LECTURE NOTES

ON

HVDC TRANSMISSION

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UNIT – I
GENERAL ASPECTS OF HVDC TRANSMISSION

1.1 INTRODUCTION:

A high-voltage, direct current (HVDC) electric power transmission system (also called a power super highway or an electrical super highway) uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems.For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be justified, due to other benefits of direct currentlinks.

HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

Power Transmission was initially carried out in the early 1880s using Direct Current (DC). With the availability of transformers (for stepping up the voltage for transmission over long distances and for stepping down the voltage for safe use), the development of robust induction motor (to serve the users of rotary power), the availability of the superior synchronous generator, and the facilities of converting AC to DC when required, AC gradually replaced DC. However, in 1928, arising out of the introduction of grid control to the mercury vapor rectifier around 1903, electronic devices began to show real prospects for high voltage direct current (HVDC) transmission, because of the ability of these devices for rectification and inversion. The most significant contribution to HVDC came when the Gotland Scheme in Sweden was commissioned in 1954 to be the World's first commercial HVDC transmission system. This was capable of transmitting 20 MW of power at a voltage of -100 kV and consisted of a single 96 km cable with seareturn.

1.2 COMPARISION OF AC AND DC TRANSMISSION:

1.3 ADVANTAGES OF HVDC OVER AC:

Technical Merits of HVDC:

The advantages of a DC link over an AC link are:

- A DC link allows power transmission between AC networks with different frequencies or networks, which cannot be synchronized, for other reasons.

- Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead line or cable. The conductor cross section is fully utilized because there is no skin effect.

For a long cable connection, e.g. beyond 40 km, HVDC will in most cases offer the only technical solution because of the high charging current of an AC cable. This is of particular interest for transmission across open sea or into large cities where a DC cable may provide the only possible solution.

- A digital control system provides accurate and fast control of the active power flow.
- Fast modulation of DC transmission power can be used to damp power oscillations in an AC grid and thus improve the system stability.

Economic considerations:

For a given transmission task, feasibility studies are carried out before the final decision on implementation of an HVAC or HVDC system can be taken. Fig.1 shows a typical cost comparison curve between AC and DC transmission considering:

- AC vs. DC station terminal costs
- AC vs. DC line costs
- AC vs. DC capitalized value of losses

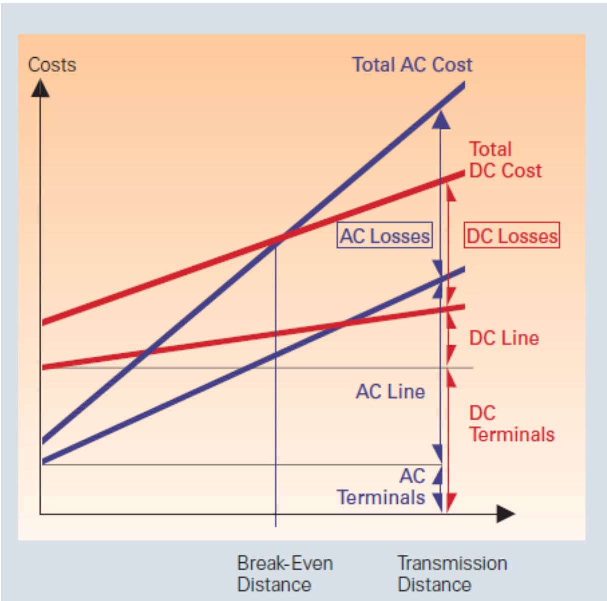


Fig 1: total cost/distance

- The DC curve is not as steep as the AC curve because of considerably lower line costs per kilometer. For long AC lines the cost of intermediate reactive power compensation has to be taken into account. The break-even distance is in the range of 500 to 800 km depending on a number of other factors, like country- specific cost elements, interest rates for project financing, loss evaluation, cost of right of wayetc.

- During bad weather conditions, the corona loss and radio interference are lower for a HVDC line compared to that in an AC line of same voltage and same conductor size.
- Due to the absence of inductance in DC, an HVDC line offers better voltage regulation. Also, HVDC offers greater controllability compared toHVAC.
- AC power grids are standardized for 50 Hz in some countries and 60 Hz in other. It is impossible to interconnect two power grids working at different frequencies with the help of an AC interconnection. An HVDC link makes this possible.
- Interference with nearby communication lines is lesser in the case of HVDC overhead line than that for an HVACline.
- In longer distance HVAC transmission, short circuit current level in the receiving system is high. An HVDC system does not contribute to the short circuit current of the interconnected ACsystem.
- Power flow control is easy in HVDClink.
- High reliability.

1.3 DISADVANTAGES OF HVDC OVER HVAC:

- Converter stations needed to connect to AC power grids are very expensive**.** Converter substations are more complex than HVAC substations, not only in additional converting equipment, but also in more complicated control and regulating systems.
- In contrast to AC systems, designing and operating multi-terminal HVDC systems is complex.
- Converter substations generate current and voltage harmonics, while the conversion process is accompanied by reactive power consumption. As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.
- During short-circuits in the AC power systems close to connected HVDC substations, power faults also occur in the HVDC transmission system for the duration of the short-circuit.
- The number of substations within a modern multi-terminal HVDC transmission system can be no larger than six to eight**,** and large differences in their capacities are not allowed. The larger the number of substations, the smaller may be the differences in their capacities.
- The high-frequency constituents found in direct current transmission systems can cause radio noise in communications lines that are situated near the HVDC transmission line.
- Grounding HVDC transmission involves a complex and difficult installation, as it is

necessary to construct a reliable and permanent contact to the Earth for proper operation and to eliminate the possible creation of a dangerous "step voltage."

1.4 APPLICATION OF HVDC TRANSMISSION:

Connecting remote generation

Some energy sources, such as hydro and solar power, are often located hundreds or thousands of kilometers away from the load centers. HVDC will reliably deliver electricity generated from mountain tops, deserts and seas across vast distances with low losses.

Interconnecting grids

Connecting ac grids is done for stabilization purposes and to allow energy trading. During some specific circumstances, the connection has to be done using HVDC, for example when the grids have different frequencies or when the connection has to go long distances over water and ac cables cannot be used because of the high losses.

Connecting offshore wind

Wind parks are often placed far out at sea, because the wind conditions are more advantageous there. If the distance to the grid on land exceeds a certain stretch, the only possible solution is HVDC - due to the technology's low losses.

Power from shore

Traditionally, oil and gas platforms use local generation to supply the electricity needed to run the drilling equipment and for the daily need of often hundreds of persons working on the platform. If the power is instead supplied from shore, via an hvdc link, costs go down, emissions are lower and the working conditions on the platform are improved.

Dc links in ac grids

HVDC links within an ac grid can be successfully utilized to strengthen the entire transmission grid, especially under demanding load conditions and during system disturbances. Transmission capacity will improve and bottlenecks be dissolved.

City-center in feed

HVDC systems are ideal for feeding electricity into densely populated urban centers. Because it is possible to use land cables, the transmission is invisible, thus avoiding the opposition and uncertain approval of overhead lines.

Connecting remote loads

Islands and remotely located mines often have the disadvantage of a weak surrounding ac grid.

Feeding power into the grid with an HVDC link, improves the stability and even prevents black-outs.

1.5 TYPES OF DC LINKS:

For connecting two networks or system, various types of HVDC links are used. HVDC links are classified into three types. These links are explained below:

Monopolarlink:

It has a single conductor of negative polarity and uses earth or sea for the return path of current. Sometimes the metallic return is also used. In the Monopolar link, two converters are placed at the end of each pole. Earthling of poles is done by earth electrodes placed about 15 to 55 km away from the respective terminal stations. But this link has several disadvantages because it uses earth as a return path. The monopolar link is not much in use nowadays.

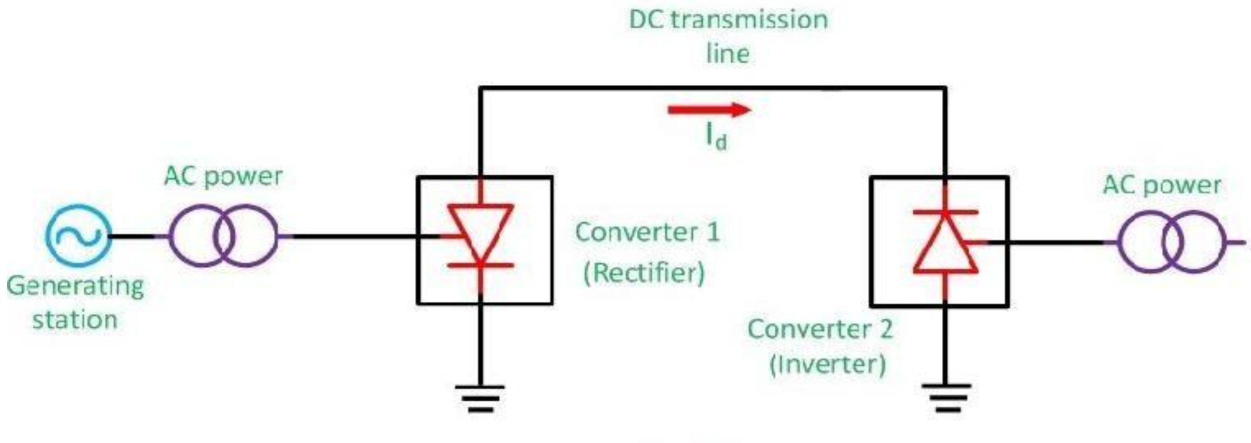


Fig 2: monopolar DC link

Bipolarlink:

The Bipolar link has two conductors one is positive, and the other one is negative to the earth. The link has converter station at each end. The midpoints of the converter stations are earthed through electrodes. The voltage of the earthed electrodes is just half the voltage of the conductor used for transmission the HVDC. The most significant advantage of the bipolar link is that if any of their links stop operating, the link is converted into Monopolar mode because of the ground return system. The half of the system continues supplies the power. Such types of links are commonly used in the HVDC systems.

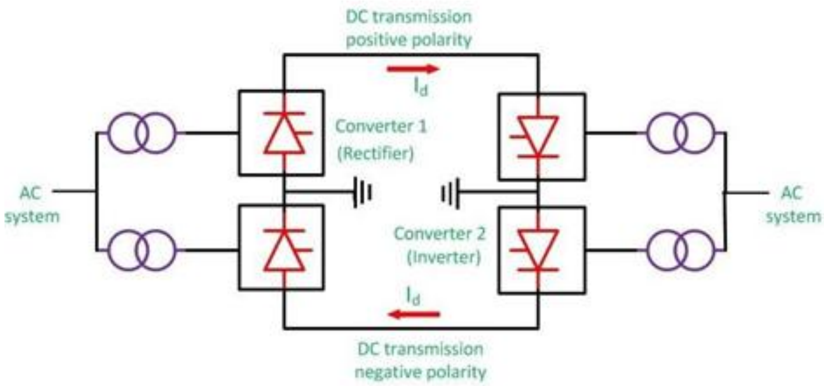


Fig 3: bipolar DC link

Homopolarlink:

It has two conductors of the same polarity usually negative polarity, and always operates with earth or metallic return. In the homopolar link, poles are operated in parallel, which reduces the insulation cost. The homopolar system is not used presently.

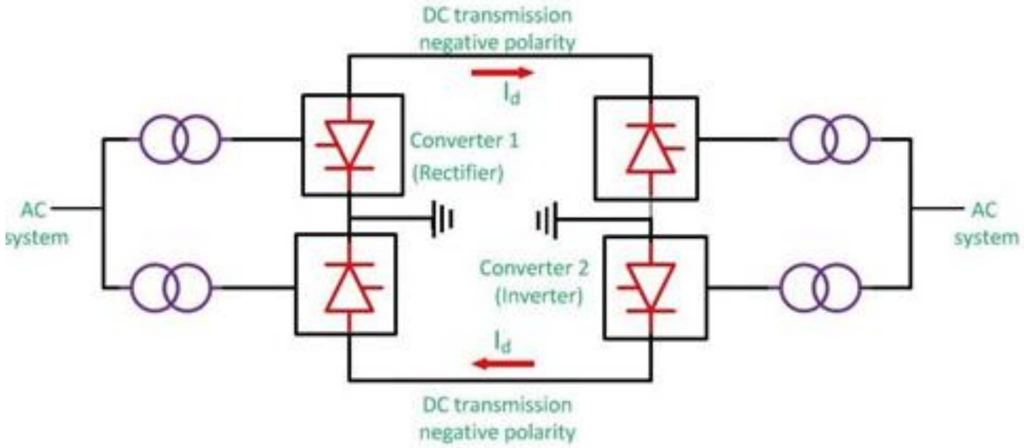


Fig 4: homopolar DC link

1.6 TYPICAL LAYOUT OF HVDC SYSTEM:

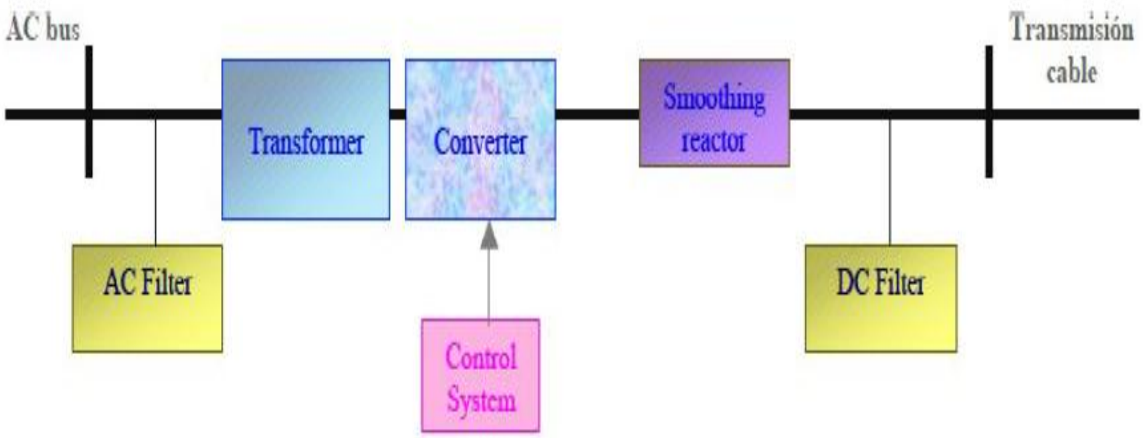


Fig 5: Layout of HVDC system

The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point to point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control.

The HVDC system has the following main components.

- ConverterStation
- ConverterUnit
- ConverterValves
- ConverterTransformers
- Filters
    - AC filter
    - DC filter
    - High-frequencyfilter
- Reactive PowerSource
- Smoothing Reactor
- HVDC SystemPole

1.6.1 CONVERTE STATION:

The terminal substations which convert an AC to DC are called rectifier terminal while the terminal substations which convert DC to AC are called inverter terminal. Every terminal is designed to work in both the rectifier and inverter mode. Therefore, each terminal is called converter terminal, or rectifier terminal. A two-terminal HVDC system has only two terminals and one HVDC line.

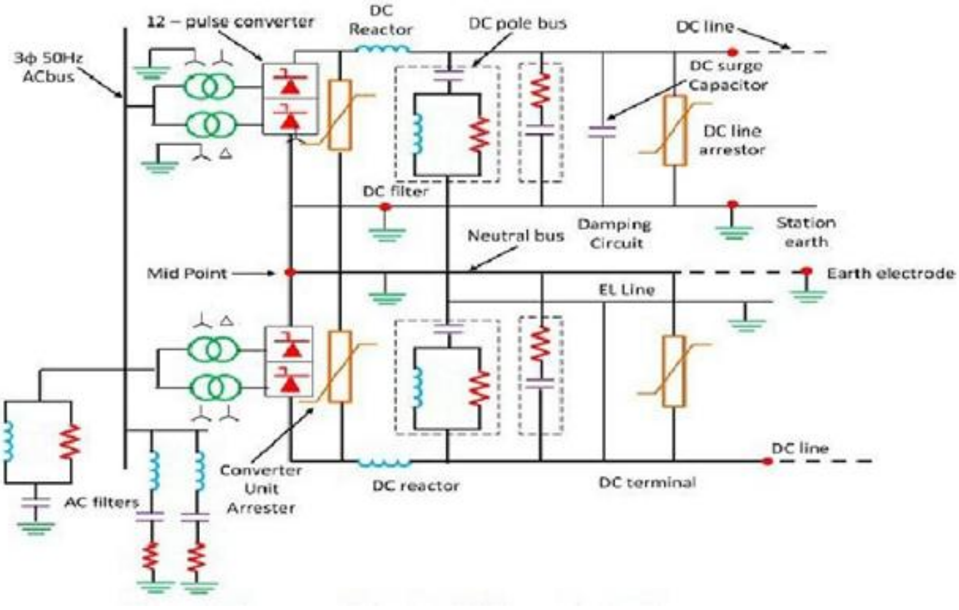


Fig 6: schematic diagram of typical HVDC converter station

1.6.2 CONVERTER UNIT:

The conversion from AC to DC and vice versa is done in HVDC converter stations by using three-phase bridge converters. This bridge circuit is also called Graetz circuit. In HVDC transmission a 12-pulse bridge converter is used. The converter obtains by connecting two or 6-pulse bridge in series.

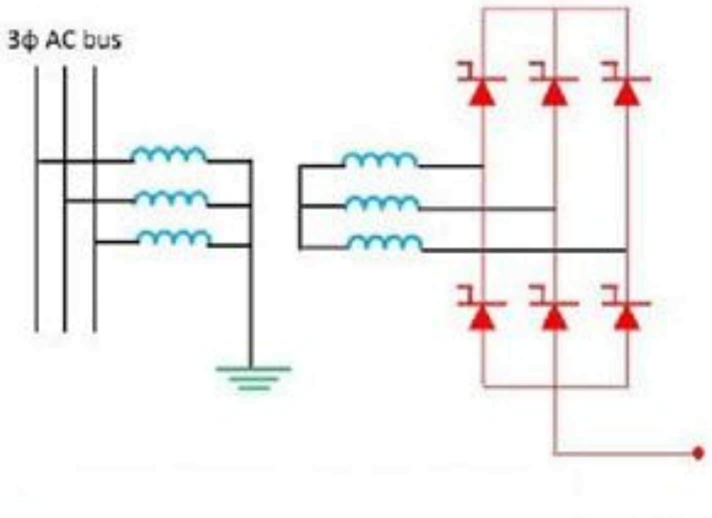


Fig 7: circuit for 6-pulse bridge

1.6.3 CONVERTER TRANSFORMER:

The converter transformer converts the AC networks to DC networks or vice versa. They have two sets of three phase windings. The AC side winding is connected to the AC bus bar, and the valve side winding is connected to valve Bridge. These windings are connected in star for one transformer and delta to another.

The AC side windings of the two, three phase transformers are connected in stars with their neutrals grounded. The valve side transformer winding is designed to withstand alternating voltage stress and direct voltage stress from Valve Bridge. There are increases in eddy current losses due to the harmonics current. The magnetization in the core of the converter transformer is because of the following reasons.

- The alternating voltage from AC network containing fundamentals and several harmonics.
- The direct voltage from valve side terminal also has some harmonics.

1.6.4 FILTERS:

The AC and DC harmonics are generated in HVDC converters. The AC harmonics are injected into the AC system, and the DC harmonics are injected into DC lines. The harmonics have the following advantages.

- It causes the interference in telephone lines.
- Due to the harmonics, the power losses in machines and capacitors are connected in the system.
- The harmonics produced resonance in an AC circuit resulting in over voltages.
- Instability of converter controls.

The harmonics are minimized by using the AC, DC and high-frequency filters. The types of filter are explained below in details.

- AC Filters – The AC filters are RLC circuit connected between phase and earth. They offered low impedances to the harmonic frequencies. Thus, the AC harmonic currents are passed to earth. Both tuned and damped filters are used. The AC harmonic filter also provided a reactive power required for satisfactory operation of converters.
- DC Filters – The DC filter is connected between the pole bus and neutral bus. It diverts the DCharmonics to earth and prevents them from entering DClines.

1.6.5 CONVERETR VALVES:

The modern HVDC converters use 12-pulse converter units. The total number of a valve in each unit is 12. The valve is made up of series connected thyristor UNITs. The number of thyristor valve depends on the required voltage across the valve. The valves are installed in valve halls, and they are cooled by air, oil, water orFreon.

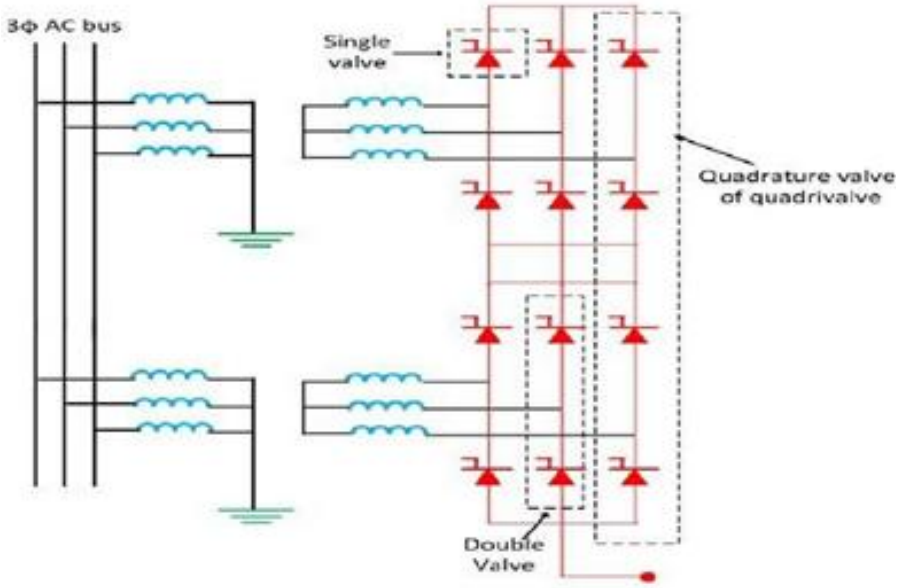


Fig 8: circuit for 12-pulse converter

1.6.6 REACTIVE POWER SOURCE:

Reactive power is required for the operations of the converters. The AC harmonic filters provide reactive power partly. The additional supply may also be obtained from shunt capacitors synchronous phase modifiers and static VAR systems. The choice depends on the speed of control desired.

1.6.7 SMOOTHNING REACTOR

Smoothing reactor is an oil filled oil cooled reactor having a large inductance. It is connected in series with the converter before the DC filter. It can be located either on the line side or on the neutral side. Smoothing reactors serve the following purposes.

- They smooth the ripples in the direct current.
- They decrease the harmonic voltage and current in the DClines.
- They limit the fault current in the DCline.
- Consequent commutation failures in inverters are prevented by smoothing reactors by reducing the rate of rising of the DC line in the bridge when the direct voltage of another series connected voltage collapses.
- Smoothing reactors reduce the steepness of voltage and current surges from the DC line. Thus, the stresses on the converter valves and valve surge diverters are reduced.

1.6.8 HVDC SYSTEM POLE

The HVDC system pole is the part of an HVDC system consisting of all the equipment in the HVDC substation. It also interconnects the transmission lines which during normal operating condition exhibit a common direct polarity with respect to earth. Thus, the word pole refers to the path of DC which has the same polarity with respect to earth. The total pole includes substation pole and transmission line pole.

1.7 TYPES OF HVDC SYSTEM

There are different types of HVDC systems:

1.7.1 BACK TO BACK SYSTEM

The HVDC system which transfers energy between the AC buses at the same location is called back-to-back system or an HVDC coupling system. In back-to-back HVDC stations, the converters and rectifiers are installed in the same stations. It has no DC transmission line.

The back-to-back system provides an asynchronous interconnection between the two adjacent independently controlled AC networks without transferring frequency disturbances. The back-to-back DC link reduces the overall conversion cost, improve the reliability of the DC system. Such type of system is designed for bipolar operation.

1.7.2TWO TERMINAL HVDC SYSTEM

The terminal with two terminals (converter station) and one HVDC transmission line is called two terminal DC system point-to-point system. This system does not have any parallel HVDC line and no intermediate tapings. The HVDC circuit breaker is also not required for two-terminal HVDC system. The normal and abnormal current is controlled effective converter controller.

1.7.3 MULTI TERMINAL HVDC SYSTEM

This system has more than two converter station and DC terminal lines. Some of the converter stations operate as rectifier while others operate as an inverter. The total power taken from the rectifier station is equal to the power supplied by the inverter station. There are two type of MTDC Systems

- Series MTDC System
- Parallel MTDC System

In series MTDC system the converters are connected in series while in parallel MTDC system, the converters are connected in parallel. The parallel MTDC system may be operated without the use of an HVDC circuit breaker.

1.7.3.1 ADVANTAGES OF MTDC:

The following are the advantages of MTDC systems

- The MTDC system is more economical and flexible.
- The frequency oscillation in the interconnected AC networks can be damped quickly.
- The heavily load AC networks can be reinforced by using MTDC systems.
- **1.7.3.2 APPLICATIONS OF MTDC:**
- The following are the applications of the HVDC systems
- It transfers the bulk power from several remote generating sources to several load centres.
- The systems are interconnected between two or more AC systems by radial MTDC systems.
- It reinforces the heavy load urban AC networks by MTDC systems
- HVDC circuit breaker is used in two terminal DC link and Multiterminal DC link for transferring from ground to metallic run.

UNIT –II
ANALYSIS OF BRIDGE CONVERTER

1.1 ANALYSIS OF GRATEZ CIRCUIT:

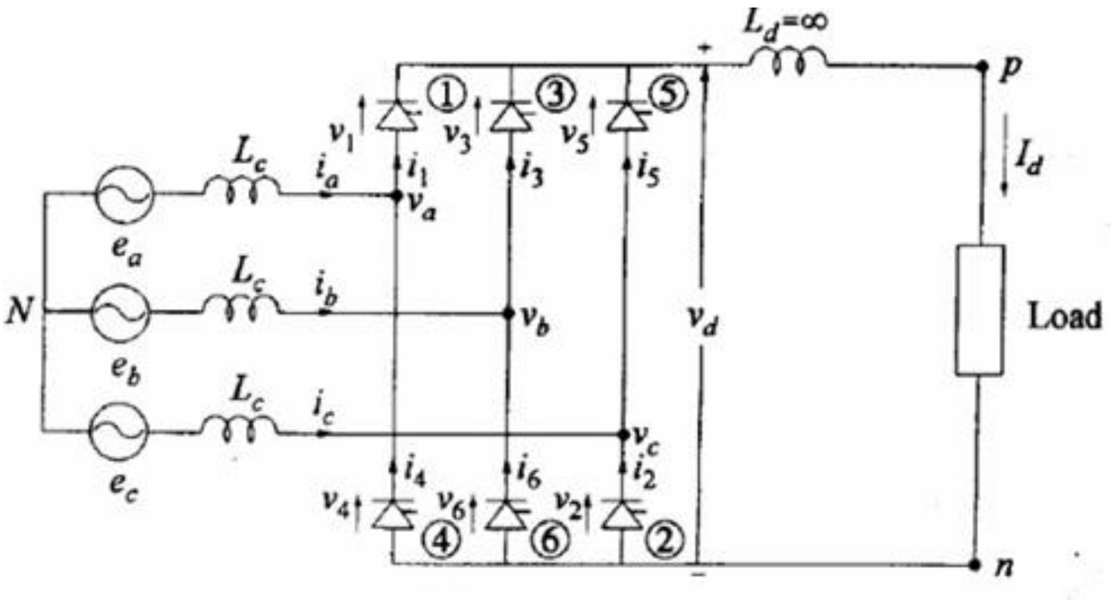


Fig 1: circuit diagram for Graetz Bridge

Let the instantaneous line – to – neutral source voltages be

ea = EmCos(ωt+60º)

eb = EmCos(ωt-60º)

ec = Em Cos(ωt-180º)

Then the line-to-line voltages are

eac = ea-ec = √3EmCos(ωt+30º)

eba = eb-ea = √3EmCos(ωt-90º)

ecb = ec-eb = √3EmCos(ωt+150º)

For the 6-valve bridge, with zero firing delay, the voltage waveforms across the thyristors are shown in figure. 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.

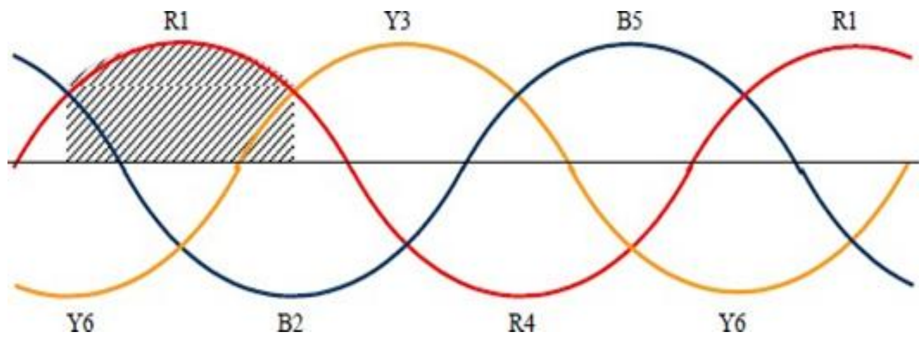


Fig 2: Thyristor voltage waveforms (α=0)

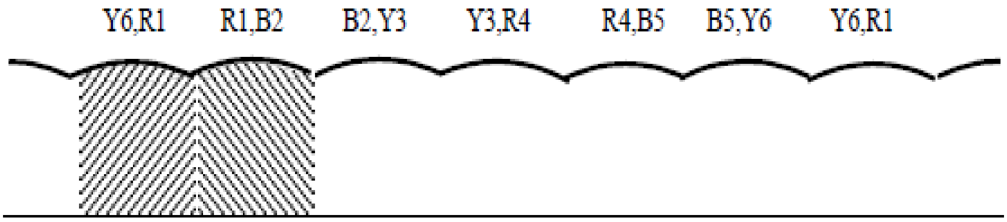


Fig 3: dc output waveforms (α=0)

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 commutationγ=0.

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 and γ=0, the direct output voltage is given by

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

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

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

2.2 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:

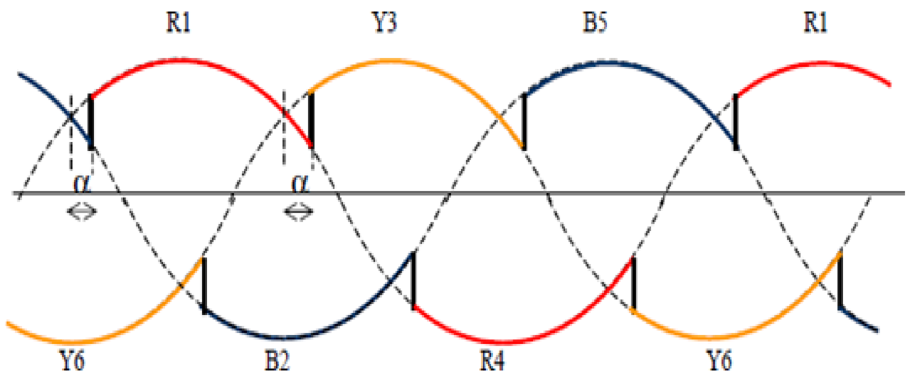


Fig 4: Thyristor voltage waveforms (with delayα)

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

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

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

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

2.3 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 2 conducting thyristors on the same side. This is shown in figure.

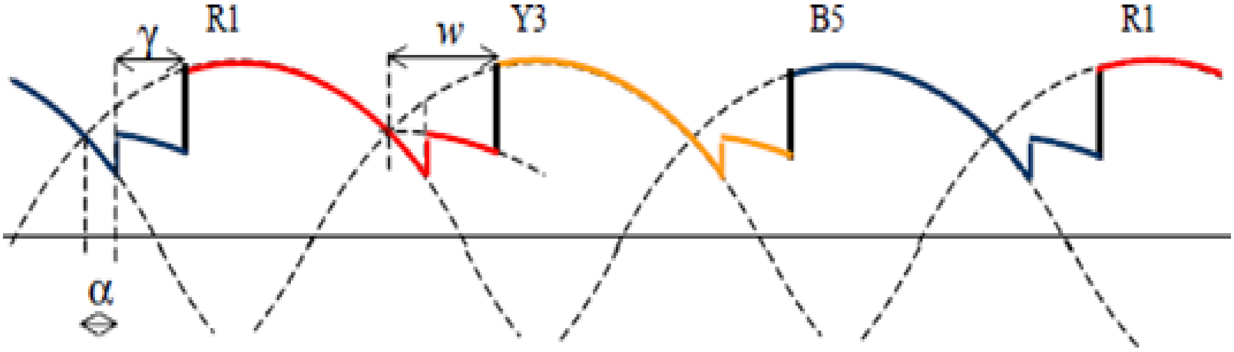


Fig 5: Thyristor voltage waveforms (with overlap)

With both the delay angle and commutation being present, the magnitude of the direct voltage may be determined from equation

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

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

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

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

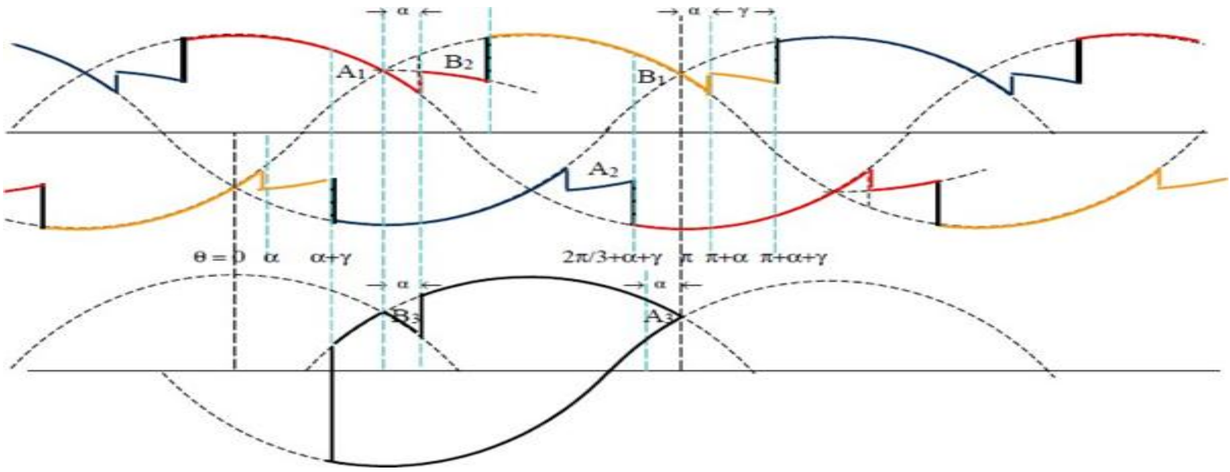


Fig 6: Thyristor voltage waveforms (alternate method)

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.

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

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

Where √2 E is the peak value of the line voltage. Simplification gives the desired result as inequation

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

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

2.4 CURENT WAVEFORM:

If Commutation is not considered, the current waveforms through each thyristor (assuming a very high value of inductance Ld in the DC circuit to give complete smoothing) is a rectangular pulse lasting exactly one-third of a cycle. This is shown in figure for the cases without delay and with delay.

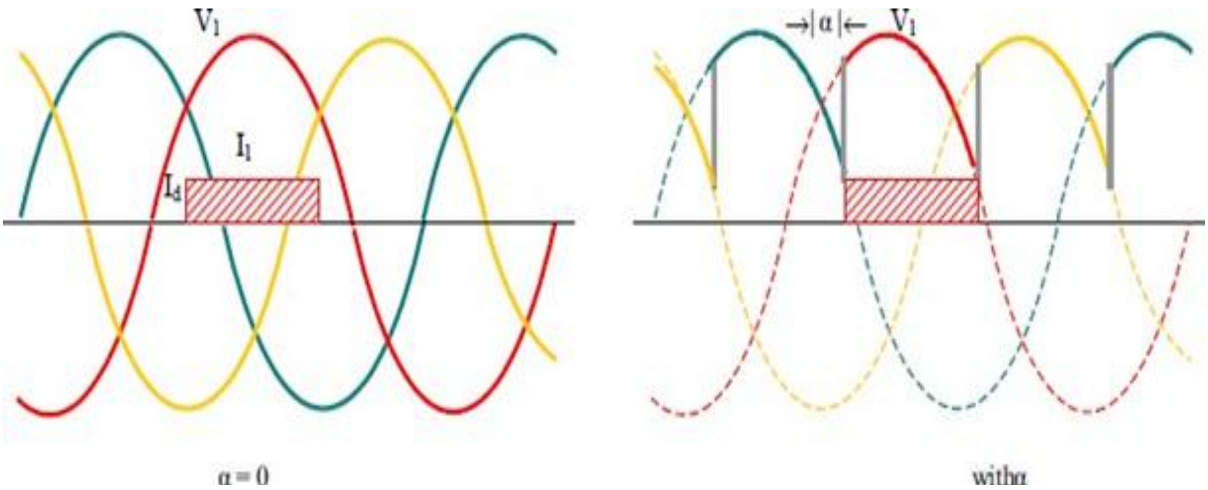


Fig 7: Thyristor current waveforms

When commutation is considered, the rise and fall of the current waveforms would be modified as they would no longer be instantaneous, as shown in figure.

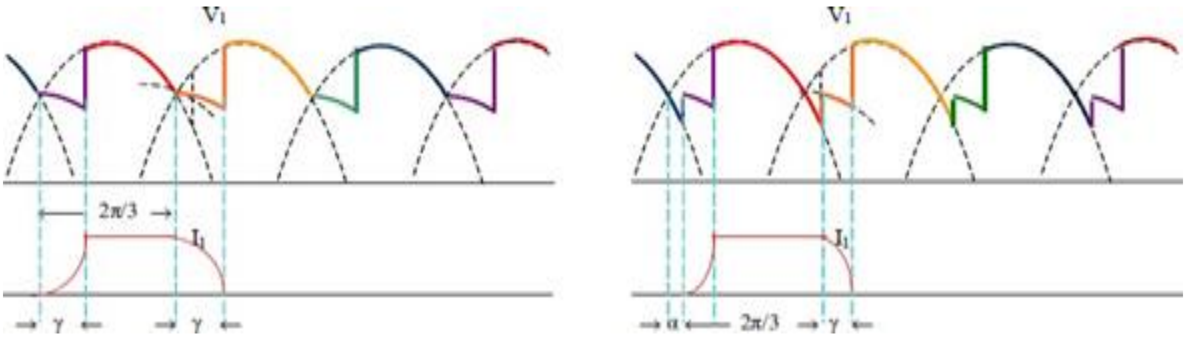


Fig 8: Thyristor current waveforms (commutation)

Since each phase has 2 thyristors on the opposite half cycles, the a.c. current waveform on the secondary side of the transformer has a non-sinusoidal waveform as shown in figure

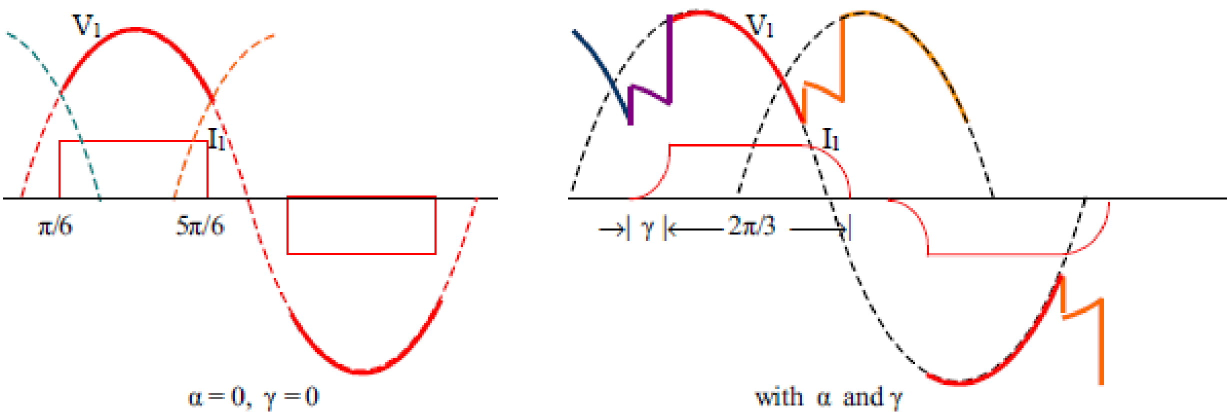


Fig 9: Thyristor current waveforms

If commutation angle is not considered, we can easily calculate the r.m.s. value of the AC current on the transformer secondary Is as in equation.

$$I_s = \sqrt{\frac{1}{\pi} \cdot \frac{2\pi}{3} \cdot I_d^{\;2}} = \sqrt{\tfrac{2}{3}}\, I_d = 0.8165\, I_d$$

Usually harmonic filters are provided on the AC system, so that only the fundamental component need to be supplied/absorbed from the AC system. From Fourier analysis, it can be shown that the fundamental component is given as follows, resulting in equation.

$$I = \frac{I_{\max}}{\sqrt{2}} = \frac{1}{\sqrt{2}} \cdot \frac{2}{\pi} \cdot \int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} I_d \cos \omega t \, d(\omega t)$$

$$I = \frac{\sqrt{2}}{\pi} I_d \, 2 \sin \frac{\pi}{3} = \frac{\sqrt{6}}{\pi} I_d = 0.78\, I_d$$

If filters were not provided, it can be shown, using the Fourier series analysis, that the RMS ripple on the AC system would be 0.242 Id (or 31 % of the fundamental)

Note: For normal operation neglecting the commutation angle, in the above calculations of the alternating current, gives rise to an error only of the order of 1%.

As can be seen from the voltage and current waveforms on the AC side, the current lags the voltage due to the presence of the delay angle α and commutation angleγ.

2.5 VOLTAGE WAVEFORM:

The DC voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can be analyzed in Fourier series and contains harmonics of the order

h = np

where, p is the pulse number and n is an integer.

The rms value of the hth order harmonic in DC voltage is given by

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

The waveforms of the direct voltage and calve voltage are shown for different values of α

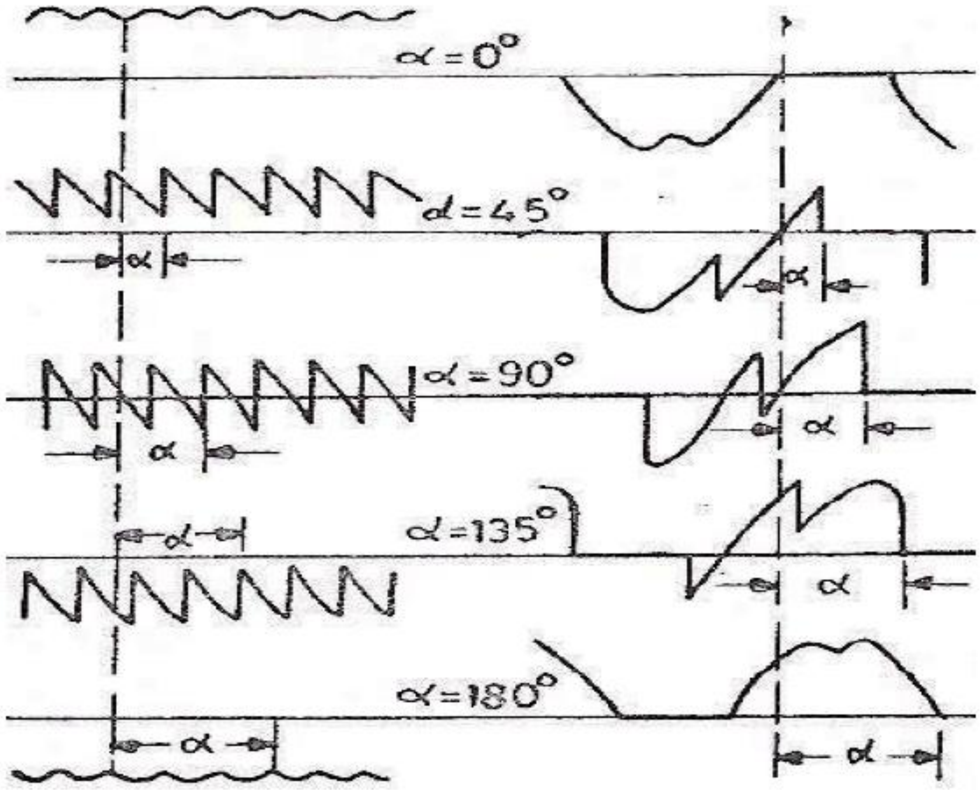


Fig 9: Thyristor voltage waveforms

2.5 INVERSION:

The inverter characteristics are similar to the rectifier characteristics. However, the operation as an inverter requires a minimum commutation margin angle during which the voltage across the valve is negative. Hence the operating region of an inverter is different from that for a rectifier.

So, the margin angle (ξ) has different relationship to γ depending on the range of operation which are

First Range: β < 60o and ξ = γ

Second Range: 60o < β < 90o and ξ =60o – μ = γ-(β-60o)

Third Range: β > 90o and ξ = γ – 30o

In the inverter operation, it is necessary to maintain a certain minimum margin angle ξo which results in 3 sub-modes of the 1st mode which are

Mode 1

β < 60o for values of μ < (60o - ξo)

The characteristics are linear defined by

$Vd = \cos\gamma o - Id$

1(b) 60o < β < 90o for

$\mu = 60o - \xi o = 60o - \gamma o = \text{constant}$

The characteristics are elliptical.

1(c) 90o < β < 90o + ξo

for values of μ in the range $60o - \xi o \leq \mu \leq 60o$

The characteristics in this case are line and defined bY

$Vd| = \cos(\gamma o + 30o) - Id$

Mode 2

For $\mu > 60o$ corresponding to $\beta > 90o + \gamma o$

The characteristics again are linear but with a different slope and is defined by

$Vd| = \sqrt{3}\cos\gamma o - 3Id$

In the normal operation of the converter Id

| is in the range of 0.08 to 0.1

2.6 CHARACTERISTICS OF 12 PULSE CONVERTER:

As long as the AC voltages at the converter bus remain sinusoidal (with effective filtering), the operation of one bridge is unaffected by the operation of the other bridge connected in series. The region of rectifier operation can be divided into five modes as

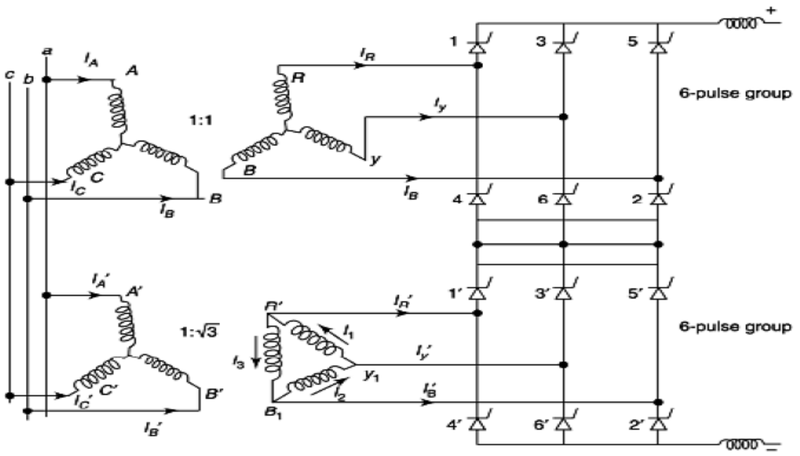


Fig 10: 12 pulse converter

Mode 1: 4 and 5 valve conduction

$0 < \mu < 30°$

Mode 2: 5 and 6 valve conduction

$30° < \mu < 60°$

Mode 3: 6 valve conduction

$0 < \alpha < 30°$, $\mu = 60°$

Mode 4: 6 and 7 valve conduction

$60° < \mu < 90°$

Mode 5: 7 and 8 valve conduction

$90° < \mu < 120°$

The second mode is a continuation of the first and similarly fifth is a continuation of the fourth.

The equivalent circuit of the twelve-pulse converter is the series combination of the equivalent circuits for the two bridges. This is because the two bridges are connected in series on the DC side and in parallel on the AC side. The current waveforms in the primary winding of the star/star and star/delta connected transformers and the line current injected into the converter bus are shown.

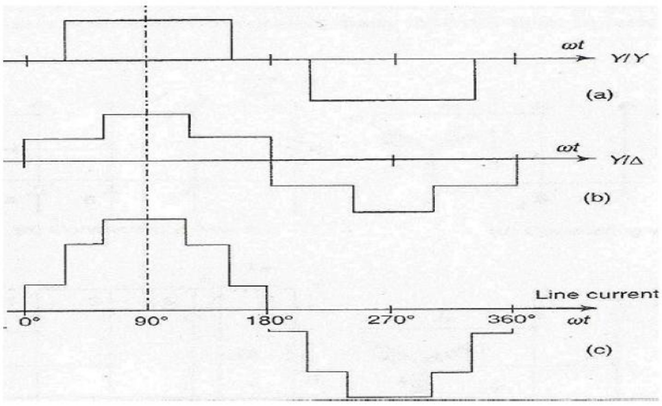


Fig 11: 12 pulse converterwaveform

UNIT –III

HVDC CONTROL TECHNIQUES

3.1 CONTROL OF HVDC CONVERTER:

The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

3.2 PRINCIPLE OF DC LINK CONTOL:

The control of power in a DC link can be achieved through the control of current or voltage. From minimization of loss considerations, we need to maintain constant voltage in the link and adjust the current to meet the required power.

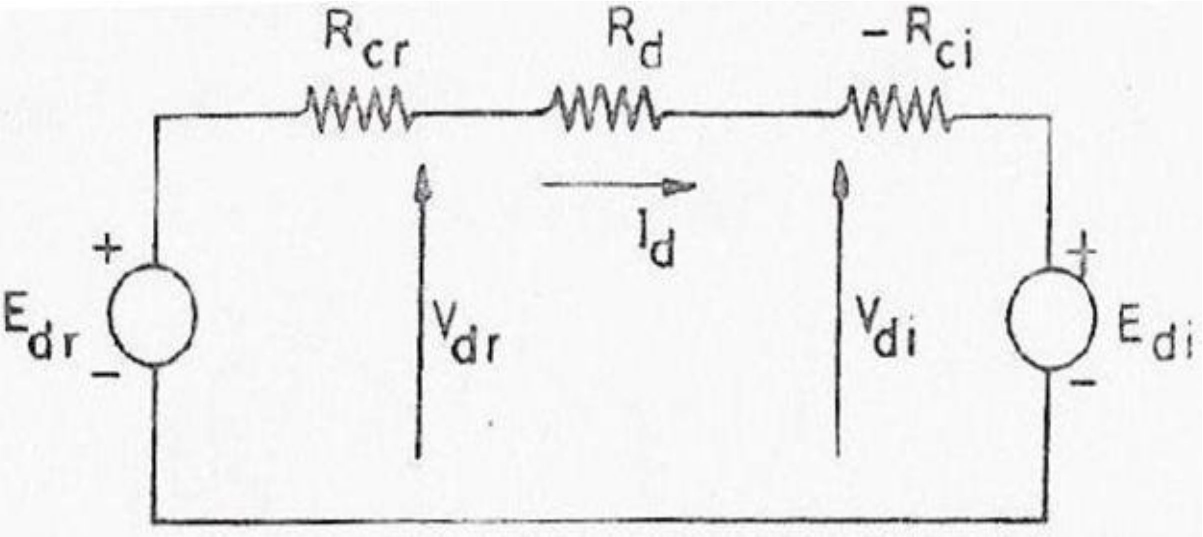


Fig 1: principle of DC link

Consider the steady state equivalent circuit of a two terminal DC link. This is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angles. Also the number of series connected bridges (nb) in both stations (rectifier and inverter) are thesame.

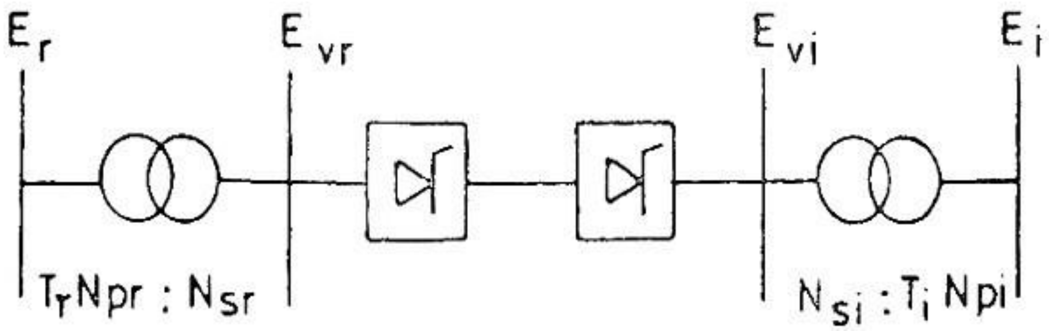


Fig 2: equivalent circuit of DC link

The voltage sources E_{dr} and E_{di} are defined by

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

$E_{di} = (3\sqrt{2}/\pi)\, n_b E_{vi} \cos\gamma_i$

where E_{vr} and E_{vi} are the line to line voltages in the valve side windings of the rectifier and inverter transformer respectively.
As the denominator in the final equation is small, even small changes in the voltage magnitude E_r or E_i can result in large changes in the DC current, the control variables are held constant. As the voltage changes can be sudden, it is obvious that manual control of converter angles is not feasible. Hence, direct and fast control of current by varying α_r or γ_r in response to a feedback signal is essential.

While there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at Constant Extinction Angle (CEA) which is slightly above the absolute minimum required for the commutation margin. This results in reduced costs of the inverter stations, reduced converter losses and reactive power consumption. However, the main drawback of CEA control is the negative resistance characteristics of the converter which makes it difficult to operate stably when the AC system is weak (low short-circuit ratios). Constant DC Voltage (CDCV) control or Constant AC Voltage (CACV) control are the alternatives that could be used at the inverter.
Under normal conditions, the rectifier operates at Constant Current (CC) control and the inverter at the CEA control.

The power reversal in the link can take place by the reversal of the DC voltage. This is done by increasing the delay angle at the station initially operating as a rectifier, while reducing the delay angle at the station initially operating as the inverter. Thus, it is necessary to provide both CEA and CC controllers at both terminals.
The feedback control of power in a DC link is not desirable because

- 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 of the reactive power, which depresses voltagefurther.
- The constant power characteristic contributes to negative damping and degrades dynamic stability.

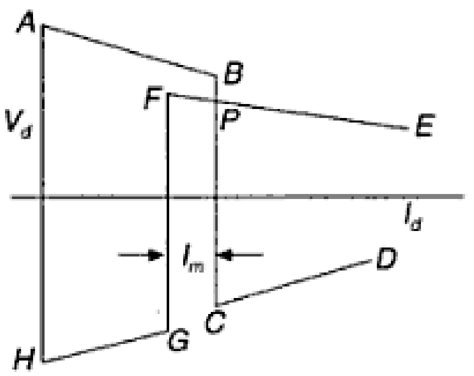
3.3 CONVERTER CONTROL CHARACTERISTICS:

3.3.1 Basic characteristics:

The intersection of the two characteristics (point A) determines the mode of operation- Station I operating as rectifier with constant current control and station II operating at constant (minimum) extinction angle.

There can be three modes of operation of the link (for the same direction of power flow) depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics which are defined below

- CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.
- With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at theinverter.
- With lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum α at therectifier.



Controllers characteristics.

Types of Station Control Characteristics

Station-I	Station-II	Controller type
AB	HG	Minimum α
BC	GF	Constant current
CD	EF	CEA (minimum γ)

Fig 3: control characteristcs

The characteristic AB has generally more negative slope than characteristic FE because the slope of AB is due to the combined resistance of (R_d + R_{cr}) while is the slope of FE is due to R_{ci} .

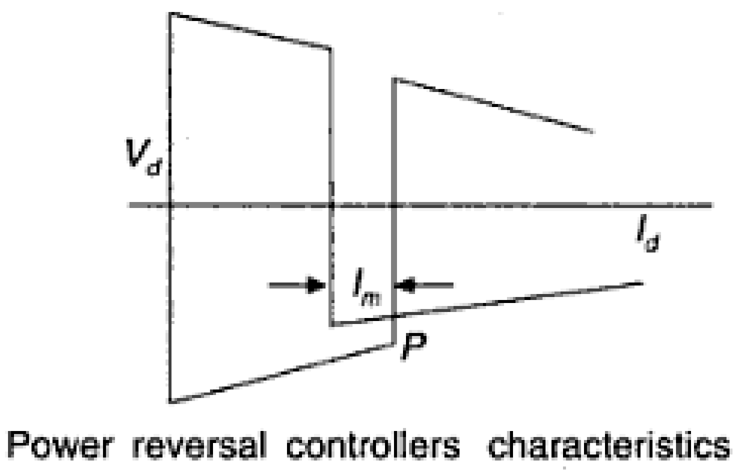


Fig 4: reverse control characteristics

The above figure shows the control characteristics for negative current margin Im(or where the current reference of station II is larger than that of station I). The operating point shifts now to D which implies power reversal with station I (now acting as inverter) operating with minimum CEA control while station II operating with CC control.

This shows the importance of maintaining the correct sign of the current margin to avoid inadvertent power reversal. The maintenance of proper current margin requires adequate telecommunication channel for rapid transmission of the current or power order.

3.3.2 VOLTAGE DEPENDENT CURRENT LIMIT:

The low voltage in the DC link is mainly due to the faults in the AC system on the rectifier or inverter side. The low AC voltage due to faults on the inverter side can result in persistent commutation failure because of the increase of the overlap angle. In such cases, it is necessary to reduce the DC current in the link until the conditions that led to the reduced DC voltage are relieved. Also the reduction of current relieves those valves in the inverter which are overstressed due to continuous current flow in them.

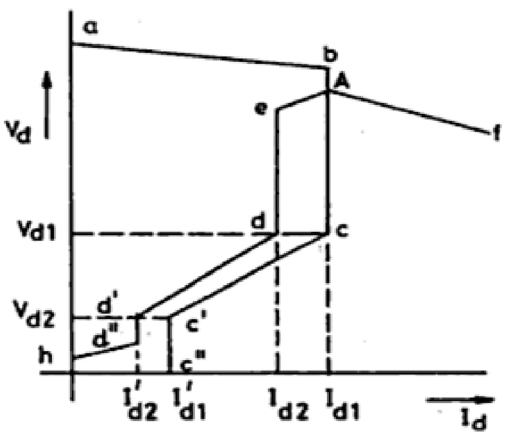


Fig 5: Diode characteristics

If the low voltage is due to faults on the rectifier side AC system, the inverter has to operate at very low power factor causing excessive consumption of reactive power which is also undesirable. Thus, it becomes useful to modify the control characteristics to include voltage dependent current limits. The figure above shown shows current error characteristics to stabilize the mode when operating with DC current between Id1 and Id2 . The characteristic cc| and c|c|| show the limitation of current due to the reduction in voltage.

3.4 SYSTEM CONTROL HIERARCHY:

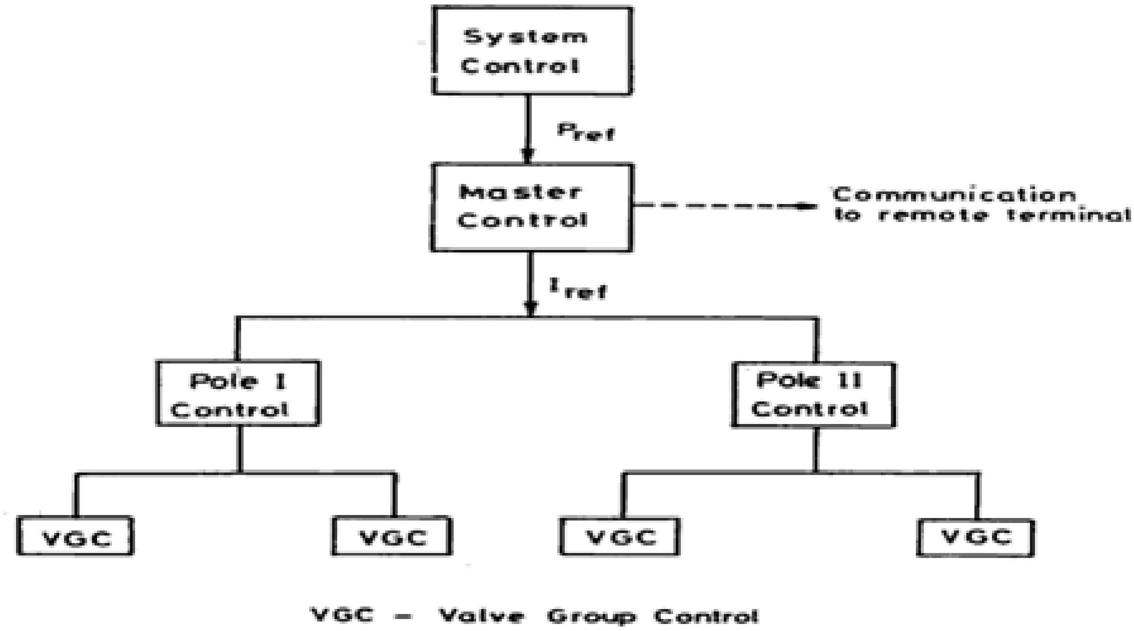


Fig 6: control of HVDC system

The master controller for a bipole is located at one of the terminals and is provided with the power order (Pref) from the system controller (from energy control centre). It also has other information such as AC voltage at the converter bus, DC voltage etc. The master controller transmits the current order (Iref) to the pole control units which in turn provide a firing angle order to the individual valve groups (converters).

The valve group or converter control also oversees valve monitoring and firing logic through the optical interface. It also includes bypass pair selection logic, commutation failure protection, tap changer control, converter start/stop sequences, margin switching and valve protectioncircuits.

The pole control incorporated pole protection, DC line protection and optional converter paralleling and deparalleling sequences. The master controller which oversees the complete bipole includes the functions of frequency control, power modulation, AC voltage and reactive power control and torsional frequency damping control.

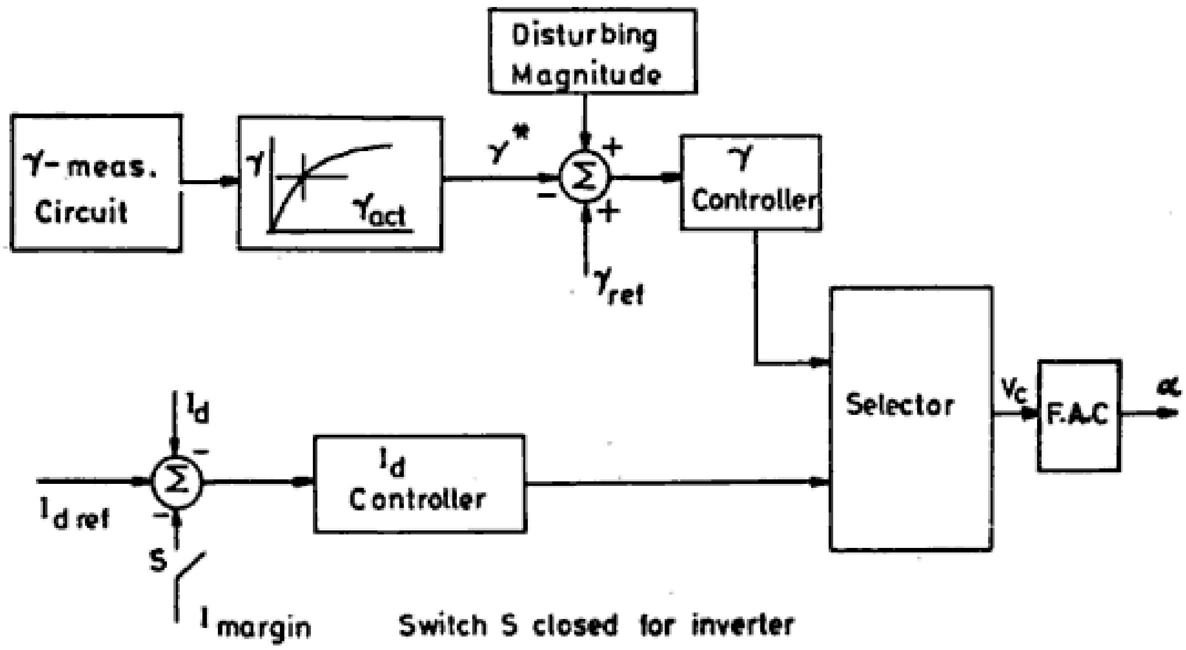


Fig 7: block diagram of control system of HVDC

The current or extinction angle controller generates a control signal V_C which is related to the firing angle required. The firing angle controller generates gate pulses in response to the control signal V_C. The selector picks the smaller of the α determined by the current and CEA controllers.

3.5.1 FIRING 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 requirements for the firing pulse generation of HVDC valves are

- The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signals through fibre-optic cables. The required gate power is made available at the potential of individual thyristor.
- While a single pulse is adequate to turn-on a thyristor, the gate pulse generated must send a pulse whenever required, if the particular valve is to be kept in a conductingstate.
- The two basic firing schemes are
    - Individual Phase Control (IPC)
    - Equidistant Pulse Control (EPC)

3.5.2 INDIVIDUAL PHASE CONTROL:

This was used in the early HVDC projects. The main feature of this scheme is that the firing pulse generation for each phase (or valve) is independent of each other and the firing pulses are rigidly synchronized with commutation voltages.

There are two ways in which this can be achieved

- Constant α Control.
- Inverse Cosine Control.

3.5.3 CONSTANT α CONTROL:

Six timing (commutation) voltages are derived from the converter AC bus via voltage transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero crossing of a particular commutation voltage corresponds to $\alpha = 0^{o}$ for that valve.

The delays are produced by independent delay circuits and controlled by a common control voltage V derived from current controllers.

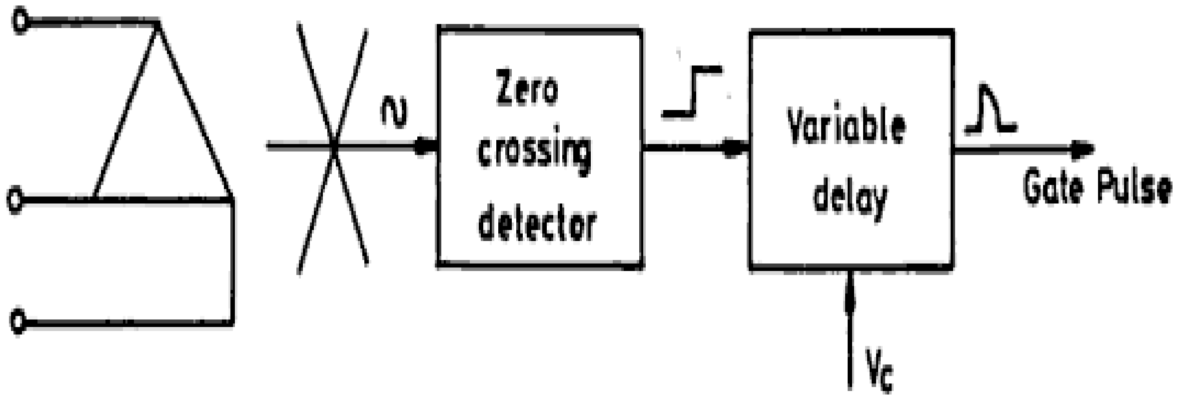


Fig 8: constant α control

3.5.4 INVERSE COSINE CONTROL:

The six timing voltages (obtained as in constant α control) are each phase shifted by 90^{o} and added separately to a common control voltage V.

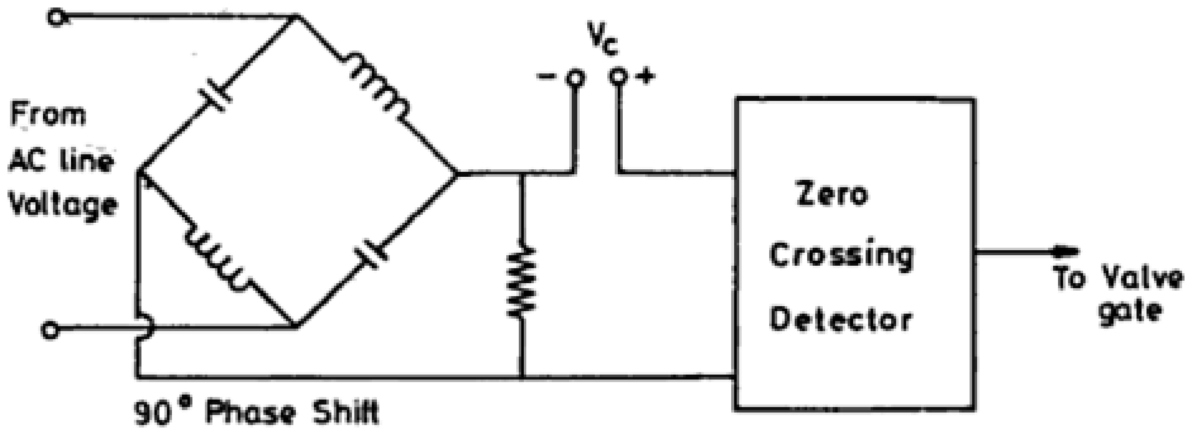


Fig 9: inverse cosine control

The zero crossing of the sum of the two voltages initiates the firing pulse for the particular valve is considered. The delay angle α is nominally proportional to the inverse cosine of the control voltage. It also depends on the AC system voltage amplitude andshape. The main advantage of this scheme is that the average DC voltage across the bridge varies linearly with the control voltage V_C.

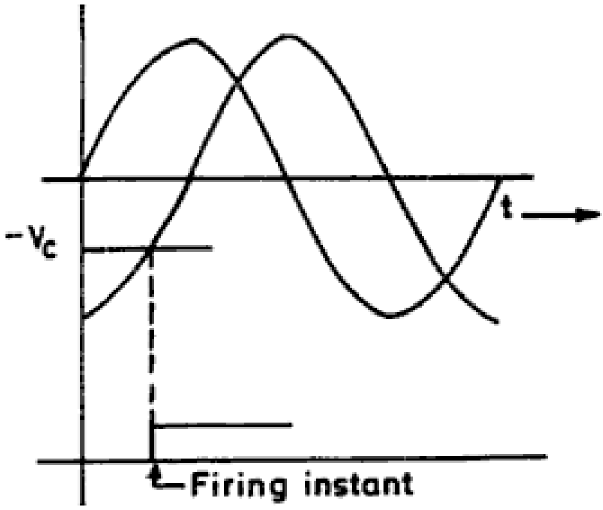


Fig 10: voltage waveform

3.5.5 DRAWBACKS OF IPC SCHEME:

The major drawback of IPC scheme is the aggravation of the harmonic stability problem that was encountered particularly in systems with low short circuit ratios (less than 4). The harmonic instability, unlike instability in control systems, is a problem that is characterized by magnification of non-characteristic harmonics in steady-state.

This is mainly due to the fact that any distortion in the system voltage leads to perturbations in the zero crossings which affect the instants of firing pulses in IPC scheme. This implies that even when the fundamental frequency voltage components are balanced, the firing pulses are not equidistant in steady-state. This in turn leads to the generation of non-characteristic harmonics (harmonics of order $h \neq np \pm 1$) in the AC current which can amplify the harmonic content of the AC voltage at the converter bus. The problem of harmonic instability can be overcome by the following measures

- Through the provision of synchronous condensers or additional filters for filtering out non characteristicharmonics.
- Use of filters in control circuit to filter out non characteristic harmonics in the commutation voltages.
- The use of firing angle control independent of the zero crossings of the AC voltages. This is the most attractive solution and leads to the Equidistant Pulse Firingscheme.

3.6 EQUIDISTANT PULSE CONTROL:

The firing pulses are generated in steady-state at equal intervals of 1/pf , through a ring counter. This control scheme uses a phase locked oscillator to generate the firing pulses. Thre are three variations of the EPC scheme

- Pulse Frequency Control (PFC)
- Pulse Period Control
- Pulse Phase Control (PPC)

3.6.1 PULSE FREQUENCY CONTROL:

A Voltage Controlled Oscillator (VCO) is used, the frequency of which is determined by the control voltage V_c which is related to the error in the quantity (current, extinction angle or DC voltage) being regulated. The frequency in steady-state operation is equal to pf_0 where f_0 is the nominal frequency of the AC system. PFC system has an integral characteristic and has to be used along with a feedback control system for stabilization.

The Voltage Controlled Oscillator (VCO) consists of an integrator, comparator and a pulse generator.

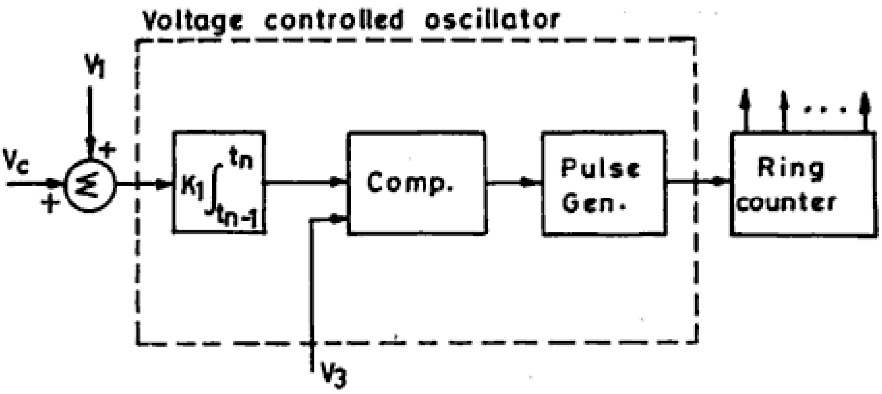


Fig 11 : pulse frequency control

The output pulses of the generator drive the ring counter and also reset the integrator. The instant (t_n) of the firing pulse is determined by

$$\int_{t_{n-1}}^{t_n} K_1 (V_c + V_1)\,dt = V_3$$

where V1 is a bias (constant) voltage and V3 is proportional to the system period. In steady-state, V_c = 0, and from the above equation, we get

$$K_1 V_1 (t_n - t_{n-1}) = V_3$$

Since, $t_n - t_{n-1} = 1/pf_o$

in steady-state, the gain K_1 of the integrator is chosen as

$$K_1 = pf_o V_3 / V_1$$

The circuit does not incorporate frequency correction (when the system frequency deviates from f_o). The frequency correction is obtained by deriving V_3 as

$$V_3 = V_2 / (1+ST_1),\ V_2 = K_1 V_1 (t_{n-1} - t_{n-2})$$

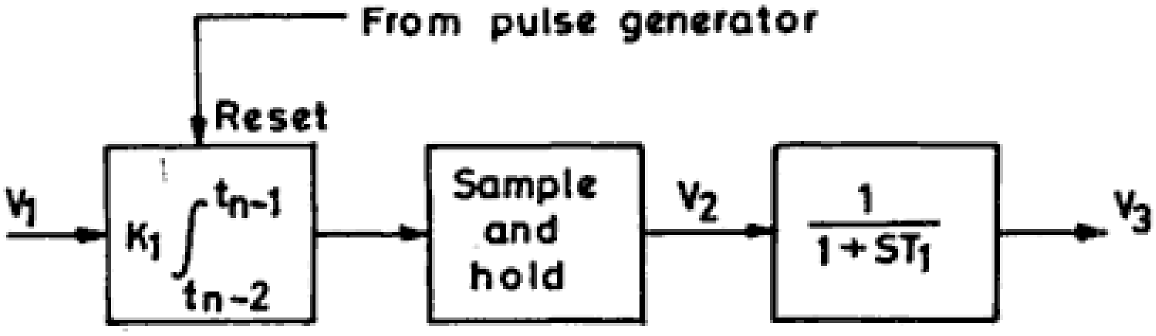


Fig 12: pulse frequency control

3.6.2 PULSE PEIOD CONTROL:

It is similar to PFC except for the way in which the control voltage V_c is handled. The structure of the controller is the same, however, V_c is now summed with V_3 instead of V_1 . Thus, the instant t_n of the pulse generation is

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_3 + V_c$$

$$K_1 V_1 (t_n - t_{n-1}) = V_3 + V_c$$

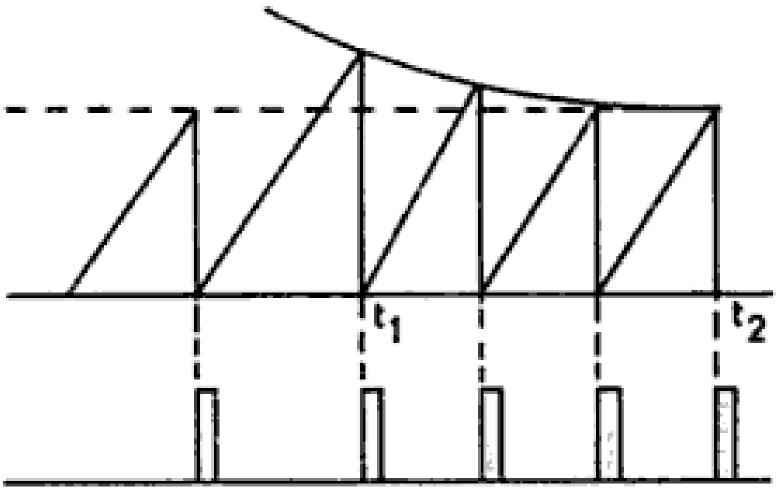


Fig 13: pulse period control

The frequency correction in this scheme is obtained by either updating V1 in response to the system frequency variation or including another integrator in the CC or CEA controller.

3.6.3 PULSE PHASE CONTROL:

An analog circuit is configured to generate firing pulses according to the following equation

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_{cn} - V_{c(n-1)} + V_3$$

where $V_{cn}$and $V_{c(n-1)}$ are the control voltages at the instants t_n and t_{n-1} respectively.

For proportional current control, the steady-state can be reached when the error of V_c is constant.
The major advantages claimed for PPC over PFC are (i) easy inclusion of α limits by limiting V_c as in IPC and (ii) linearization of control characteristic by including an inverse cosine function block after the current controller. Limits can also be incorporated into PFC or pulse period control system.

3.6.4 DRAWBACKS OF EPC SCHEME:

EPC Scheme has replaced IPC Scheme in modern HVDC projects; it has certain limitations which are

- Under balanced voltage conditions, EPC results in less DC voltage compared to IPC. Unbalance in the voltage results from single phase to ground fault in the AC system which may persist for over 10 cycles due to stuck breakers. Under such conditions, it is desirable to maximize DC power transfer in the link which calls forIPC.
- EPC Scheme also results in higher negative damping contribution to torsional oscillations when HVDC is the major transmission link from a thermalstation.

3.7 CURRENT AND EXTICTION ANGLE CONTROL:

The current controller is invariably of feedback type which is of PI type.

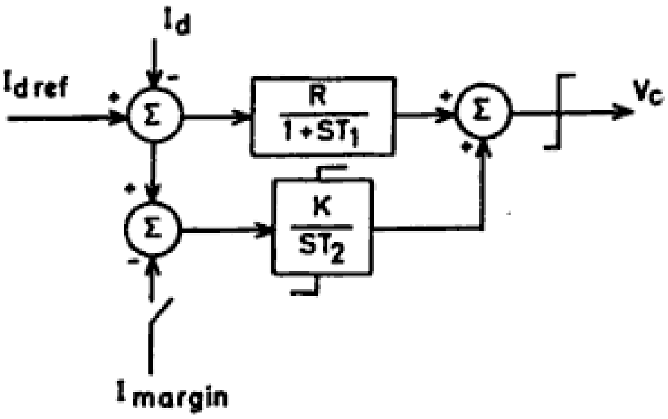


Fig 14: extinction angle control

The extinction angle controller can be of predictive type or feedback type with IPC control. The predictive controller is considered to be less prone to commutation failure and was used in early schemes. The feedback control with PFC type of Equidistant Pulse Control overcomes the problems associated with IPC.

The extinction angle, as opposed to current, is a discrete variable and it was felt the feedback control of gamma is slower than the predictive type. The firing pulse generation is based on the following equation

$$0 = \int_{-\pi+\delta_{n-1}}^{\omega t_n} e_{cj}\, d(\omega t) + 2X_c I_d$$

where e_{cj} is the commutation voltage across valve j and t_n is the instant of its firing.

In general, the prediction of firing angle is based on the equation

$B_j = \gamma_{ref} + \mu_j$

where μ_j is the overlap angle of valve j, which is to be predicted based on the current knowledge of the commutation voltage and DC current.

Under large disturbances such as a sudden dip in the AC voltage, signals derived from the derivative of voltage or DC current aid the advancing of delay angle for fast recovery from commutation failures.

UNIT –IV
CONVERTER FAULTS AND PROTECTION

4.1 INTRODUCTION TO CONVERTER FAULTS:

Studies Shows transmitting DC is more efficient than AC supply. As losses in HVDC are less than HVAC. But as we mostly generate AC supply hence, we need converter stations to convert AC in to DC for efficient transmission. Mostly studies have been done on Transmission line faults or AC faults but Converter station faults or DC faults also cause the stressing of equipment due to overvoltage or current. As in AC system, the faults in DC system are caused by external sources such as lighting, pollution or internally due to failure of converter valves. Electrical disturbance in the power system can cause more torsional stressing on the turbine generator shafts of the system than in the case of a three-phase fault at the generator terminals. As turbine-generator shaft torsional systems can interact with other power system stabilizers; static-var compensators, high-voltage direct current (HVDC) systems, high-speed governor controls, and variable speed drive converters.

4.2 CONVERTER FAULTS:

4.2.1 NATURE OF CONVERTER FAULTS:

- AC faults at rectifier end
- AC faults at inverter end
- Dc line/cable faults
- Converter station faults

4.3 TYPES OF CONVERETER FAULTS:

There are three basic types of faults that can occur at converter station:

- Faults due to malfunctions of valves and controllers
- Arc backs (or back fire)
  - Arc trough (Fire through)
  - Misfire
  - Quenching or current extinction
- Commutation Failures in inverters
- Short circuits in a converter Station

The arc back is the failure of the valve to block in the reverse direction and result in the temporary destruction of the rectifying property of the valve due to conduction the reverse direction. This is a major fault in mercury arc valve and is of random nature.

This is non self clearing fault and result in severe stresses on transformer windings as the incidence of arc backs is common. Fortunately, thyristor don’t suffer from arc back which has led to the exclusion of mercury arc valves from modern converter stations.

TYPES OF FAULTS	OCCURRENCE	FAULT CURRENT	PROTECTION
Converters and internal faults	Rare	10pu	Valves are rated for small duration of fault occurace
DC line fault	Frequent	2-3pu	Force retardation of firing angle
Commutation failure	Frequent	1.5-2.5pu	Single self clearing and multiple beta and control and VDCOL

4.3.1 COMMUTATION FAILURE:

This type of faults occurs in thyristor as they required a definite turn – off time so there is a need to maintain a minimum value of extinction angle defined by

$$\gamma = 180 - \alpha - u$$

Where the overlap angle (u) is a function of the commutation voltage and the DC current. The reduction in the voltage or increase in current or both can result in an increase in the overlap angle which can result in $\gamma<\gamma min$. This give rise to commutation failure.

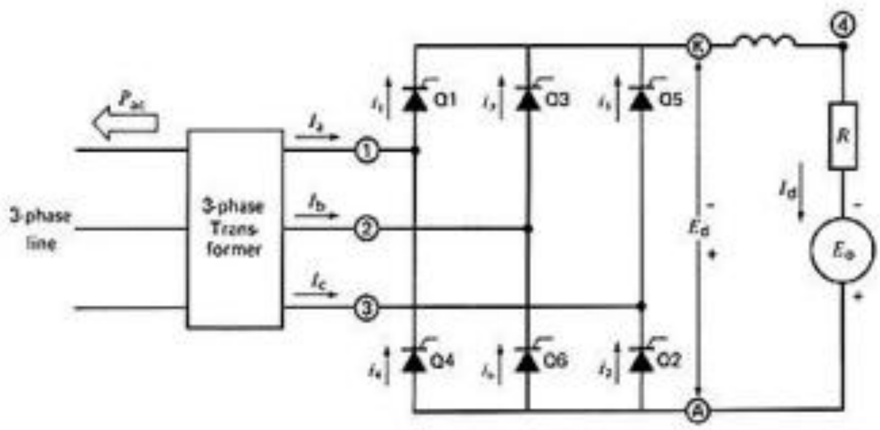
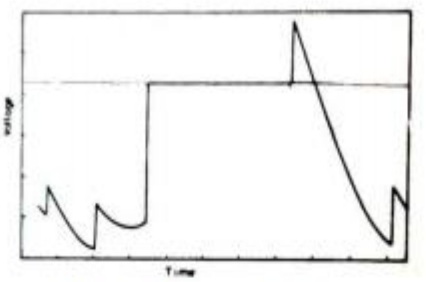


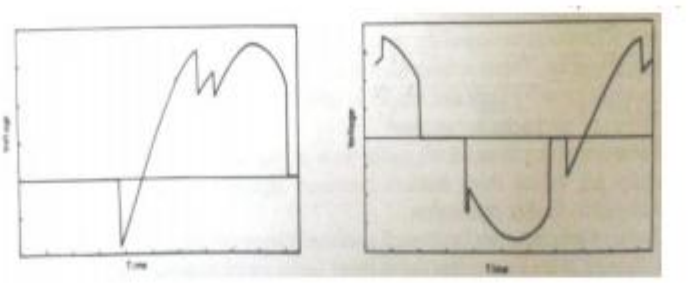
Fig 1: converter-based rectifier

In the fig.1 If the current in the incoming valve (say valve Q3) which starts conduct after valve Q1 will diminish to zero and the outgoing valve (valve Q1) will be left carrying the full sink current. As the firing of next valve in sequence is of valve Q4 this will result in a short circuit of the bridges as both the valve Q1and Q4of the same arm will conduct. If the conduction from valve Q2 to Q4 is successful, only valve Q1 and Q4 are left conducting and this state continues until the valve Q6 is fired.

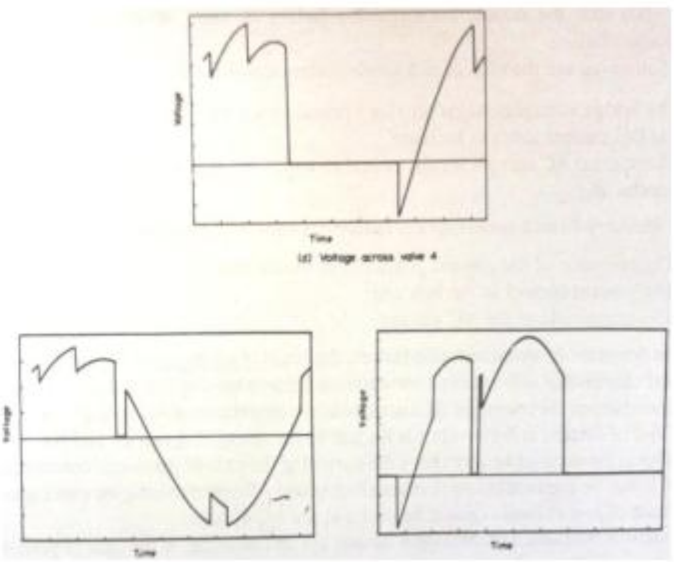
The firing of valve Q6 is unsuccessful as the valve Q5 is reverse biased at the time of firing. If the commutation from valve Q4 to Q6 is successful, the conduction pattern returns to normal except the bridge voltages is negative at the instant where Q4 ceases conduction. If the causes which led to commutation failure in valve Q1 in the first instant have disappeared, the bridge operation returns to the normal state. Thus, a single commutation failure is said to be self-clearing. The wave form of the bridge voltage and valve voltage are shown in fig. 2



(a) bridge voltage



across valve 2 and 3



across valves 4,5 and 6

Fig 2: voltage waveforms

The failure of two successive commutations in the same cycle is called “double commutation failure”. If the commutation failures occur when valve Q4 is also fired the valves Q1 and Q2 are left in conducting state until the instant in the next cycle when valve Q3will be fired.

EFFECTS OF 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 left conducting.

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
3. The magnitude of the AC voltage

4.3.2 ARC THROUGH:

This is a fault likely to occur at the inverter station, where the valve voltages are positive most of the time (when they are not conducting). A malfunction in the gate pulse generator or the arrival of spurious pulse can fire a valve which is not supposed to conduct, but is forward biased. For such fault, the firing delay angle of the faulted valve is reduced from its normal value to a smaller value or zero. For example, in a bridge, when valve 1 has successfully commutated its current valve 3, then initial current across it is a negative (for the duration of the extinction angle) and then become positive. If the valve 1 is fired at this time, the current will transfer back to valve 1 from valve 3. The effect of an arc through are similar to that of commutation failure – the voltage across the bridge falls as valve 4 is fired (with valve 1 is conducting) and the AC current goes to zero when valve 2 current goes to zero. The firing of valve 5 is unsuccessful and the bridge recovers to its normal operation after valve 6 is fired and the subsequent firings are according to the normal sequence. Such fault also introduces a significant increase in the harmonic contents of the turbine-generator shaft torsional torques

4.3.3 MISFIRE:

Misfire occurs when the required gate pulse is missing and the incoming valve is unable to fire. The probability of the occurrence of misfire is very small in modern converter stations because of duplicate converter controls, monitoring and protective firing of valves. While misfire can occur in rectifier or inverter stations, the effects are more severe in the latter case. This is due to the fact that in inverters, persistent misfire leads to the average bridge voltage going to zero, while an AC voltage is injected in to the link. This result in large current and voltage oscillations in the DC link as it presents a lightly damped oscillatory circuit viewed from the converter. The DC current may even extinguish and result in large overvoltage across the valves. The waveform of the DC voltage and current in the link of persistent misfire in the inverter are shown in fig.9 Also such fault introduces significant distortion to the electromagnetic torque.

The effects of a single misfire are similar to those of commutation failure and arc through. When valve 3 in a bridge misfires, the valves 1 and 2 are still conducting until valve 4 is fired. However, at the end of cycle the normal sequence of valve firing is restored. Thus, a single misfire is also self-clearing.

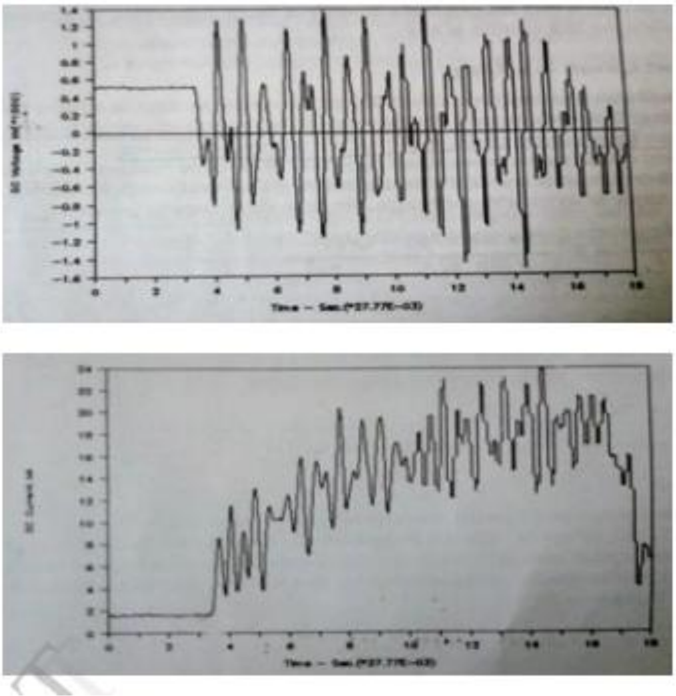


Fig 3: Voltage and Current Waveform of Misfire

4.3.4 CURRENT EXTINCTION:

The extinction of current can occur in a valve if the current through it falls below the holding current. This can arise at low value of the bridge currents when any transient can lead to current extinction. The current extinction can result in overvoltage across the valve due to current chopping in an oscillatory circuit formed by the smoothing reactor and the DC line capacitance. The problem of current extinction is more severe in the case of short pulse firing method. However, in modern converter stations, the return pulses coming from thyristors levels to the valve group control, indicate the buildup of voltage across the thyristors and initiate fresh firing pulses when the valve is supposed to be conducting. It may happen that a number of firing pulses may be generated during a cycle when then current link is low.

4.3.5 SHORT CIRCUIT ON A BRIDGE:

This fault also has very low probability as the valves are kept in a valve hall with air conditioning. However, bushing flashover can lead to a short circuit across the bridge and produce large peak currents in the valve that are conducting. The short circuit currents are significant only in rectifier bridges. The worst case is when the short circuit occurs at the instant of firing a valve at $\alpha = 0^{o}$. Assuming that there is no inductance in series with the bridge, the peak short circuit current (i_{peak}) is given by

$$\frac{ipeak}{Is} = 3 \; \frac{(1+\sin {}^{\pi}/_{p})}{p\sin {}^{\pi}/_{p}} + \frac{({}^{p}/_{3})-1}{{}^{p}/_{3}} * \left(\frac{ido}{Is}\right)..$$

Where p = pulse number of the converter (6 or 12)
ido = the dc current at the instant of firing the valve
Is = 2 E_{LL} / 2 X_c
For a six-pulse converter,
the peak current is

$$i_{peak} = \frac{1}{2}[3\ I_s + i_{do}]$$

The bridge voltage and current waveform are shown in fig.4, the effect of network impedance in limiting the current is neglected. The maximum peak current in a valve results when it is conducting in to a valve fault. For example, the maximum current in valve 3, when it starts conducting with short circuit across valve 1, is given by

$ipeakIs = (1 + \cos\alpha) + (Id\ /2Is)$

The peak currents are of the order of 10 to 12 times the rated current and the thyristor valve must be having surge rating above this value. The fault clearing is performed by blocking the pulse when the fault current goes to zero. The detection of bridge or valve short circuit is also performed by comparing the AC and DC currents.

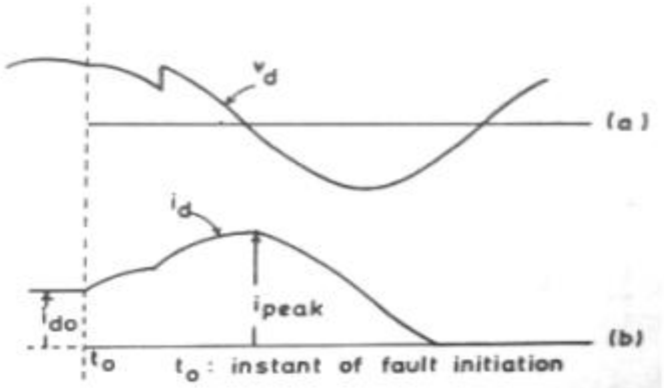


Fig 4:Bridge voltage and current waveforms for short circuit fault

4.3.6 QUENCHING:

This happened mostly in the mercury arc valves. It is the premature extinction of the valve in the normal conduction period. This malfunction has the same effect as misfire and causes a Dc short at terminal.

4.4 STARTING AND SHUTTING OF DC CONVERTER:

4.4.1 ENERGISATION AND DEENERGISATION OF BRIDGE:

Consider N series connected bridges at a converter station. If one of the bridges is to be taken out of service, there is need to not only block, but bypass the bridge. This is because of the fact that just blocking the pulses does not extinguish the current in the pair of valves that are left conducting at the time of blocking. The continued conduction of this pair injects AC voltage into the link which can give rise to current and voltage oscillations due to lightly damped oscillatory circuit in the link formed by smoothing reactor and the line capacitance. The transformer feeding the bridge is also subjected to DC magnetization when DC current continues to flow through the secondary windings.

The bypassing of the bridge can be done with the help of a separate bypass valve or by activating a bypass pair in the bridge (two valves in the same arm of the bridge). The bypass valve was used with mercury arc valves where the possibility of arc backs makes it impractical to use bypass pairs. With thyristor valves, the use of bypass pair is the practice as it saves the cost of an extra valve.

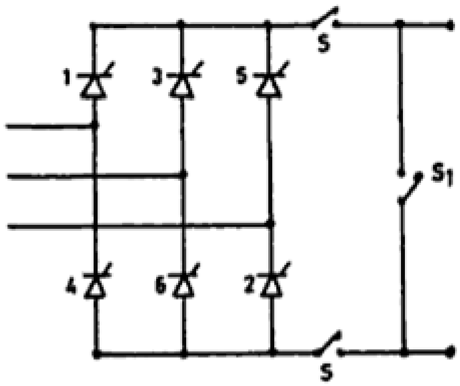


Fig 5: energizing of bridge

With the selection of bypass pair 1 and 4, the commutation from valve 2 to4 is there, but the commutation from valve 3 to valve 5 is prevented. In the case of a predetermined choice of the bypass path, the time lapse between the blocking command and the current transfer to bypass path can vary from 60^0 and 180^0 for a rectifier bridge. In the inverter, there is no time lag involved in the activation of the bypass pair. The voltage waveforms for the rectifier and inverter during de-energization are shown below where the overlap isneglected.

The current from bypass pair is shunted to a mechanical switch S1. With the aid of the isolators S, the bridge can be isolated. The isolator pair S and switch S1 are interlocked such that one or both are always closed.

The energization of a blocked bridge is done in two stages. The current is first diverted from S1 to the bypass pair. For this to happen S1 must generate the required arc voltage and to minimize this voltage, the circuit inductance must be small. In case the bypass pair fails to take over the current, S1 must close automatically if the current in that does not become zero after a predetermined time interval. AC breakers with sufficient arc voltage, but with reduced breaking capacity are used as switch S1 .

In the second stage of energization, the current is diverted from the bypass pair. For the rectifier, this can take place instantaneously neglecting overlap. The voltage waveforms for this case are shown below.

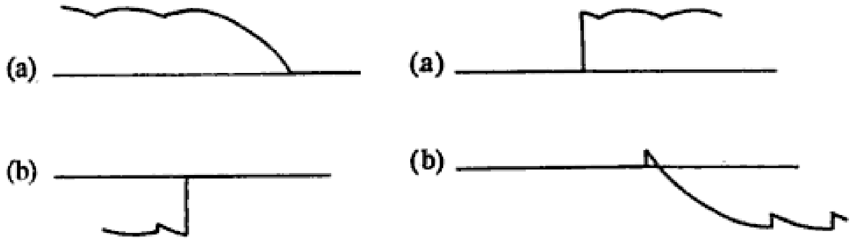


Fig 6: voltage waveform

4.4.2 STARTUP OF DC LINK:

There are two different start-up procedures depending upon whether the converter firing controller provides a short gate pulse or long gate pulse. The long gate pulse lasts nearly 120^0, the average conduction period of avalve.

4.4.2.1 STARTUP WITH LONG PULSE:

1. Deblock inverter at about $\gamma = 90^0$
2. Deblock rectifier at $\alpha = 85^0$ to establish low direct current
3. Ramp up voltage by inverter control and the current by rectifier control.

4.4.2.2 STATUP WITH SHORT PULSE:

1. Open bypass switch at one terminal
2. Deblock that terminal and load to minimum current in the rectifier mode
3. Open bypass switch at the second terminal and commutate current to the bypass pair
4. Start the second terminal also in the rectifier mode
5. The inverter terminal is put into the inversion mode
6. Ramp up voltage and current.

The voltage is raised before raising the current. This permits the insulation of the line to be checked before raising the power. The ramping of power avoids stresses on the generator shaft. The switching surges in the line are also reduced.
The required power ramping rate depends on the strength of the AC system. Weaker systems require fast restoration of DC power for maintaining transient stability.

4.5 CONTROL AND PROTECTION LEVEL:

The Control and Protection Level consists of the Control and Protection Systems including the respective measuring systems. The operator commands are sent to the controls, e.g. power order, bus voltage reference etc. They are executed by the closed-loop controls. Automatic converter control achieves the desired power transmission and AC bus voltage magnitude coupled with automatic switching of filters, capacitor and reactor banks. The operator's open/close commands to the high voltage devices are interlocked in the controls to prevent out of-step operation of breakers, disconnectors and ground switches. Also interlocks to prevent forbidden system or switchyard configurations are installed here. Interlocking to prevent personnel access to the valve hall and filter, areas that are not walk through, is provided by means of key interlocks – controlled by the Station Controls. The protections use the analog inputs, currents and voltages from the field level to protect the equipment. Trip commands are sent to the respective breakers, alarms are generated in the HMI's Sequence-of-Events Recorder and the Transient Fault Recorder is triggered from the protections.

4.6 STATION CONTROL:

The Station Control manages the equipment which is necessary to integrate the HVDC System into the customer's power system and also those functions common to both poles. The main Station Control areas are:

- AC and DC Switchyard Control
- Control and monitoring of the auxiliary system
- DC Configuration Control
- Reactive Power Control
- AC Voltage Limitation Control
- Managing the control authority between different control locations

4.5.1 AC AND DC SWITCHYARD CONTROL WITH OPERATOR GUIDANCE:

The Station Control monitors and operates the high-voltage devices and handles the acquisition and the preprocessing of measured values in the AC and DC switchyards. All safety interlocking is implemented at device level as hardware or software interlocks. Station Control monitors the condition of the whole switchyards in combination with the status of the HVDC system. An additional process interlock continuously checks which preconditions have been fulfilled. Dependent on the result of these checks, the switching release for each device is defined and sent to the HMI. Only when all interlock conditions for a device have been fulfilled does the operator receive indication that device operation is possible.

4.5.2 POLE CONTROL AND DC PROTECTION:

The Pole Controls are the heart of the HVDC control system. Here, the DC power flow is controlled to the operator's setpoint. Steady-state and dynamic performance of the AC systems is also enhanced by the Pole Controls. Features such as power swing stabilisation, frequency limit control and sub-synchronous resonance damping are some of the available features. The primary function of the Pole Control System is to maintain the transmitted power at the operator selected value. This is achieved with an optimal response during system disturbances and is robust and stable for all system configurations. During normal undisturbed operation, DC current control is active at the Rectifier and DC voltage control at the Inverter. A backup extinction angle control provides a safety margin to minimise commutation failures at the Inverter following disturbances in its AC system. An Inverter current control function becomes active should the Rectifier station be unable to provide the ordered DC current during AC System disturbances.

4.5.2.1 ACTIVE AND REACTIVE POWER CONTROL

The prime function of DC Power Control is to control the active steady-state Power Order selected by the operator. It must also respond to inputs from stability control functions. Reactive Power Control is achieved by co-ordinated switching of reactive power components and firing angle control of the converter. Since filter and capacitor elements are common for the whole station, this control is located in the Station Controls. The reactive power is controlled according to minimum and maximum limits selected by the operator. Alternatively, AC Voltage Control is possible using a similar control method as used for the Reactive Power control.

4.5.2.2 DC CURRENT AND VOLTAGE CONTROL:

DC Current Control is provided for both Rectifier and Inverter operation but used in different ways. At the Rectifier, DC Current Control is normally active controlling Id as defined by the Power Control. At the Inverter, the current controller is a backup function and becomes active in case of abnormal conditions in the Rectifier AC system. The task of DC Voltage Control is to maintain the DC voltage at a set value. It is used in different ways at the Rectifier and the Inverter. DC Voltage control is the normal control at the inverter and operates to control the DC voltage to the rated value. At the Rectifier, the DC voltage controller operates to limit the DC voltage to a maximum value, which is set just above the nominal converter voltage. Extinction Angle Control comes into operation automatically to prevent operation with Inverter extinction angles below a Reference Value of 17°. The Measured Value is the smallest extinction angle of the 12 valves sampled in the previous cycle. Gamma measurement is made for each valve with an accurate measurement of the time between the end of the valve‘s commutation (current zero) and its respective AC voltage zero crossing.

4.5.2.3 ON-LOAD TAP CHANGER CONTROL

Different tap changer control modes are used depending on the operating configuration and the desired control modes. In one mode, the tap changer is controlled according to a firing angle reference at Rectifier (e.g.=15°±2°) and extinction angle at Inverter (e.g.= 20°±2°). An alternative mode at both the Rectifier and Inverter side is for the tap changer to control the Udi0 (valve side AC voltages) to the nominal value over the complete operating range of the converter. It operates to compensate for changes in AC system voltage. Udi0 control mode is used especially in back to back application.

4.5.2.4 STABILITY CONTROL FUNCTIONS

AC systems may require transient or fixed power changes in the HVDC system to enhance their stability. Stability functions are system-dependent, the optimum control response is determined by comprehensive studies and verified with dynamic performance tests. Power runback and run-up functions can be provided based on inputs from the AC system. Binary signals derived from AC system state changes are used to execute a run-back or run-up. Run-backs are utilized to stabilize the AC system upon sudden loss of an infeed at the Rectifier or loss of export at the Inverter. DC power reduction can also help prevent AC system voltage instability.

Power Swing Stabilization is a large amplitude modulation signal which is active after major AC system disturbances. Power Swing Damping is a small amplitude modulation signal which could be continuously active to provide positive damping to AC power flow in a parallel AC system or local machines. Typically, its output would be limited to ±0.1 p.u. Frequency Limit Control (Power Frequency Control) is a contingency control function that becomes active when the system frequency moves outside the defined frequency range. This is likely to occur in an islanded situation where the AC system has split apart. The control limits the overfrequency (and underfrequency) in the Inverter or Rectifier AC systems, but not simultaneously.

AC Voltage Limit Control is an emergency function. Of course, other control characteristics are provided to minimize the need for this function, e.g. the reactive power controller. The simplest strategy to protect the AC system from voltage drops below 0.9 p.u. is to initiate a fixed DC power reduction for a predefined AC undervoltage. Other more complex AC voltage dependent power changes can also be implemented. The mechanical torsional shaft resonances of large thermal generators are typically present in the frequency range between 10 Hz and 25Hz. Oscillations at these sub synchronous frequencies are generally excited by any contingency in the system. The current and power controllers of an HVDC interconnector may cause negative electrical damping in the frequency range where the torsional frequencies of large thermal units are present.

This means that undamped torsional oscillations can be excited under certain circumstances. This is especially true when large thermal generators are directly connected to the same busbar as the HVDC system. HVDC can be used to damp the sub synchronous oscillations actively when the HVDC converter is very close to the generator. To do this, the oscillations of the shaft speed or the frequency oscillations are measured and then passed to a circuit which applies a suitable phase shift. The phase-shifted signal is then used to modulate the firing angle or the current order.

4.2.5.4 HIGH-PERFORMANCE FIRING CONTROL

The Pole Control outputs are the firing pulses for the thyristor valves, see Figure 4-16. Based on information from the Pole Controls and the AC system voltage, the trigger set generates the firing pulses. Synchronization of the trigger set with the AC system plays an important role following major AC system disturbances. The synchronization voltage is derived from the positive phase sequence of the AC voltages and ‘tracks’ any phase changes of the system fundamental frequency very quickly. During severe disturbances in the AC voltages (e.g. Uac< 0.1 p.u.), the trigger set phase is frozen until normal voltage returns. Under balanced conditions, HVDC converters are fired equidistantly (to avoid generation of non-characteristic harmonics by the converter) and therefore it is advantageous to synchronize with the phase angle of the positive sequence component of the fundamental frequency. The equidistant accuracy for the firing control system is better than 0.01° electrical degree

4.2.5.5 OPERATIONAL STATES AND SWITCHING SEQUENCES

The Pole Startup and Shutdown Sequences carry out and monitor the sequential steps for correct switching on and switching off of all pole-dedicated equipment. Four states of operation (EARTHED, STANDBY, BLOCKED and DEBLOCKED) are defined for each pole. Processing of a start or stop sequence will be activated by selecting a state of operation at the HMI.

According to the operator guidance, the Pole Control indicates which state the pole is in. Correct execution of the sequences is checked by monitoring the time interval for each step. If the time is excessive, then the sequence will be stopped and an alarm sent to the Sequence-of-Events Recorder. After fault correction, the sequence can be continued, but if not possible, the correct steps are automatically initiated to return the pole to the previous safe state. For long-distance transmission applications, the Open Line/Cable Test sequence provides a method for testing the voltage withstand capability of the line or cable. For this test, the DC line/cable is disconnected from the remote converter station. Then the DC voltage is slowly increased up to the maximum level via a ramp at the testing station. Deblocking of the converter is managed by the Deblock Sequence in a coordinated manner between both stations utilizing interstation telecommunication.

It ensures that the Inverter is always deblocked before the Rectifier. Should interstation telecommunication be unavailable, deblocking of the converter is still possible. Both operators must coordinate deblocking via telephone to ensure that the Inverter is deblocked before the Rectifier. The converter is blocked by the converter Block Sequence to shut down the converter with minimum disturbance to the system.

It coordinates the shutdown at each station and always blocks the Rectifier station first. For major faults where a protection has operated or control of the converter Ud and Id is disturbed or lost, the

Emergency Switch-Off Sequence (ESOF) shuts down the converter as quickly as possible. It also is used for any situation where AC voltage should be removed from the converter as quickly as possible.

4.5.3 DC PROTECTION IN CONVERTER:

The Converter Protection detects faults on the converter transformer secondary side, in the valve hall and failures which lead to overstress of the thyristor valves. It consists of a completely redundant scheme incorporating the following functions:

- Overcurrent Protection.
- Bridge Differential Protection for Wye and Delta Group.
- Group Differential Protection.
- Short-Circuit Protection for Wye and Delta Group.
- DC Differential Protection.
- DC Overvoltage Protection
- AC Overvoltage Protection

4.5.3.1 DC BUSBAR PROTECTION

The DC Busbar Protection detects ground faults on the high-voltage and on the low voltage busbar. It consists of a completely redundant scheme incorporating the following functions:

- High-Voltage DC Busbar Differential Protection
- Low-Voltage DC Busbar Differential Protection
- DC Differential Backup Protection (includes the converter)

4.5.3.2 DC FILTER PROTECTION

The DC Filter Protection detects short circuits, over currents and faulty capacitor units in the DC filter circuit. It consists of a completely redundant scheme incorporating the following functions:

- Differential Protection
- Overcurrent Protection
- HV Capacitor Unbalance Protection
- HV Capacitor Differential Overcurrent Protection

4.5.3.3 ELECTRODE LINE PROTECTION

The Electrode Line Protection equipment detects earth faults, short circuits, over currents and open circuit electrode lines. It consists of a completely redundant scheme incorporating the following functions:

- Current Unbalance Protection
- Overcurrent Protection

- Overvoltage Protection
- Switch Protections

4.5.3.4 DC LINE/CABLE PROTECTION

The DC Line/Cable protection detects any ground fault at the DC Line/Cable to limit any damage and to restore operation as soon as possible. It consists of a completely redundant scheme incorporating the following functions:

- Travelling Wave Protection
- Undervoltage Detection.
- DC Line/Cable Differential Protection

4.5.3.5 HARMONIC PROTECTION

A Fundamental Frequency Protection function detects 1st or 2nd harmonics in the DC current or in the DC voltage. These harmonics arise from converter misfiring or asymmetrical faults in the AC system. If the harmonic content exceeds a preset limit, then a binary signal initiates the 1st or 2nd harmonic protective action. The Sub synchronous Resonance Protection detects resonances e.g. caused by oscillation of the power plant’s generator. The resonances can be detected in the DC current. If the sub synchronous resonances exceed a preset limit, then a binary signal initiates the sub synchronous resonance protective action.

UNIT –V
REACTIVE POWER MANAGEMENT

5.1 INTRODUCTION:

In the design of an HVDC station, smoothing reactor rating is challenging and presents several interesting questions: How large should it be? Where should it be arranged? Is a smoothing reactor needed at all? Before attempting to answer these questions, a few functions of an HVDC smoothing reactor will be presented.

5.2 FUNCTIONS OF SMOOTHNING EACTOR:

Limitation of the rate of rise of current in the event of dc-side faults, i.e. line-to-ground faults or commutation failures of the inverter station, in combination with dead time and regulating speed of the rectifier current control, results in a limitation of peak short-circuit current. Since dc current causes an equivalent current on the ac-side, the degree of disturbance of the ac network is directly dependent on this limiting function.

For the inverter which has suffered a commutation failure, the limitation of the rate of current rise is critical for recovery of operation. The lower the current slope in the dc circuit, the greater the chance for the next commutation, which is due after 30° to be successfully. On the other hand the fast response of HVDC system prefers a low inductive dc circuit, which means a moderate smoothing reactor size. Therefore, a trade off of all dynamic aspects shall be considered in the selection of reactor size.

The limitation of the direct current ripples has already been discussed in chapter “DC Harmonic Filters” as being important with respect to frequency transfer between asynchronous networks (non-harmonic oscillations) and the avoidance of current discontinuities in the light load range. The smoothing reactor plays a key role in this process, though the leakage inductances of the converter transformer are also involved.

An increase in operating security can be achieved, because voltage jumps in one of the two ac systems result in a change of the direct current until current control becomes effective. The rate of change of direct current is inversely proportional to the effective inductance in the dc circuit. In order to avoid commutation failures in inverter operation due to a rapidly rising direct current, the dc-side inductance should not be too low.

Suppression of telephone interference caused by the dc overhead line is, of course, an essential function of the dc filter circuits, but the smoothing reactor also plays an important role as a series impedance. Therefore, the selection of smoothing reactor size is closely related to the dc filter performance requirements.

A dc-side resonance at the network frequency or other low order harmonic frequencies must be avoided. The issue exists both for sea cable connections and for the overhead line transmission. The resonant circuit can be detuned through the selection of an appropriate smoothing reactor inductance in conjunction with dc filter impedance.

In summary, it can be said that it would be possible to operate an HVDC scheme without a smoothing reactor at least a back-to-back link, if necessary, because a usual transformer short-circuit voltage of 10-20% and the transformer leakage inductances present a significant inductance in the dc circuit. In any case, this is not a recommended kind of operation. At long-distance transmissions with overhead line or cable, the smoothing reactor is probably indispensable.

5.3. RATING OF SMOOTHNING REACTOR:

While the current and voltage rating of the smoothing reactor can be specified based on the dc circuit data, the inductance is the determining factor for the reactor. While the HVDC links in the early stage uses sometimes extreme large smoothing reactor (reactance in the range of 1000 mH or higher), is the smoothing reactor size in the recent DC links rather in the range from 100 to 300 mH for long distance scheme, from zero to 80 mH in theback-to-back scheme. This reduction may have various reasons like better voltage / current capability of thyristor valves against mercury arc valves, better performance of digital control than the analogue controls, better performance of multiple tuned dc filters than single tuned filters, etc.

There is no international accepted rule to define the adequate smoothing reactor size. The selection is more based on the results of various design studies as described in last section and the existing operating experience. Furthermore, the smoothing reactor inductance needs to be evaluated in context with the whole station inductance.

The leakage inductances of the converter transformer still have to be considered as far as effective in the dc circuit. In order to explain this, Figure 1 shows the equivalent circuit of a station pole with one twelve-pulse group.

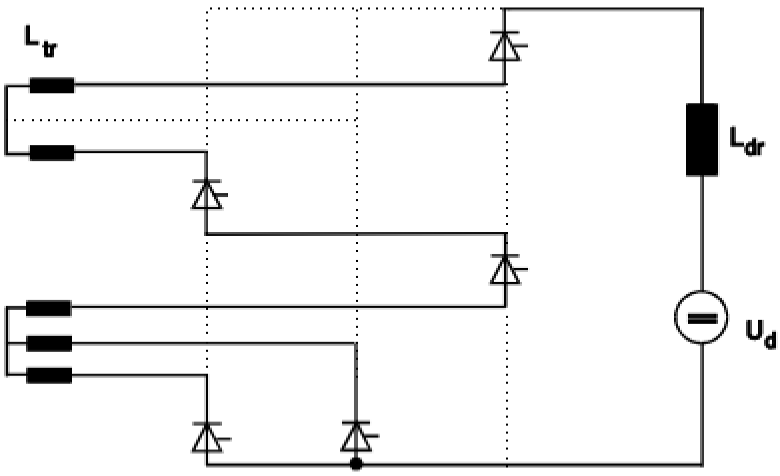


Figure 1 equivalent circuit of a station pole

5.4 REACTOR TYPES:

Generally, there are two types of reactors:

- air insulated dry-type reactors
- oil immersed reactors in a tank

The air-insulated dry-type reactor is cost-effective for small reactor ratings (I d 2 * Ldr). An advantage of this type is the keeping of spare units (as far as necessary), because the smoothing reactor usually consist of several partial coils. On the other hand, dry-type reactors are prone to contamination. In earthquake regions, the arrangement on post insulators or on an insulating platform is a critical problem. The dry type reactor is maintenance free and no fire risk, which are important factors in evaluation.

The oil-immersed reactor is economical for very high rating (I d 2 * Ldr). It is resistant to earthquakes. Only bushings are subjected to contamination. Maintaining of spares is expensive. The oil-immersed reactor is similar to the transformers with regard to the maintenance and fire fighting facilities.

In case that the reactor uses a iron core the saturation of the reactor at high currents shall also be considered. In back-to-back links, it may be reasonable to omit spares, because: · the probability of a reactor failure is very low · operation is also possible without smoothing reactor, though with slight trade-offs There is still a dispute about which type of reactor is more favorable with respect to noise generation. Therefore, it is always worth to evaluate both options from project to project to find a best solution to meet the particular requirements.

5.5 HARMONICS:

Electrical energy transmitted through AC transmission or DC transmission is to be delivered at the consumer's terminals at specified voltage level of constant magnitude without deviation from the ideal waveform.

An HVDC transmission system generates harmonic currents on the AC side and harmonic voltages on the DC side during operation. The harmonic currents generated at the AC bus of the converter get transmitted to the AC network and then cause the following adverse effects.

- Heating of the equipment's connected.
- Instability of converter control.
- Generates telephone and radio interference in adjacent communication lines, thereby inducing harmonic noise.
- Harmonics can lead to generation of over voltages due to resonance when filter circuits are employed.

An HVDC transmission system consists of a rectifier and an inverter whose operation generates harmonics on AC and DC side of the converter. The three distinct sources of harmonics in HVDC systems are

1) Transformer.
2) AC Generator.
3) Converter along with its control devices

5.5.1 TRANSFORMER AS SOUCE OF HARMONICS:

Transformers can be considered as source of harmonic voltages, which arise from magnetic distortion and magnetic saturation due to the presence of a DC component in its secondary. The magnitude of these harmonics depends upon the operating flux density. Converter transformers are usually operated at high flux densities than conventional 3-phase transformers, and therefore the possibility of generation of harmonics is more.

Although the waveform is usually good, an AC generator may be regarded as a source of balanced harmonics because of non-uniform distribution of flux on the armature windings.

The converter which forms the basic unit in HVDC transmission imposes changes of impedances in the current.

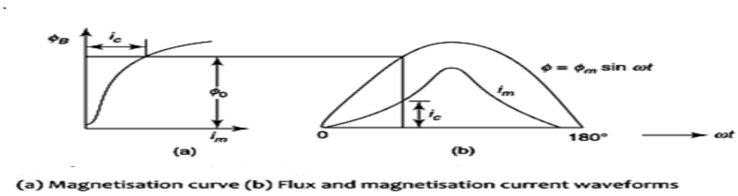


Fig 2 Transformer magnetization

When hysteresis effect is considered, then the non-sinusoidal magnetizing current waveform is no longer symmetrical which is mainly caused by triple n harmonics and particularly the third harmonic. Thus, in order to maintain a reasonable sinusoidal voltage supply, it is necessary to supply a path for triple n harmonics which is achieved by the use of delta-connected windings.

5.5.2 HARMONICS DUE TO CONVERTER:

A 12-pulse connection consists of two 6-pulse groups. One group having Y-Y connected converter transformer with 1:1 turns ratio and the other group having Y-Δ converter transformer bank with 1:√3 turns ratio.

5.6 GENERATION OF HARMONICS:

The harmonics which are generated are of two types.

- Characteristic harmonics.
- Non- characteristic harmonics.

5.6.1 CHARACTERISTIC HARMONICS:

The characteristic harmonics are harmonics which are always present even under ideal operation.
In the converter analysis, the DC current is assumed to be constant. But in AC current the harmonics exist which are of the order of

$h = np \pm 1$

and in DC current it is of the order of

$h = np$

where n is any integer and p is pulse number

Neglecting overlap, primary currents of Y-Y and Y-Δ connection of the transformer are considered taking the origin symmetrical where

$i = I_d$ for $-\pi/3 \leq \omega t \leq \pi/3$

$= 0$ for $\pi/3 \leq \omega t \leq 2\pi/3$ and $-\pi/3 \leq \omega t \leq -2\pi/3$ } for Y-Y connection converter

$= -I_d$ for $-2\pi/3 \leq \omega t \leq -\pi$ and transformer $2\pi/3 \leq \omega t \leq \pi$

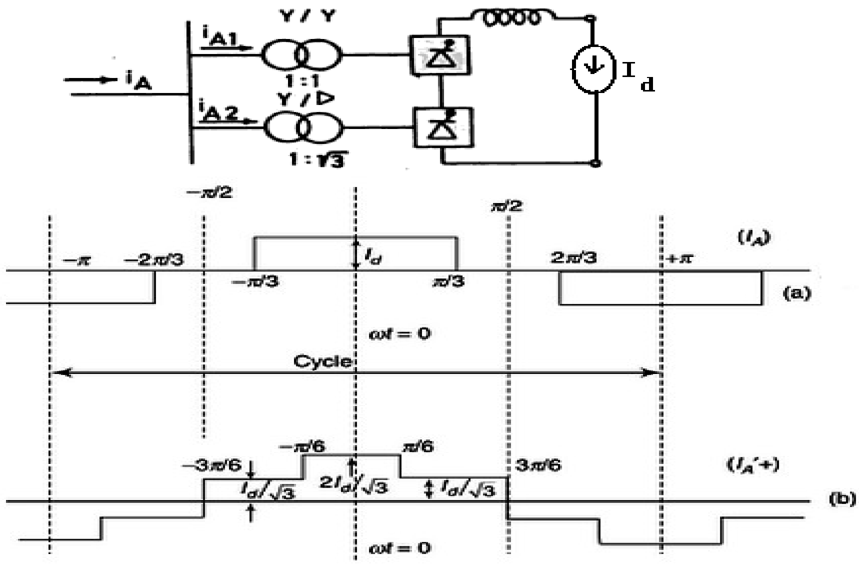


Figure 3(a): Phase current on primary side of Y-Y connection converter transformer

Figure 3(b): Phase current on primary side of Y-Δ connection converter transformer

5.7 HARMONIC FILTERS:

The filter arrangements on the AC side of an HVDC converter station have two main duties:

- to absorb harmonic currents generated by the HVDC converter and thus to reduce the impact of the harmonics on the connected AC systems, like AC voltage distortion and telephone interference
- to supply reactive power for compensating the demand of the converter station

5.8 DESIGN OF AC FILTER:

5.8.1 HARMONICS DESTORTION:

Harmonic Distortion is given by,

$$D_n = \frac{I_n Z_n}{E_1} \times 100$$

Where,

I_n – harmonic current injected

Z_n – harmonic impedance of the system

E_1 – fundamental component of line to neutral voltage m – highest harmonic considered

5.8.2 TELEPHONE INFLUENCE FACTOR:

An index of possible telephone interference and is given by,

$$THFF = \left[\frac{\sum_{n=2}^{m} (I_n Z_n F_n)^2}{E_1} \right]^{1/2}$$

Pn is the c message weighting used by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) in USA. This weighting reflects the frequency dependent sensitivity of the human ear and has a maximum value at the frequency of 1000Hz.

5.8.3 IT PRODUCT:

In BTS-EEI system, there is another index called IT product and is defined by,

$$IT = \left[\sum_{n=2}^{m} (I_n F_n)^2 \right]^{1/2}$$

$$KIT = \frac{IT}{1000}$$

5.9 TYPES OF AC FILTERS:

The different types of AC filters used in HVDC systems were as follows

1. Band pass filter
2. Single tuned filter
3. Double tuned filter
4. High pass Filter
    - Second order filter
    - C type filter

5.9.1 DC FILTER CIRCUIT:

Harmonic voltages which occur on the DC side of a converter station cause AC currents which are superimposed on the direct current in the transmission line. These alternating currents of higher frequencies can create interference in neighbouring telephone systems despite limitation by smoothing reactors. DC filter circuits, which are connected in parallel to the station poles, are an effective tool for combating these problems. The configuration of the DC filters very strongly resembles the filters on the AC side of the HVDC station. There are several types of filter design. Single and multiple-tuned filters with or without the high-pass feature are common. One or several types of DC filter can be utilized in a converter station.

5.9.2 DESIGN CRITERIA FOR DC FILTER CIRCUITS:

The equivalent disturbing current combines all harmonic currents with the aid of weighting factors to a single interference current. With respect to telephone interference, it is the equivalent to the sum of all harmonic currents. It
also encompasses the factors which determine the coupling between the HVDC and telephone lines:

- Operating mode of the HVDC system (bipolar or monopolar with metallic or ground return)
- Specific ground resistance at point x the intensity of interference currents is strongly dependent on the operating condition of the HVDC. In monopolar operation, telephone interference is significantly stronger than in bipolar operation.

5.10 PROTECTION OF FILTERS:

The filter is exposed to overvoltage during switching in and the magnitude of this overvoltage is a function of the short-circuit ratio (higher with low values of SCR) and the saturation characteristics of the converter transformer.
During switching in, the filter current (at filter frequencies) can have magnitudes ranging from 20 to 100 times the harmonic current in normal (steady-state) operation. The lower values for tuned filters and higher values are applicable to high pass filters. These over currents are taken into consideration in the mechanical design of reactor coils.
When filters are disconnected, their capacitors remain charged to the voltage at the instant of switching. The residual direct voltages can also occur on bus bars. To avoid, the capacitors may be discharged by short-circuiting devices or through converter transformers or by voltage transformers loaded with resistors.
If the network frequency deviates from the nominal value, higher currents and losses will result in AC filters.

5.11 POWER FLOW ANALYSIS:

Most of the solution techniques for AC/DC power flow are divided into two different approaches. The sequential and the unified (or simultaneous) solution methods. The sequential solution methods, AC and DC system equations are solved separately in each iteration until the terminal conditions of converters are satisfied. Because of modular programming, the sequential methods are generally easy to implement and simple to incorporate various control specifications. In the unified methods, the

AC as well as DC system equations are combined together with the residual equations, describing the rectifier terminal behaviors, in one set of equations to be solved simultaneously. The unified methods, with their better computing efficiency and convergence, seem more suitable than the sequential methods for use in industrial AC/DC power systems, even if they might be more complicated to program. The Gauss-Seidel (G-S), the Newton-Raphson (N-R), and the fast-decoupled N-R methods may be used to solve the power flow problems in AC/DC systems as they do in the pure AC systems. The G-S method generally needs accelerating factors to improve the iteration process because of its slow rate of convergence. The N-R method, with its powerful convergence characteristics, appears to be the most attractive technique in solving the AC/DC power flows.

5.12: REACTIVE POWER REQUIREMENT:

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.

5.12.1 HARMONIC PERFORMANCE REQUIRMENT:

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.

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: Dn individual harmonic voltage distortion of order n in percent of the fundamental AC busbar voltage (typical limit 1%) Drms total geometric sum of individual voltage distortion Dn (typical limit2%)

5.13 EQUIRMENTS OF RATINGS:

5.13.1 **Steady state calculation:**

The voltage and current stresses of AC filters consist of the fundamental frequency and harmonic components. Their magnitudes depend on the AC system voltage, harmonic currents, operating conditions and AC system impedances. The rating calculations are carried out in the whole range of operation to determine the highest steady-state current and voltage stresses for each individual filter component.

5.13.2 Transient Calculation:

The objective of the transient rating calculation is to determine the highest transient stresses for each component of the designed filter arrangement. The results of the transient calculation should contain the voltage and current stresses for each component, energy duty for filter resistors and arresters, and the insulation levels for each filter component.

To calculate the highest stresses of both lightning and switching surge type, different circuit configurations and fault cases should be studied:

Single-Phase Ground Fault

The fault is applied on the converter AC bus next to the AC filter. It is assumed that the filter capacitor is charged to a voltage level corresponding to the switching impulse protective level of the AC bus arrester.

Switching Surge

For the calculation of switching surge stresses, a standard wave of 250/2500 with a crest value equal to the switching impulse protective level of the AC bus arrester is applied at the AC converter bus.