much less than the currents in AC line faults, the clearing of the fault requires the current to be brought to zero and sufficient time given for the deionization of the arc path.

For fast clearing of dc line faults, it is necessary that the inverter is not allowed to operate as a rectifier and the rectifier is put into the inverter mode by sudden increase in delay angle to its maximum limit(about 135°). The converters at both terminals then help in discharging the energy stored in the DC circuits (in capacitances and inductances) and delivering it to the ac system. The current and voltage in the dc line fault to zero ad help in

deionizing the arc path. After some time has elapsed (say 0.2 to 0.5 sec), the line may be automatically energized by restarting the converters (in the usual manner by ramping up the direct voltage and current). If the restart is unsuccessful, due to a persistent fault, the protective action will de energize the line again normally three attempt are made to restart automatically with increasing dead time. The failure to restart even after three attempts implies a permanent fault and requires shutdown of link until the fault is located and cleared.

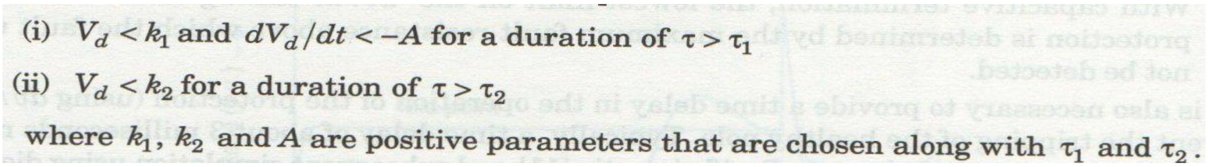
Alternately, reduced voltage restart may try out if the insulation failure is due to heavy pollution on the line insulators and in bad weather.

The automatic deenergization and restarting of the dc link is similar to the clearing of the fault and automatic enclosure in ac lines. The major difference in the two cases being that while breakers are used in AC lines, the clearing and restarting is performed in DC systems using only converter control with the help of protective relays.

DETECTION OF LINE FAULTS:

As mentioned earlier, the normal converter control is not adequate for clearing the fault. The de energization of the line by driving the rectifier into the inverter mode requires special control action which is initiated on detecting the line fault.

The detection of the line fault is based on the following conditions (i) a sudden drop in the DC voltage measured on the line side of the reactor, or (ii) sustained low direct voltage.



(i) $V_d < k_1$ and $dV_d/dt < -A$ for a duration of $\tau > \tau_1$

(ii) $V_d < k_2$ for a duration of $\tau > \tau_2$

where k_1, k_2 and A are positive parameters that are chosen along with τ_1 and τ_2.

The criteria for selecting these parameters are as follows:

1. Selectivity –to ensure that the protection operates rapidly for the dc line faults and not for ac faults or converter faults. The smoothing reactor prevents the rate of voltage of in the line exceeding a limit for ac and converter faults. By choosing A higher than this limit, it is ensured that the voltage derivative unit does not operate for faults other than dc line faults.

Selectivity is desirable as the dead time require for deionization of the arc path in the case of dc line faults, is unnecessary in the case of ac or converter faults. To ensure that the dc fault protection does not operate for ac faults, it is also necessary to set k2below a certain limit determined by most common ac faults (single line to ground faults). Furthermore by setting greater than the clearing time of ac breakers, the operation with multiphase faults is also avoided. Alternatively, low ac voltages can be used to block the operation of the voltage level unit (which operates subject to the second condition).

2. Sensitivity -the dc line protection must operate satisfactorily for normal values of the arc resistance. This puts an upper limit on A.

3. Reliability – the protection must operate reliably for all dc line faults including faults through a high resistance. This is the reason for providing the voltage level unit. k_1 and are selected such that the protection does not operate for the healthy pole (and only for the faulted pole). This is essential as, in bipolar dc lines, the power can be transmitted at sufficient levels even after a monopolar ground fault.

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UNIT IV

REACTIVE POWER AND HARMONICS IN HVDC

Sources of reactive power - static VAR system – Reactive power control during transients Generation of harmonics – Types and design of various AC filters, DC filters interference telephone - RI noise.

Two Marks:

1. **How reactive power control is achieved by forced commutation?**

   The reactive power requirements of a converter can be reduced to zero or even reversed if forced commutation is used. This also helps in avoiding commutation failures in inverters.

2. **How forced commutation is used?**

   Forced commutation involves addition of voltage component to the normal commutation voltage to shift the zero-crossing. This can be implemented by providing series capacitors. This method is adopted in capacitor commutated inverters.

3. **What are the sources of reactive power?**

   The reactive power requirements of converter can be met by one or more of the following sources

   - AC system
   - AC filters
   - Shunt capacitors
   - Synchronous condensers
   - Static VAR Compensator (SVC) or STATCOM

4. **What are synchronous condensers?**

   Synchronous condensers are essentially synchronous motors operating at no load, with excitation control to maintain terminal voltage.

5. **Advantage of synchronous condensers?**

   a) The availability of voltage source for commutation at the inverter evenif the connection to the AC system is temporarily interrupted. This also implies increase in SCR as the fault is increased. When the load supplied by the inverter.

   b) Better voltage regulation during transient due to maintenance of flux linkage in the rotor windings. The effect of the armature reaction is counter acted during a transient by induced currents in the field and a mortisseur circuits.

6. **Disadvantages of synchronous condensers?**
   a) High maintenance and cost
   b) Possibility of instability due to the machine going out of synchronism.
7. **What are the configurations of SVC?**
   a) Fixed capacitor(FC)
   b) Thyristor controlled reactor(TCR)
   c) Thyristor switched capacitor(TSC)
8. **Compare SVC and STATCOM?**

   A STATCOM has several advantages over SVC
   a) Faster response which is independent of the network impedance.
   b) Requires less space as bulky passive components are eliminated.
   c) Inherently modular and re locatable.
   d) It can be interfaced with real power sources such as battery, fuel cell, SMES.
9. **Why suitable reactive power control is required during transients?**
   a) Controls of dynamic over voltages caused by load rejection.
   b) Speed recovery of power following a fault in the inverter systems
   c) Control of instability.
10. **What are the problems associated with injection of harmonics?**
    a) Telephone interference
    b) Extra power loss and consequent heating in machines and capacitors connected in the system
    c) Over voltages due to resonance
    d) Interference with ripple control systems used in load management
11. **What are the types of harmonics?**
    a) Characteristic harmonics
    b) Non-characteristic harmonics

12. **What are the characteristics harmonics?**

    These are harmonics which are always present even under ideal operations balanced AC voltages, symmetric three phase networks and equidistant pulses.

13. How non characteristic harmonics are generated?

They are due to

a) Imbalance in operation of two bridges forming a 12 pulse converter.

b) Firing angle errors

c) Unbalance and distortion in AC voltages

d) Unequal transformer leakage impedances

14. What are the types of filters?

Filters are of two types

a) Active filters

b) Passive filters

Passive filters are classified as tuned filters and damped filters

15. What are the problems involved in analysis of interference?

a) Determination of magnitude of noise produced by converter valves

b) Coupling between noise source and carrier system

c) Methods of reducing the coupling to avoid harmful interference.

Eleven Marks

1. Explain in detail the concept of reactive power requirements in HVDC converters?

The reactive power requirements of the converter are met by one or more of the following sources:

1). AC system

2). AC filters

3). Shunt capacitors

4). Synchronous condensers

5). Static var system.

From voltage regulation, losses and stability considerations,it is not desirable to draw reactive power from the system. These are for two cases,

(i). SCR=2.0 and

(ii). SCR=3.0

In both cases, an impedance angle of 84.3◦ is assumed and V=1.0p.u.

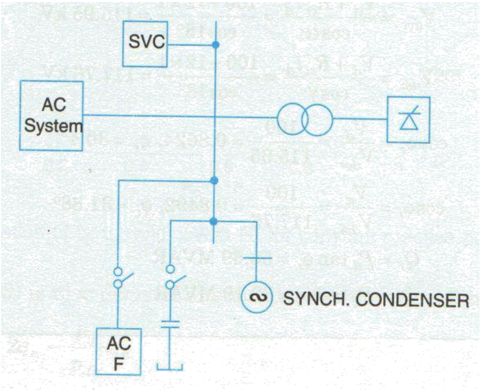


Fig. Reactive power source at converter

The voltage regulation at the converter bus is desirable not only from the voltage control view point but also from the minimization of loss and stability considerations. This requires adjustable reactive power as demanded. For slow variations in the load, switched capacitors or filters can provide some control. However, this is discrete type of control and result in voltage flicker unless the size of the unit, which is switched, is made sufficiently small. In contrast, the synchronous condensers and static var systems provide continuous control of the reactive power and can follow fast load changes.

The synchronous condensers are essentially synchronous motors operating at no load, with excitation control to maintain the terminal voltage. Their advantages are as follows:

1. The availability of voltage source for commutation at the inverter even if the connection to the AC system is temporarily interrupted. This also implies an increase in SCR as the fault level is increased. When the load supplied by the inverter is passive, the synchronous condenser is essential for providing voltage sources for the line commutation at the inverter.
2. Better voltage regulation during a transient due to the maintenance of flux linkages in the rotor windings. The effect of the armature reaction is counteracted during a transient by induced current in the field and amortisseur circuits.

There are also disadvantages of synchronous condensers. They are

(i). High maintenance and cost- the former necessitated by slip rings and brushes on the rotor.

(ii). Possibility of instability due to the machine going out of synchronism.

The static var systems (SVS) provide the fastest response following a disturbance. The configurations normally used are

(i) Fixed capacitor (FC), Thyristor controlled reactor (TCR)
(ii) Thyristor switched capacitors (TSC) - TCR combination.

The passive AC filters that are provided at the converter bus for filtering out AC current harmonics appear as capacitors at the fundamental frequency and thus provide reactive power. These filters and shunt capacitors are mechanically switched. Although these devices are less expensive than SVS, they suffer from the inability of continuous control. Also they can cause low order resonances with the network impedance, resulting in harmonic over voltages.

2. Explain about the DC filters?

DC FILTERS

The harmonic in the DC voltage across the converter contain both characteristic orders. These harmonic results in current harmonics in DC lines and cause noise in telephone circuits.

The harmonic current generated in the line can be computed from the knowledge of harmonic voltage sources at the converters, smoothing reactor, DC filter and line parameters. The harmonic current varies with the distance (from the converter station) along the line.

The effectiveness of the DC filter is judged by one of the following criteria:

1. Maximum voltage TIF on DC high voltage bus
2. Maximum induced noise voltage (INV) in milli volts/km in a parallel test line one kilometer away from the HVDC line
3. Maximum permissible noise to ground in dBrnc in telephone lines close to HVDC lines.

The second criterion is widely used and involves the computation of harmonic currents and the mutual impedance which depends upon factors such as

(i) earth resistivity
(ii) monopolar or bipolar operation
(iii) ground or metallic returns.

The variation of C message weighed INV for the three cases,

(i) bipolar mode
(ii) monopolar with earth return
(iii) monopolar with metallic return as function of the distant from the converter station.

Typically INV kg 18- 20 m V/km for monopolar operation is allowed.

The DC filters are also of single or double tuned type to filter out 6th and 12th harmonics and a high pass filter for higher order harmonics.

The choice of DC filters also affect over voltages due to DC line resonances and line faults. The smoothing reactor and the surge capacitor play a role in the first and the second case respectively. It is found that DC filters help in limiting the overvoltage at the DC terminals caused by monopolar DC line faults.

The design of DC filters is similar to that of the AC filters except that the value of the capacitor in the filter is chosen from considerations other than that of the reactive power (at fundamental frequency) which becomes irrelevant. The DC filters are also stressed by direct voltages in addition to harmonic voltages. Computer programmes are generally used in evaluating the performance of filters (both AC and DC) and dimensioning them

3. What are the types of AC filters?

ANS: The following are various types of AC filters that can be used:

1. Single tuned filter
2. Double tuned filter
3. High pass filter
    (i)Second order filter
    (ii) C type filter

The configuration of these filters and their impedance characteristics as a function of the frequency, are shown in table

The single tuned filters are designed to filter out characteristic harmonic of single frequency. The double tuned filters are used to filter out two discrete frequencies, instead of using two single tuned filters. Their main advantages are

(i) only one inductor is subject to full line impulse voltage

(ii) Power loss at the fundamental frequency is considerably reduced.

The second order high pass filters are designed to filter out the higher harmonics. The tuning of these filters is not critical. The losses at the fundamental frequency can be reduced by using a C type filter where the capacitor C2 in series with L, provides a low impedance path to the fundamental component of current.

A typical converter system with 12 pulse converters has double tuned filter banks to filter out 11th and 13th harmonics and a high pass filter bank to filter out the rest of harmonics. Sometimes a third harmonic filter may be included to filter out the non-characteristic harmonic of the third order (particularly with weak AC systems where some voltage unbalance is expected).

All the filter branches appear capacitive at fundamental frequency and supply reactive power.

4. Design criterion for AC filters?

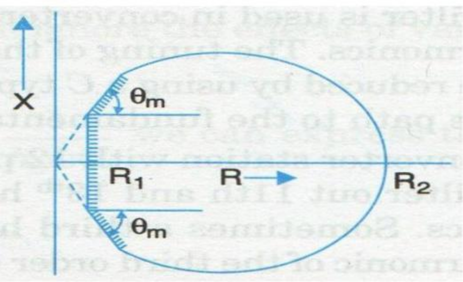
REACTIVE POWER REQUIREMENTS

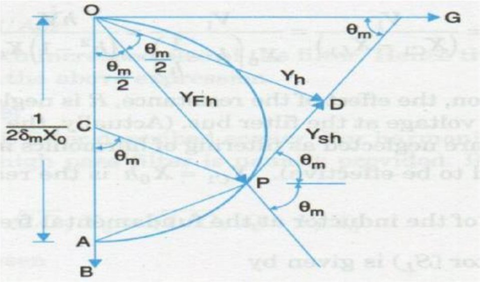
The reactive power consumption of an HVDC converter depends on the active power, the transformer reactance and the control angle. It increases with increasing active power. A common requirement to a converter station is full compensation or overcompensation at rated load. In addition, a reactive band for the load and voltage range and the permitted voltage step during bank switching must be determined. These factors will determine the size and number of filter and shunt capacitor banks

HARMONIC PERFORMANCE REQUIREMENTS

HVDC converter stations generate characteristic and non-characteristic harmonic currents. For a twelve-pulse converter, the characteristic harmonics are of the order $n = (12 * k) \pm 1$ ($k = 1,2,3$ ...). These are the harmonic components that are generated even during ideal conditions, i.e. ideal smoothing of the direct current, symmetrical AC voltages, transformer impedance and firing angles.

The characteristic harmonic components are the ones with the highest current level, but other components may also be of importance. The third harmonic, which is mainly caused by the negative sequence component of the AC system, will in many cases require filtering. An equivalent circuit for determination of harmonic performance is given in figure 5.4.1-3. The most commonly used criteria for harmonic performance are related to the harmonic voltage on the converter station bus bar.





The purpose of the filter circuit is to provide sufficiently low impedances for the relevant harmonic components in order to reduce the harmonic voltages to an acceptable level. The acceptance criteria for the harmonic distortion depend on local conditions and regulations. A commonly used criterion for all harmonic components up to the 49th order is as follows: D_n individual harmonic voltage distortion of order n in percent of the fundamental AC bus bar voltage (typical limit 1%) D_{rms} total geometric sum of individual voltage distortion D_n (typical limit 2%)

The BTS Telephone Interference Factor (TIF) and the CCITT Telephone Harmonic Form Factor (THFF) are determined with weighted factors in order to evaluate the voltage distortion level on the AC bus bar with respect to the expected interference level in nearby analogue telephone systems. The IT product is a criterion for harmonic current injected into AC overhead lines. The criteria based on telephone interference are in many cases irrelevant, because modern digital telephone systems are insensitive to harmonic interference.

NETWORK IMPEDANCE

The distortion level on the AC bus bar depends on the grid impedance as well as the filter impedance. An open circuit model of the grid for all harmonics is not on the safe side. Parallel resonance between the filter impedance and the grid impedance may create unacceptable amplification of harmonic components for which the filters are not tuned. For this reason, an adequate impedance model of the grid for all relevant harmonics is required in order to optimize the filter design.

There are basically two methods to include the network impedance in the filter calculations: • to calculate impedance vectors for all relevant harmonics and grid conditions • to assume locus area for the impedance vectors the modeling of a complete AC network with all its components is very complex and time-consuming. For this reason, the locus method is very often used. It is based on a limited number of measurements or calculations.

Different locus areas for different harmonics or bands are often determined to give a more precise base for the harmonic performance calculation. A typical locus area is shown in fig. It is assumed that the impedance vector will be somewhere inside the perimeter of the coloured area. The impedance vector of the filter is transformed into the Y plane for each harmonic frequency. With both the network and the filter impedances plotted in the admittance plane, the shortest vector between the filter admittance point and the network admittance boundary gives the lowest possible admittance value for the parallel combination of the network and the filter. This value is used to determine the highest possible harmonic voltage.

5. Explain in detailed about the carrier frequency and radio interference?

HVDC converter stations can 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 Hertz range of frequencies. However, converters are usually located in buildings which are effectively shielded against electromagnetic radiation. Hence the contribution due to direct radiation from valves can be neglected. The radiation from the switchyard can predominate over that produced by DC lines. Effective PLC – RI filters are necessary to minimize the impact if the noise and elimination of interference with power line carrier communication.

The configuration of a PLC/RC filter shown figure. The attenuation requirements of the filters are shown figure. The actual attenuation of the noise by the filter must be above the curve shown in figure.

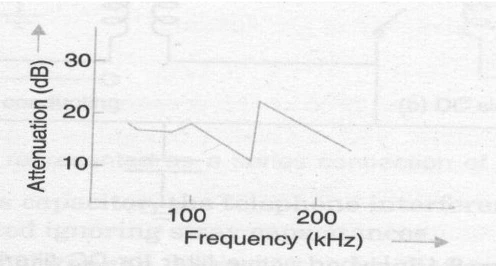


Fig: Configuration of PLC/RC filter

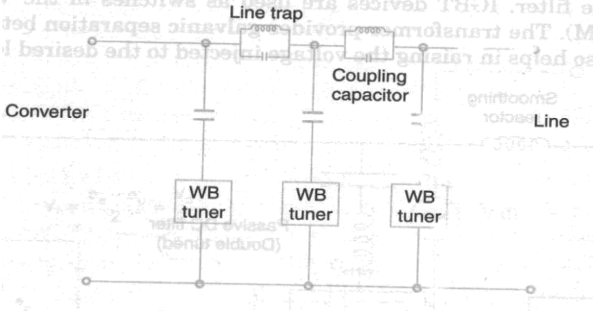


Fig: Noise of filter

RADIO INTERFERECE

The most predominant corona effect that may determine the conductor design is the radio interference. This is measured at a frequency of 1MHz and for a receiver bandwidth of 9kHz, at a horizontal distance of 30 meter from the outermost conductor.

The RI is mainly due to the positive conductor. This is because of the fact that the corona discharges from the negative conductor are in the form of Trichel pulses which are uniformly distributed over the conductor surface. Positive corona discharge are of three types-Hersteing low, plume discharge and usually associated with high stress points due to surface imperfection. These are mainly responsible for the RI.

The expression for RI (in decibels above the field strength of 1µV per meter)is empirically obtained as

$$RI=25+10\log n+20\log r+1.5(g-g_{o})$$

This is due to the positive conductor. The RI due to the negative conductor is about 20 db lower and is not of consequence. Interestingly, DC-RI levels are decrease by rain and wet snow which completely wet the conductor. This phenomenon is opposite to that in AC conductors.

DC-RI level are increased by wind, with maximum increase during the wind flow from negative to positive conductor.

The bipolar lateral RI profile is symmetric about the positive pole and attenuates inversely as the square of the distance from the conductor initially(upto 50 meter) and inversely as the distance thereafter.

The television interface (TVI) with DC lines is mainly due to the ion current and is of little consequence at distance greater than 25 meters from the right of way.

AUDIBLE NOICE (AN)

The corona discharges from the conductor produce compressions ad rarefactions that are propagated thought the medium as acoustical energy .The portion of the acoustical energy spectrum that lines within the sonic range is perceived as audible noise (AN).

The sound level is decibels and is defined as

$$dB = 20 \log (P/PR)$$

where P is the measured sound – pressure level and PR is the reference pressure level . The standard level for PR is 20µ Pascal which is the average threshold of audio perception at 1 kHz. Test line studies [3] indicate that ±600 kV DC lines would produce an audible noise of 45 to 55dB measured at 30 meters from the ROW centerline. This is not considered to be serious. In general, the annoyance produced by the audible noise varies linearly with the conductor surface voltage gradient.

The test results also show that positive polarity conductor is the primary source of AN. Rain causes a very slight reduction of AN.

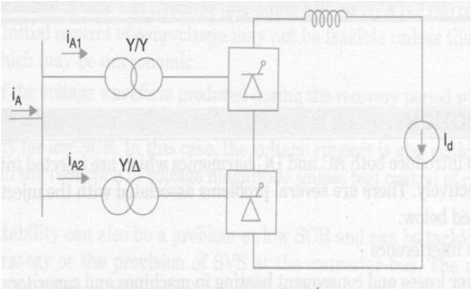
Audible noise is produced in converter stations by converter transformers and smoothing reactors due to the phenomenon of magnetostriction. Although higher AN is to be expected in converter transformers (compared to transformers in AC substations) due to the presence of harmonics, this is counterbalanced by the operation at lower flux densities in the core. Audible noise has not been a serious problem in converter stations

6.Derive the Expression fro calculation of ac harmonics.

Consider 12 pulse converter unit and from Fourier analysis, it can be shown neglecting overlap, that the current in the primary side of star-star connected transformer is given by

The line current Ia in Fig can be expressed in a Fourier series as

$$I_a = 2\sqrt{3}\,\pi\, I_d\{\sin(\omega t-\varphi) - 1/5 \sin 5(\omega t-\varphi) - 1/7 \sin 7(\omega t-\varphi) + 1/11 \sin 11(\omega t-\varphi) + 1/13 \sin 13(\omega t-\varphi) - 1/17 \sin 17(\omega t-\varphi) - 1/19 \sin 19(\omega t-\varphi) + \ldots\ldots\}$$



12 pulse converter

where, φ is the phase angle between the supply voltage Va and the fundamental frequency line current ia1.

The rms value of Ia can be given as Ia=2√ 3 Id = 0.816 Id

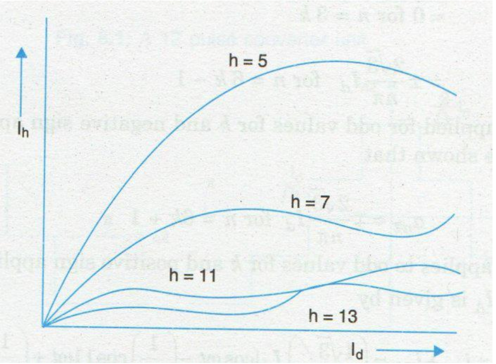


Fig :Harmonic Magnitudes with variation in DC currents

NON-CHARACTERISTIC HARMONICS:

The harmonics of the order other than the characteristic harmonics are termed as non characteristic.

These are due to

(i) Impedance in the operation of two bridges forming a 12 pulse converter

(ii) Firing angle errors

(iii) Unbalance and distortion in AC voltages

(iv) Unbalance and distortion in AC voltages

(v) Unequal transformer leakage impedances.

The harmonics produced due to the first cause are termed as residual harmonics. These are mainly due to the difference in the firing angles in the two bridges which lead to unequal cancellation of the harmonics of order 5, 7, 17, 19, etc. the unequal leakage impedances of the two converter transformers feeding the two bridges also lead to residual harmonics. The last three causes can lead to the generation of triplen and even harmonics and their analysis is complex.

HARMONIC SPECTRUM AND DISTORTION FACTOR

Harmonic spectrum and distortion factor Ideally, the harmonics produced by the semiconductor converter equipment in steady state condition of operation are called characteristic harmonics of the converter and are expressed as: $h=np \pm 1$

where, h = order of harmonics n = an integer 1, 2, 3,….

p = number of pulses per cycle

For a single phase bridge rectifier, the number of pulses $p = 2$ for one cycle of line frequency and therefore the characteristic harmonics are: $h = n .2 \pm 1 = 1$ (fundamental), 3 , 5 , 7 , 9 , 11 …..

For a three phase bridge rectifier, since the number of pulses $p = 6$ per line frequency cycle, the characteristic or dominant harmonics are: $h = n \cdot 6 \pm 1 = 5, 7, 11, 13, 17, 19, 23, 25, 35, 37\ldots$ Similarly, the characteristic harmonic currents for a 12-pulse rectifier will be: $h = n \cdot 12 \pm 1 = 11, 13, 23, 25, 35, 37\ldots$ Above mentioned characteristic harmonics are for an ideal steady state operation of the converter and assuming the AC power supply network is symmetrical and the AC supply is pure sinusoidal (free from harmonics).

Any divergence from the abovementioned hypothesis will introduce “non-characteristic” harmonics including possibly DC component. In practical situation, the supply networks or connected equipments never follow the abovementioned ideal condition and therefore, the actual measured harmonics will not be exactly as calculated from above Equation. Moreover, it should be noted that in four-wire distribution systems (three-phase and neutral), the currents in the three phases return via the neutral conductor, the 120-degree phase shift between respective phase currents causes the currents to cancel out in the neutral, under balanced loading conditions.

However, when nonlinear loads are present, any “Triplen” (3rd, 9th…) harmonics in the phase currents do not cancel out but add cumulatively in the neutral conductor, which can carry up to 173% of phase current at a frequency of predominately 180 Hz (3rd harmonic). The amount of distortion in the voltage or current waveform is quantified by means of an index called the total harmonic distortion (THD).

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UNIT V

MULTI TERMINAL HVDC SYSTEMS

Types of MTDC system – Comparison of series and parallel MTDC system – HVDC insulation – DC line insulators – DC breakers – Characteristics and types of DC breakers.

Two Marks

1. What is a MTDC system?

A multi terminal DC (MTDC) SYSTEM has more than two converter stations some of them operating as rectifiers and others as inverters. The simplest way of building multi terminal system from an existing two terminal system is to introduce tappings. Parallel operation of converters and bipoles can also be viewed as multi terminal operation.

2. What are the potential applications of MTDC systems?

a) Bulk power transmission from several remote generating stations to load centers.
b) Asynchronous interconnection between adjacent power systems
c) Reinforcing an AC network which is heavily loaded.

3. What are the types of MTDC systems?

There are two possible types of MTDC systems

a) Series
b) Parallel

The parallel MTDC system can be further divided as

  a. Radial
  b. Mesh

4. Define series MTDC system.

This is a natural extension of the two terminal systems which is a series connected system. A there-terminal MTDC system is shown in below figure. This shows a monopolar arrangement; however, homopolar arrangement with two conductors is also possible. The system is grounded at only one point which may be conveniently chosen. If the line insulation is adequate, the grounding point can be shifted, based on changes in the operating conditions. Grounding capacitors may also be used to improve insulation coordination and system performance during transients.

5. Define parallel MTDC system.

The operating philosophy of constant voltage AC systems is extended to DC systems. The currents in all the converter stations except one are adjusted according to the power requirement. One of the terminals operates as voltage setting terminal at constant angle or voltage. An example of 3 terminals radial system is shown as below this shows a monopolar system but bipolar arrangement would be normally used.

6. Compare series and parallel MTDC systems

SERIES	PARALLES
High speed reversal is possible without mechanical switching	Not possible
Increased losses in lines and valves losses	Less losses
As voltage increases insulation coordination problem is increased	No insulation coordination problem

7. Why series tap was rejected?

It was rejected due to the following reasons

a) The operating current due to frequency control can be as low as 10% of the rated current; this increases the voltage rating of the series tap.

b) A series tap in the inverter operation reduces voltage at main inverter terminal requiring increased extinction angle.

8. What are the applications of DC breaker?

a) When two converters feed two parallel DC lines

b) When parallel connected converters feed the same line.

c) When current needs to be transferred from ground return to metallic return during monopolar operation.

9. What are the methods available in MTDC systems?

The various methods suggested are reviewed below:

1. Current margin method
2. Voltage limiting control
3. Decentralized current reference balancing
4. Tow ACR method

10. What is voltage limiting control?

In the voltage limiting control method, the rectifier and inverter characteristics are arranged as shown below. The loss of rectifier station does not have any significant effect on the system operation even in the absence of communication failure. The inverter currents are reduced in order to prevent voltage collapse. Also, the loss of an inverter station (operating on current control) would not be overload the voltage controlling inverter because of its voltage reserve.

11. What are the drawbacks of voltage limiting control?

The drawbacks of this scheme are (i) the distribuance in the AC system connected to an inverter station can result in other inverters getting unloaded (due to drop in the DC voltage). This may causes adverse effect on the AC systems supplied by healthy inverter stations, (ii) two or more terminals can operate in the voltage controlling mode forcibly, in the case of loss of a terminal resulting in indeterminate distribution of currents in those terminals (iii) currents during DC line fault or commutation failure are likely to be higher without additional measures.

12. What are the protection requirements of MTDC systems?

Protection of MTDC systems:

The system can be shut down following a fault in DC line or converter station and the faulted component isolated using high speed disconnected switches. The system can be restarted after adequate time for deionization of the art path (in case of short circuits)

System reliability consideration dicate the need for fast clearing of fault with minimum disturbance to the healthy parts of the system. The DC breaker ratings can be minimized by utilizing the interventation of fast current controls to reduce the magnitude of the fault currents. The detection of DC line faults gets complicated in a mesh system. A major problem is the large drop in the DC voltage even for distance faults. There requires fast detection and clearing of faults to maintain power transfers. Differential type of protection or directional sensitive measurements of the current can be used to locate the fault. Communication would be required in both methods.

13. How to reduce the typical problems in MTDC system?

Some of the typical problem that has been considered for study is as follow:

1. Operation of small inverter taps connected to week AC systems.
2. Integration of existing HVDC convertor stations in MTDC system without major modifications in control
3. Evaluation of communication, reactive power and filtering requirements.

Eleven Marks

1. **Explain the types of MTDC system in detail?**

There are two possible types of MTDC system

Series

Parallel

The parallel MTDC system can be further subdivided into the following two categories:

a) Radial

b) Mesh

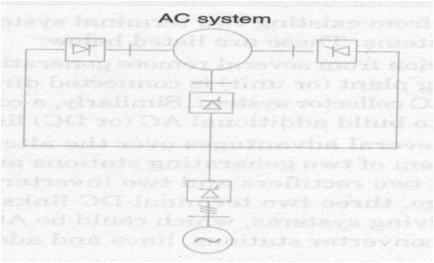

Fig: **MTDC system**

SERIES MTDC SYSTEM: This is a natural extension of the two terminal system which is a series connected system. A three-terminal MTDC system is shown. This shows a monopolar arrangement; however, a homopolar arrangement with two conductors is also possible. The system is grounded at only one point which may be conveniently chosen. If the line insulation is adequate, the grounding point can be shifted, based on changes in the operating condition. Ground capacitors may also be used to improve insulation co performance during transients.

In a series connected system, the current is set by one converter station and is common for all the stations. The remaining stations operate at constant angle (extinction or delay) or voltage control. In order to minimize the reactive power requirement and the losses in valve damper circuits, the normal operating values of firing angle may be adjusted using tap changer control. At all times, the sum of the voltages across the rectifier stations must be larger than the sum of the voltages across the inverter station. In case of a drop I the voltage at the current controlling rectifier station, the inverter with the larger current reference takes over the current control.

The switching in or out of bridge is accomplished by deblocking/block and bypass in a manner similar to that in a two terminal system. The clearing of a fault in the DC line is also similar. The power reversal at a station is also done as in a two terminal system, by reversing the DC voltage by converter control. The power control in a two terminal system is accomplished by adjusting the current while trying to maintain a constant voltage in the system. This is done to minimize the losses.

However, in a MTDC series system, central control would be required to adjust the current in response to changing loading condition. The local control of power would imply adjusting voltage at the converter station using angle and tap controls. Using only one bridge or a 12 pulse unit for the voltage control and operating remaining bridges at minimum (or maximum) delay angle can reduce the reactive power requirements.

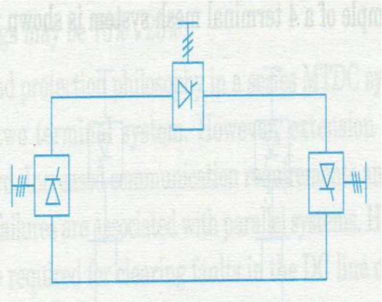

FIG : **Series MTDC system**

PARALLEL MTDC SYSTEM:

Here, the operating philosophy of constant voltage AC systems is extended to DC systems the current in all the converter stations except one are adjusted according to the power requirement. One of the terminals operates as a voltage setting terminal at constant angle or voltage. An example of three terminal radial systems is shown. This shows a mono polar system but bipolar arrangement would be normally used.

A radial system is one in which the disconnection of one segment of transmission would result in interruption of power from one or more converter stations. In a mesh system, the removal of one link would not result in a disruption, provided the remaining links are capable of carrying the required power (with increased losses). Evidently, a mesh system can be more reliable than the radial system..

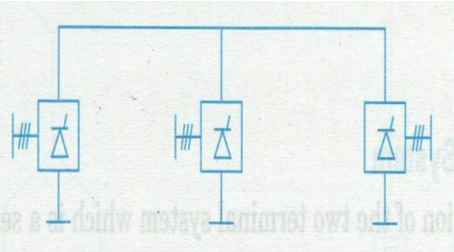

FIG : **Parallel MTDC system**

The power reversal in a parallel MTDC system would involve mechanical switching as the voltage cannot be reversed. Also loss of a bridge in one converter station would require either the disconnection of a bridge in all the station or disconnection of the affected station.

2. Comparison of serial and parallel MTDC system ?

The advantages and disadvantages of series and parallel MTDC systems are given below:

1. High speed reversal of power is possible in series system without mechanical switching. This is not possible I parallel systems.

2.The valve voltage rating in a series system is related to the power rating, while the current rating in a parallel connected system is related to power. This would imply that of small power ratings of the tap, series connection may be cheaper even though valves have to be insulated for full voltage to ground. The parallel connection has the advantage of staged development in the converter stations by adding parallel converters as the power requirements increase

3. There are increased losses in line and valves in series systems, in comparison to parallel systems. The system operation in series systems can be optimized by operating the largest inverter at rated voltage.

4. Insulation coordination is a problem in series systems as the voltage along the line varies.

5.The permanent faults in a line section would lead to complete shutdown in a series connected system, while it lead to only the shutdown of a converter station connected to the line section in a radial MTDC system.

With provisions for fast identification and clearing of faults in mesh connected system, there is no disruption of power transfer.

6.The reduction in AC voltages and commutation failures in an inverter can lead to overloading of converters as current is transferred from other terminals in a parallel system. The problem is severe if the rating of the inverter is relatively small. Increased values of smoothing reactor and voltage dependent current limits can reduce the severity. However, the valve ratings would increase, resulting in increased unit costs.

A recent study shows that the cost of 500 MW DC equipment (at ±500kV) would be 74% of the cost of 1000 MW DC equipment. It is concluded that a practical limit to unequal inverter ratings may be 75%: 25%.

7.The control and protection philosophy in a series MTDC system is a natural extension of that in a two terminal system. However, extension to parallel systems is not straightforward. Increased communication requirements and problems in recovery from commutation failures are associated with parallel systems. HVDC breakers of appropriate rating may be required for clearing faults in a DC line or converter stations.

From the relative merits and demerits of series and parallel MTDC systems described above, it may be concluded that series connection is appropriate for taps of rating less than 20% of the major inverter terminal. Parallel connection is more versatile and is expected to be widely used as in AC systems.

The first application of a MTDC system is the Sardinia-Corsica-Italy link where an existing link between Sardinia and Italy is tapped at Corsica. This is a 50 MW parallel connected tap with two 100kV six pulse thyristor bridges connected in series. A series tap was rejected for two reasons (i) the operating current due to frequency control can be as low as 10% of the rated current. This increase the voltage rating of series taps. (ii) A series tap in inverter operation reduces voltage at the main inverter terminal, requiring increased extinction angles. This is harmful to mercury arc valves as the possibility of arc through increases.

Commutation failure at Corsica can result in over currents of 7 p.u. smoothing reactors of 2.5H are chosen to limit the over currents due to disturbances in the AC systems. Quebec-New Hampshire-Massachusetts link is expected to be operational in early 1990’s with two inverters and one rectifier of capacity 2000 MW. With the integration of an existing two terminal DC link (from Des Cantons to Comerford), the system will finally consist of five terminals. Other MTDC systems are also being planned.

3. Describe the DC line insulators of HVDC system?

The insulators strings of a dc line are made up of porcelain or toughened glass as in the cases of AC lines. The insulators performance is evaluated in terms of critical flashover voltages (CFO) and critical withstand voltages (CWS). The critical flashover voltage is defined as the statistical mean (with 50% probability) of a data group (usually 20 flashovers) on a specific insulator specimen. The analysis assumes Gaussian distribution.

The critical withstand voltage (CWS) is defined as

$$\mathbf{CWS=CFO-3\sigma}$$

Where σ is the standard deviation. The CWS represents a voltage level with 0.13% probability of flashover.

It is to be noted that the overvoltage should result only in flashover and not puncture of the insulators.

There are special problems with direct voltage stresses on an insulator. The first problem is that of ion migration that takes place in the insulating material, which is a function of the temperature. An insulating material should have very little ion migration even at high ambient temperatures. There can be thermal runaway due to the ionic conduction in a very narrow zone of the dielectric which results in ageing of the dielectric. The current that flows in the insulator body is dependent on the resistivity which is a function of the temperature.

There is also the phenomenon of electrolytic process due to the creepage currents along the surface of the insulator. These currents can cause the electrodes to increase in volume, partly through the deposition of material and party as a result of chemical processes. The insulator design must take this into account to avoid mechanical failures.

The insulator string is subjected to the direct voltage in addition to transient impulses of different waveforms. The creepage distance of an insulator is determined by the operating direct voltage, while the string length is determined by the impulse voltage level. Increasing the string length influences the height of towers and their costs.

A transient overvoltage are smaller with DC lines (as compared to AC lines), there is an economic incentive to make the ratio of creepage distance to string lengths as great as possible.

A major problem with DC insulators is that the accumulation of contamination through direct voltage stresses is higher than with AC lines. The collection of dirt particles is also less uniform than with AC, providing collector rings close to the ends of the string helps in making the field distribution more uniform and reducing the accumulation of contamination.

The insulators are cleaned by heavy rain while the fog or dew, which makes the dirt conductive without removing it, can result in flashover. At times of unfavorable weather conditions, it may be desirable to operate the DC line at lower voltages by converter control or by removing some of the series connected bridges.

The geometry between the conductor and the tower can be viewed as that of rod-plane gap. The withstand strength of such gaps is higher with the combination of impulse and direct voltage than with pure impulse alone. This behavior is shown in fig. where the CWS is plotted as a function of the gap length.

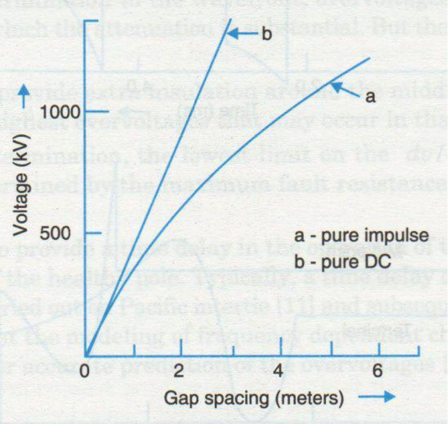

Fig : Withstand voltage VS gap length

The flashovers are caused by lightning strokes which usually affect one pole of the bipolar line. Due to coupling between the two poles, overvoltages can occur in the healthy pole. The insulation design must take this into account and prevent consequential fault on the healthy pole.

4. Explain the concepts of DC breakers with schematic arrangement?

The development of HVDC circuit breakers has been under way in recent years and recently a 500 kV breaker with current interrupting capability upto 4000 A, has been reported. Although several type of DC breaker have been developed by different manufacturers, the basic components are the same in all the cases.

BASIC CONCEPTS OF DC CIRCUIT INTERRUPTION:

The major problem in the current interruption in DC circuits is that there is no natural current zero as in the case of AC circuits. The current can be brought to zero only by applying a counter voltage higher than the system voltage. The second problem is the dissipation of a large energy stored in the inductance of the circuit.

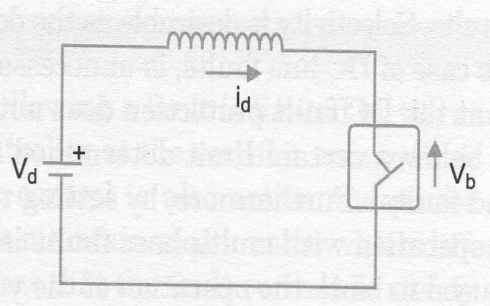

Fig. Simple representation of DC circuit with Breaker

Consider the simple representation of DC circuit shown in figure . The breaker has counter voltage Vb. It can be shown that energy absorbed by the breaker is

$$W_b = \frac{1}{2} L I_d^2 \left(V_b / (V_b - V_d)\right)$$

And the time required to bring the current to zero is given by

$$T_i = L I_d / (V_b - V_d)$$

Where I_d is the current in the breaker prior to interruption.

The current is brought down to the rated value by the normal action of current control in converters. Although this requires certain amount of time (say 30 to 50 msec), the time required for interruption reduced. The alternate strategy is to interrupt the fault current fast but this will increased the interruption time apart from increasing the cost of the breaker.

The counter voltage produced by the arc that is struck when the breaker contacts separate, is not sufficient in HVDC breakers. This requires a auxiliary circuit in which a capacitor is inserted to develop the required counter voltage. However, a capaccitor is unable to dissipate the energy and the current in the capacitor has to be commutated to nonlinear resistors which then dissipate the energy without undue increase in the voltage across them.

The general arrangement of a HVDC circuit breaker is shown. The current in the breaker (when closed) is normally carried through CB with moving contacts. This may be vacuum, oil, airblast or SF6 device. After a trip signal is given to the breaker, the breaker contacts open to draw an arc. This is initiated at time t1(which the fig shows the current and voltage waveforms).

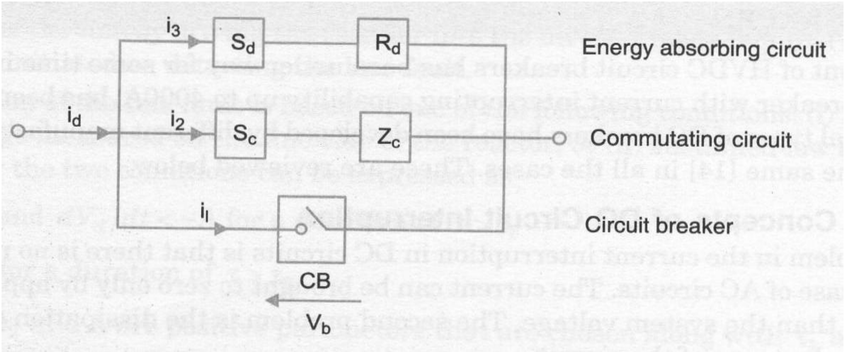

Fig : Arrangement of a DC breaker

At a short time t2, the commutation circuit is inserted through the insertion device Sc. The commutating impedance is primarily made up of a series LC circuit which is tuned to a certain frequency. The capacitor may or may not pre charged. The insertion devices Sc may be a triggered vacuum gap or spark gap or in the so called ‘passive’ commutation n circuit, just a solid connection (no switching required). The main purpose of inserting commutating impedance is to create current zero in CB and transfer the current to Zc with sufficient contact separation in CB to rega in its dielectric strength.

This current transfer is completely by time t3. The dc circuit current, flowing through the capacitor in Z_c rap idly builds up to a high voltage V_b across the breaker. When the voltage reaches V_b at time t4, the energy absorber Rd is inserted through a device Sd. The nonlinearity of the resistance Rd acts as a switch which closes when its w hen its clipping voltage is reached. The direct current now decays to zero by discharging its energy to Rd after the interval of Ti(at time t5). The breaker operation is completely by t5 if the three parallel paths CB,Zc and Rd have adequate voltage withstand capability. Otherwise, fast acting isolators that operate at zero current level may be used to prevent overstressing of the breaker until the converter control restores the voltage to a level that can be withstood by the breaker under steady state conditions.

In the passive commutation method, a series LC circuit is connected across CB. The interrupter element CB in an air blast or SF6 breaker similar to that used in AC circuits. Field tests are shown that the air blast breaker is superior in performance compared to SF6.The commutation of the current to Zc in the passive commutation method is initiated by the arc itself. The differential equation for the current i2 is given by

$$L\left(d^2 i_2/dt^2\right) + (dV_{arc}/di_1)(di_2/dt) + (1/C)i_2 = 0$$

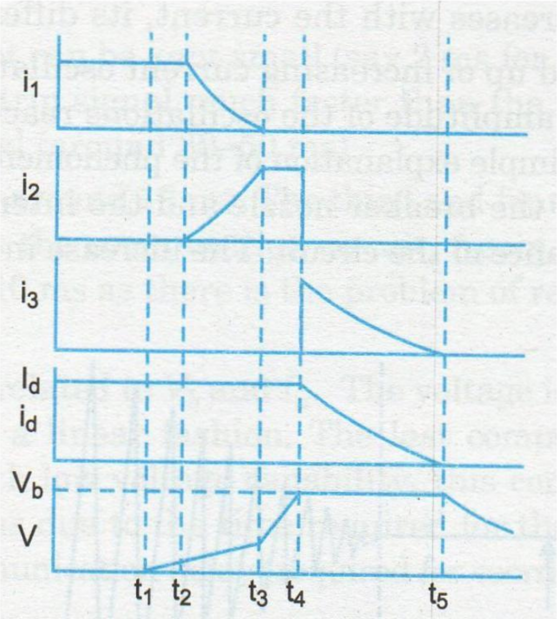

Fig: Waveform

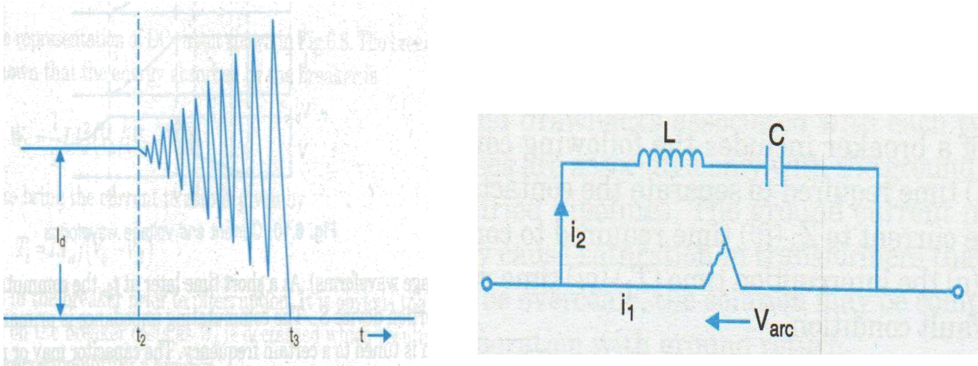

Fig: Current oscillation in commutation circuit

Since the arc voltage decreases with the current, its differential resistance is negative. This causes the buildup of increasing current oscillations in the circuit and the arc current goes to zero when the amplitude of the oscillations reach the value of direct current . While this is a simple explanation of the phenomenon, the process of commutation is affected by the geometry of the breaker nozzle and the interruption chamber, the natural frequency and the stray resistance of the circuit. The increase in the oscillation magnitude may also occur in steps.

5. What are the characteristics and types of dc breakers?

The breaker is characterized by four variables of interest in application to the system.

They are:

1. Voltage capability
2. Current capability
3. Energy capability
4. Switching time

The voltage capability is related to two parameters-

(i) the voltage during the interruption process and

(ii) Steady-state operating voltage and transients in the system. The breaker voltage requirements can be kept low by coordination with converter control and fast isolators. In general, the lightest permissible voltage gives the best performance in terms of lower energy absorption and shorter switching time.

The interrupting capability of a breaker does not have to much above the rated current in the circuit, because the converter control can be relied on to bring the fault current down to the rated levels. The required energy capability of a breaker depends upon many factors such as the inductance, converter voltage and current, breaker voltage and the duty cycle. In HVDC breakers, series connected modules are used to give the required voltage and energy capabilities.

The switching time of a breaker includes the following components:

(i) Time required to generate the trip signal

(ii) Time required to separate the contacts in the main breaker

(iii) Time required to commutate the current to zc

(iv) time required to commutate current from zc to rd (energy absorbing circuit)

(v) The interruption time (Ti)

(vi) Time required to bring the DC system back to steady-state post fault condition.

While the first component can be kept small (say 2 ms for station faults), there is no real advantage in generating the trip signal much faster than the time taken to reduce the fault current using current control (around 30-50 ms).

The second component is around 10 ms. the third and fourth components can be reduced by using charged capacitor in the commutation circuit. Again, there is no real advantage in keeping the total time below 10 ms as there is the problem of restriking of the arc in the main breaker. The voltage is normally around 1.7 p.u, The reduction in reduces in a linear fashion.

The last component depends on the voltage capability of the breaker. With low voltage capability, this component of the switching time could be of the order of 100 ms due to time required for the operation of the isolator, the converter control and the communication delay (required for coordination of the breaker operation and converter controls. The above analysis shows that there is significant saving in switching time possible by increased voltage capability while the current capability may be limited to the rated current.

The requirements on the switching time depends on the AC system requirements for maintaining DC power flow I transient conditions, taking into account the considerations of system stability.

APPLICATIONS OF DC BREAKERS:

The application of DC breaker is required mainly for fault clearing in MTDC systems.

However, even for two terminal DC systems, the DC breakers can be useful I the following situations:

1. When the converter feed two parallel DC lines.
2. When parallel connected converters feed the same line
3. When current needs to be transferred from the ground return to the metallic return during the monopolar operation. The breakers for this application are termed as Metallic Return Transfer Breakers (MRTB). Although voltage capability required for this application is moderate, the energy capability required may be substantial.