HVDC TRANSMISSION(BPSB03)

I M. Tech I semester (Autonomous IARE R-18)

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UNIT - I

GENERAL ASPECTS OF HVDC TRANSMISSION

INTRODUCTION TO HVDC SYSTEM

HVDC technology is used to transmit electricity over long distances by overhead transmission lines or submarine cables.

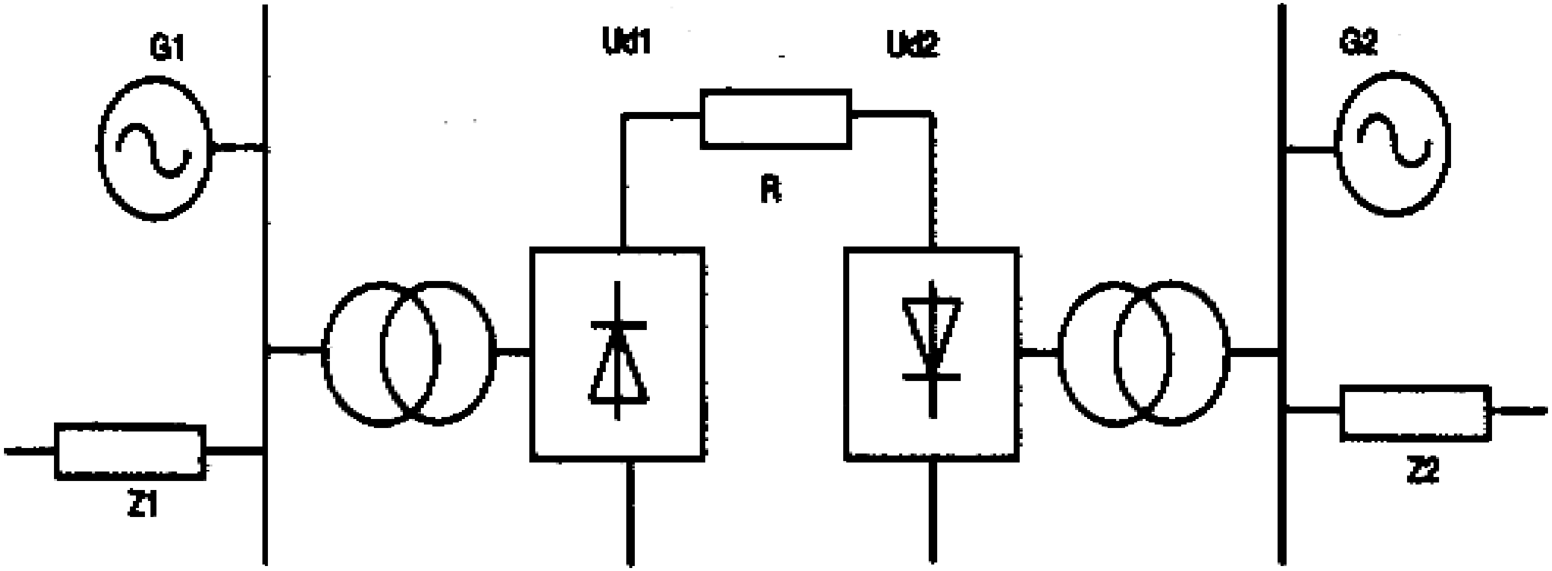


fig 1: layout of HVDC system

REASON FOR AC GENERATION AND TRANSMISSION

- Due to ease of transformation of voltage levels (simple transformer action)
- Alternating Current is universally utilized.—Both for GENERATION and LOADS and hence for Transmission.
- Generators are at remote places, away from the populated areas i.e. the load centers.
- Turbines drive synchronous generators giving an output at 15-25 kV.
- Voltage is boosted up to 220 or 400 KV by step-up transformers for transmission to LOADS.
- To reach the loads at homes/industry at required safe levels, transformers step down voltage

COMPARISSION OF HVDC AND HVAC SYSTEMS

- HVAC transmission is having several limitations like line length , uncontrolled power flow, over/low voltages during lightly / over loaded conditions, stability problems, fault isolation etc

- The advantage of HVDC is the ability to transmit large amounts of power over long distances with lower capital costs and with lower losses than AC.

- HVDC transmission allows efficient use of energy sources remote from load centers. Depending on voltage level and construction details, losses are quoted as about 3% per 1,000 km.

COMPARISSION OF HVDC AND HVAC SYSTEMS

- In a number of applications HVDC is more effective than AC transmission. Examples include:
    - Undersea cables, where high capacitance causes additional AC losses. (e.g. 250 km Baltic Cable between Sweden and Germany) .
    - 600 km NorNed cable between Norway and the Netherlands
- In HVDC Long power transmission without intermediate taps, for example, in remote areas .
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install
- Power transmission and stabilization between unsynchronized AC distribution systems

COMPARISSION OF HVDC AND HVAC SYSTEMS

- Connecting a remote generating plant to the distribution grid
- Asynchronous operation possible between regions having different electrical parameters .
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies
- Reducing line cost:
  - fewer conductors
  - thinner conductors since HVDC does not suffer from the skin effect

COMPARISSION OF HVDC AND HVAC SYSTEMS

- HVDC Cheaper than HVAC for long distance.

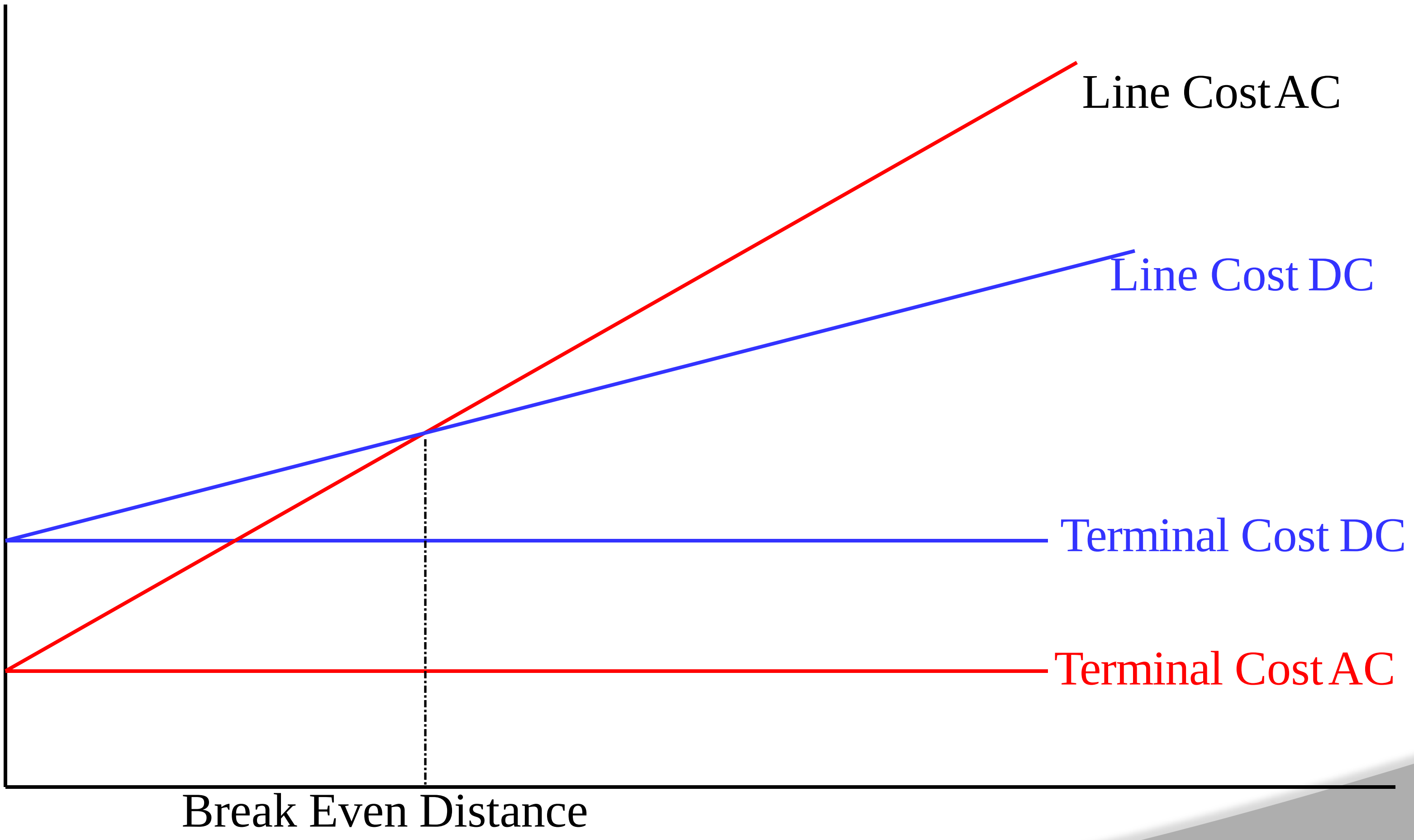


Fig 2: COST: HVAC vs. HVDC Transmission

COMPARISSION OF HVDC AND HVAC SYSTEMS

- No restriction on line length as no reactance in dc lines
- HVDC can carry more power per conductor because, for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line.

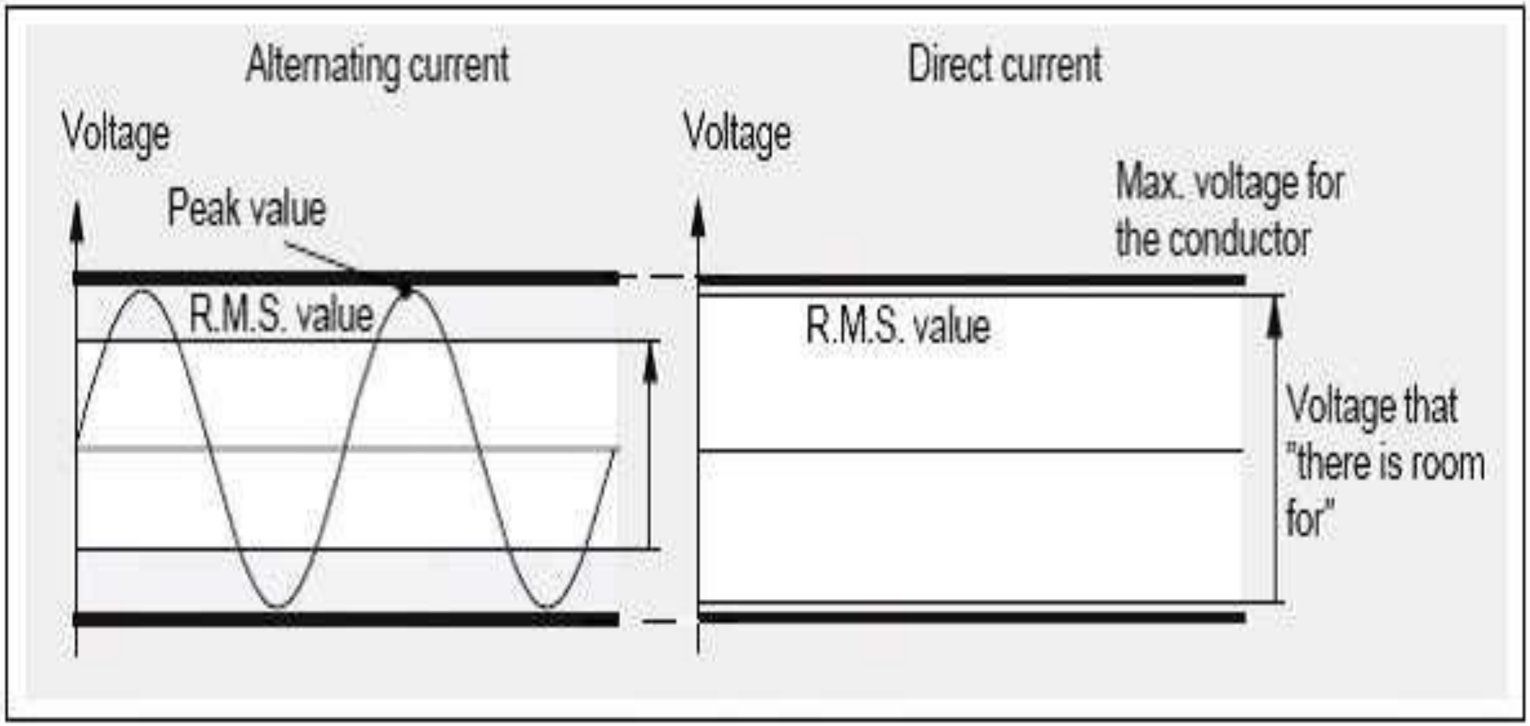


fig 3: comparison of AC and DC

COMPARISSION OF HVDC AND HVAC SYSTEMS

- HVDC uses less current i.e. low losses.
- AC current will struggle against inertia in the line (100times/sec)-electrical resistance –inductance- reactive power
- Direct current : Roll along the line ; opposing force friction (electrical resistance)

COMPARISSION OF HVDC AND HVAC SYSTEMS

Distance as well as amount of POWER determine the choice of DC over AC

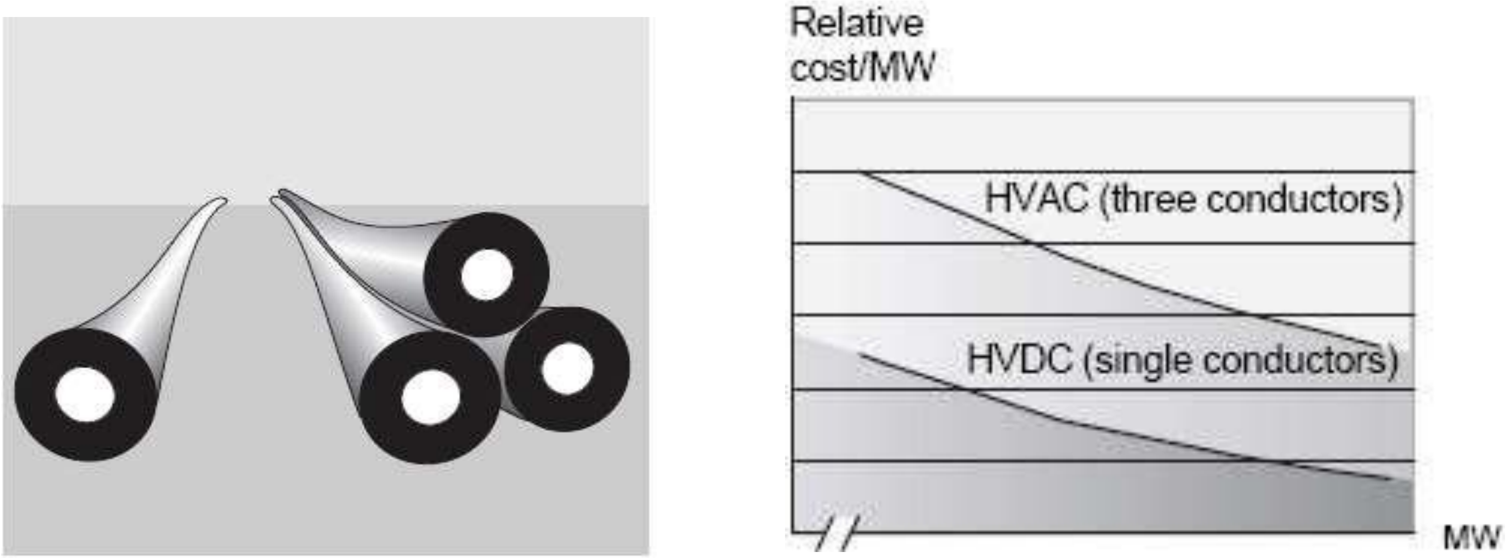


fig 4: comparison of distance HVDC and HVAC

COMPARISSION OF HVDC AND HVAC SYSTEMS

- Direct current conserves forest and saves land
- The towers of the dc lines are narrower, simpler and cheaper compared to the towers of the ac lines.

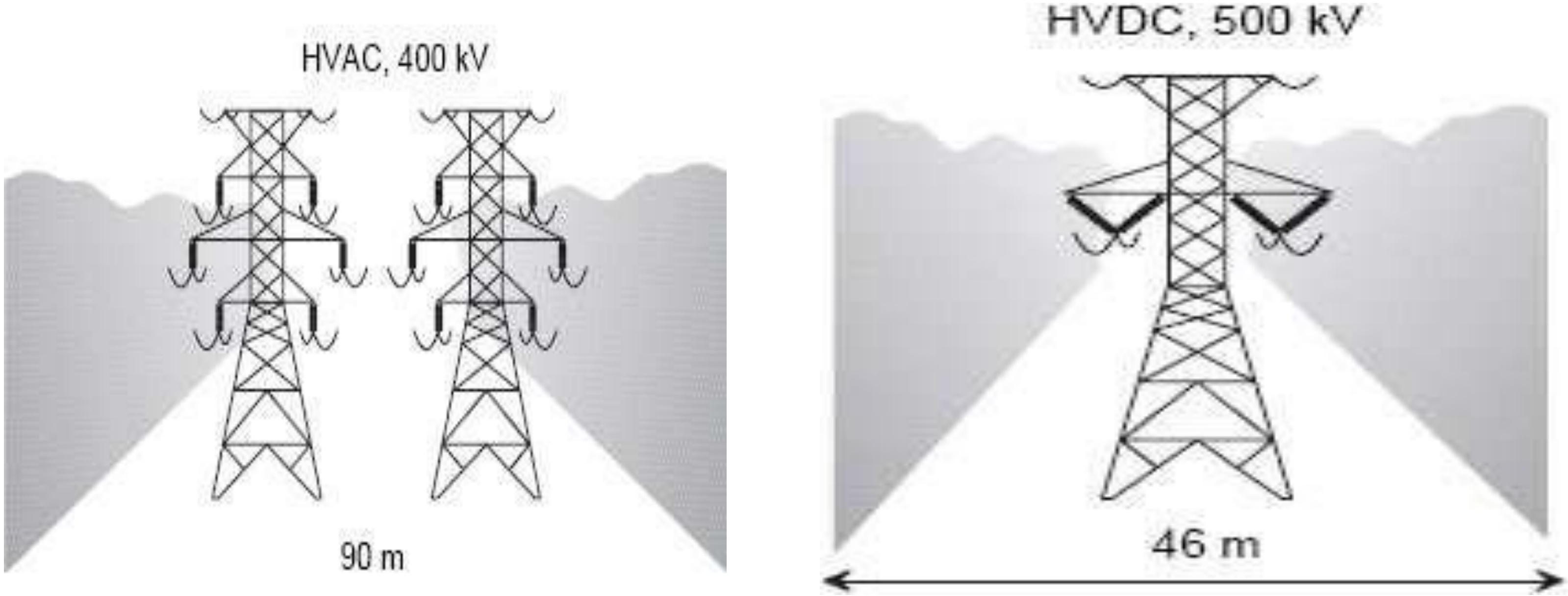


fig 5: comparison of towers in HVDC and HVAC

COMPARISSION OF HVDC AND HVAC SYSTEMS

- Lesser Corona Loss than HVAC at same voltage and conductor diameter and less Radio interference.
- Direction of power flow can be changed very quickly
- HVDC has greater reliability. i.e. bipolar dc is more reliable than 3 phase HVAC.
- DC requires less insulation.
- An optimized DC link has smaller towers than an optimized AC link of equal capacity.
- DC line in Parallel with AC link.

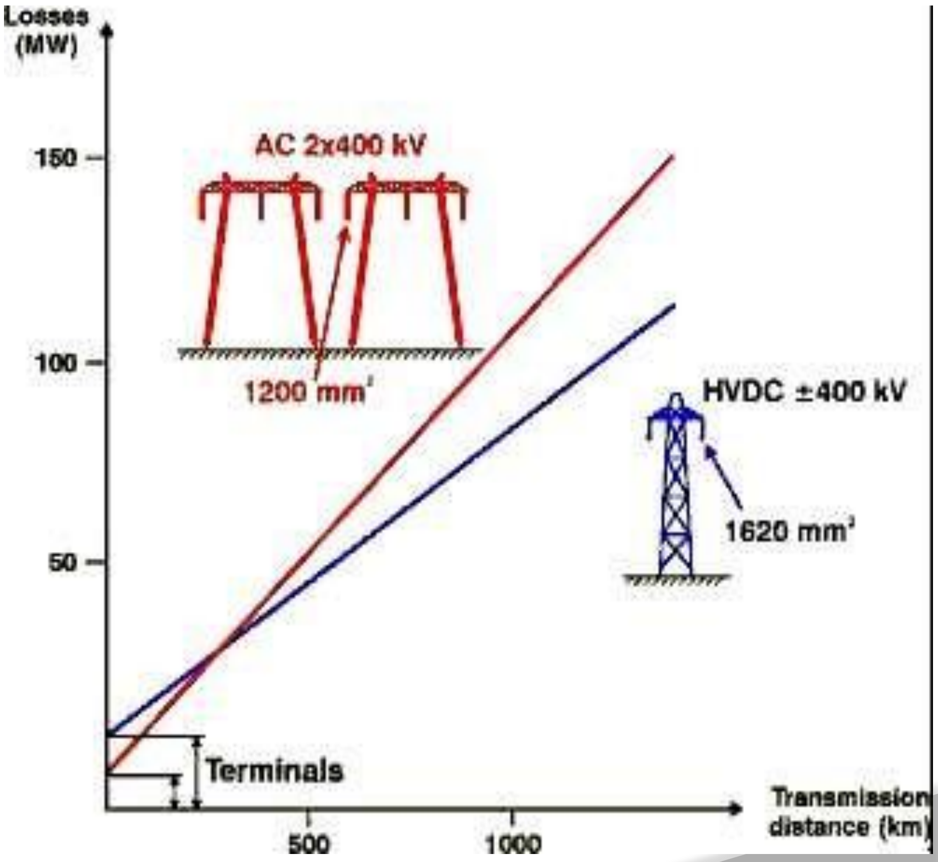


fig 6: comparison of HVDC and HVAC

COMPONENTS OF HVDC SYSTEM

- Converters
- Smoothing reactors
- Harmonic filters
- Reactive power supplies
- Electrodes
- DC lines
- AC circuit breakers

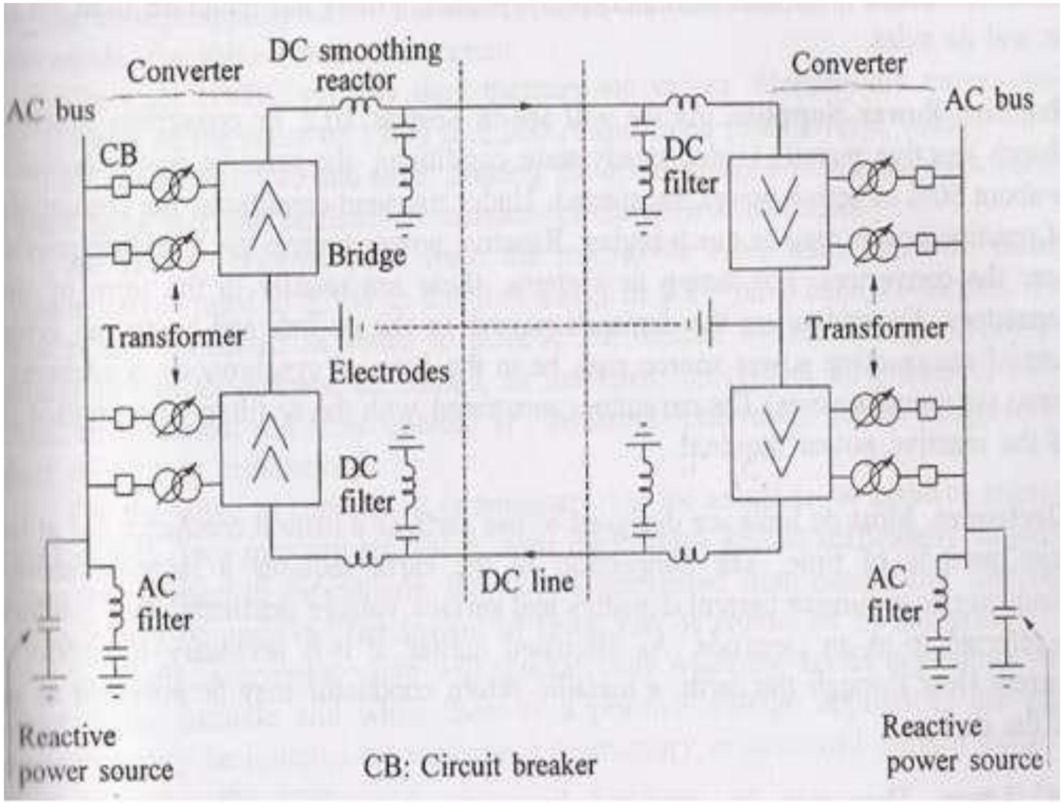


Fig 7 Components of HVDC

COMPONENTS OF HVDC SYSTEM

Converters

- They perform AC/DC and DC/AC conversion
- They consist of valve bridges and transformers
- Valve bridge consists of high voltage valves connected in a 6-pulse or 12-pulse arrangement
- The transformers are ungrounded such that the DC system will be able to establish its own reference to ground

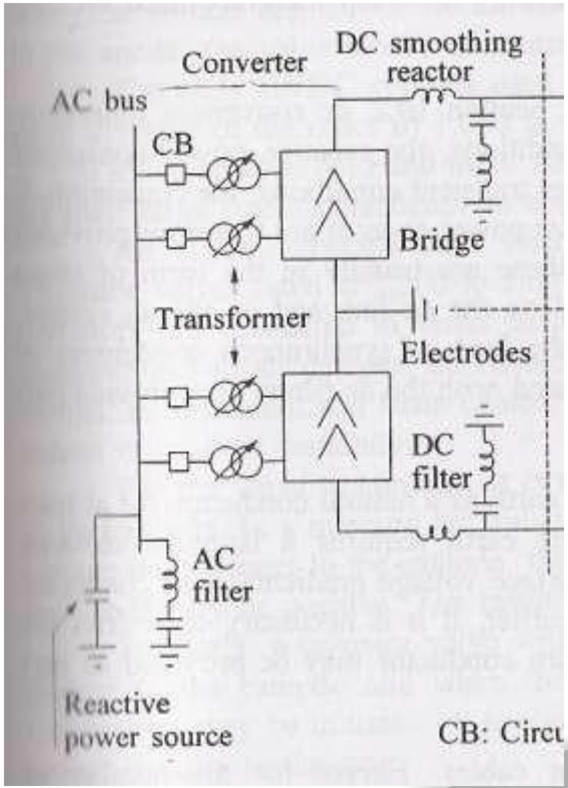


fig 8: converters

COMPONENTS OF HVDC SYSTEM

Smoothing reactors

- They are high reactors with inductance as high as 1 H in series with each pole They serve the following:
- They decrease harmonics in voltages and currents in DC lines
- They prevent commutation failures in inverters
- Prevent current from being discontinuous for light loads

Harmonic filters

- Converters generate harmonics in voltages and currents. These harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems
- Harmonic filters are used to mitigate these harmonics

COMPONENTS OF HVDC SYSTEM

Reactive power supplies

- Under steady state condition, the reactive power consumed by the converter is about 50% of the active power transferred
- Under transient conditions it could be much higher Reactive power is, therefore, provided near the converters
- For a strong AC power system, this reactive power is provided by a shunt capacitor

Electrodes

- Electrodes are conductors that provide connection to the earth for neutral. They have large surface to minimize current densities and surface voltage gradients

COMPONENTS OF HVDC SYSTEM

DC lines

- They may be overhead lines or cables DC lines are very similar to AC lines

AC circuit breakers

- They used to clear faults in the transformer and for taking the DC link out of service
- They are not used for clearing DC faults
- DC faults are cleared by converter control more rapidly

APPLICATION OF HVDC TRANSMISSION SYSTEM

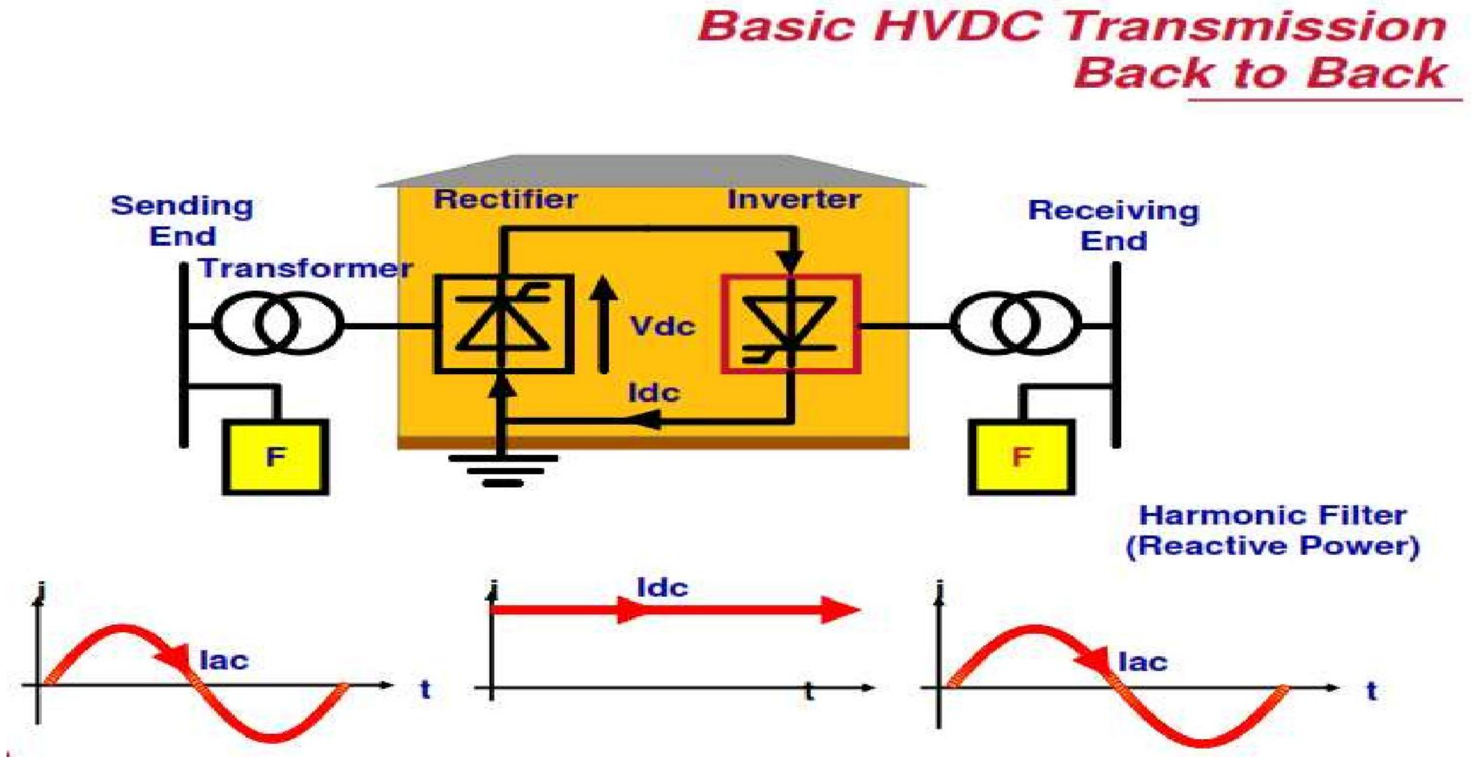


Fig 9: applications of HVDC system

HVDC is the unique solution to interconnect Asynchronous systems or grids with different frequencies.

APPLICATION OF HVDC TRANSMISSION SYSTEM

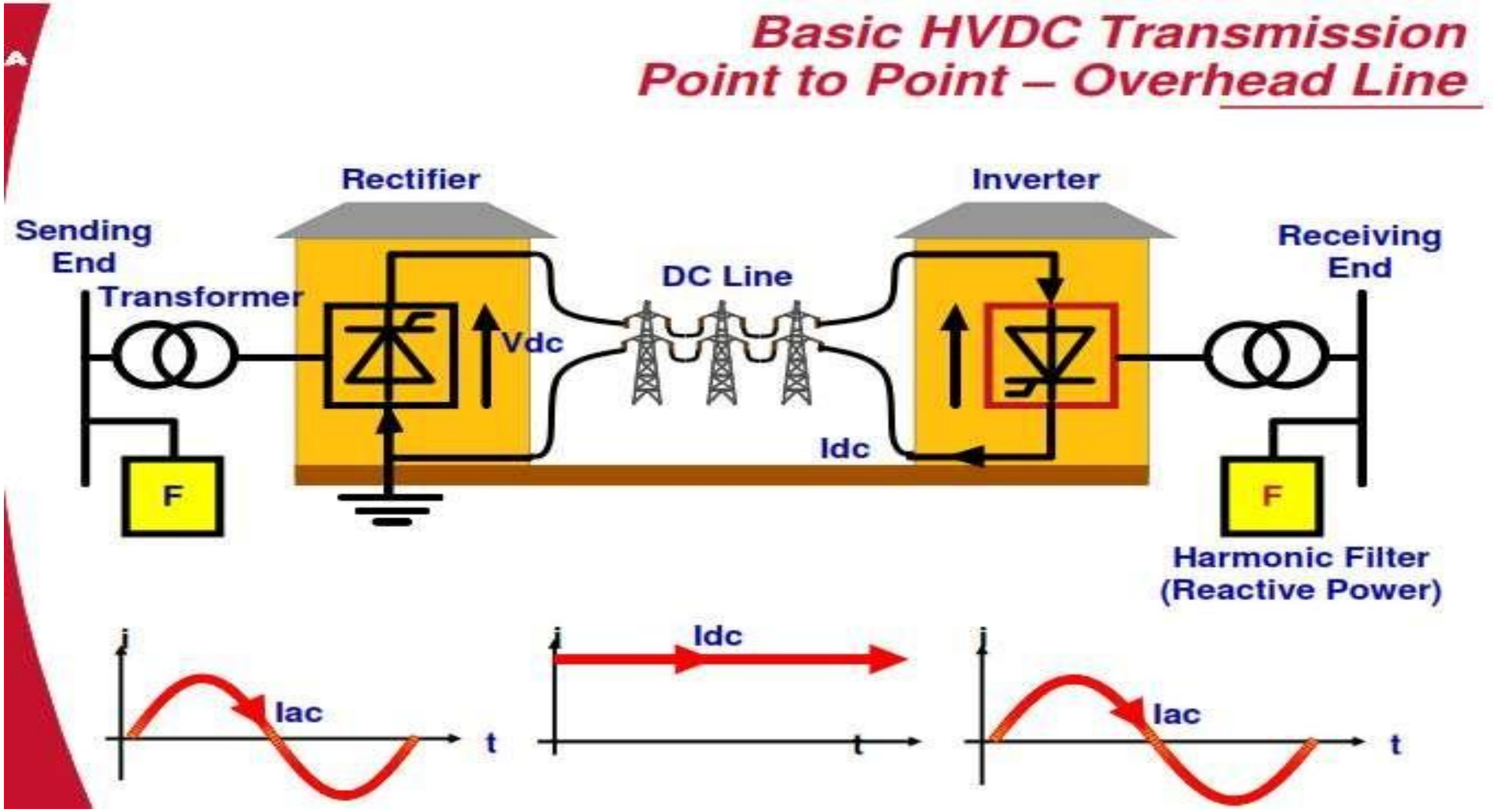


Fig 10: applications of HVDC system

HVDC represents the most economical solution to transmit electrical energy over distances greater than approx. 600 km

TYPES OF HVDC SYSTEM

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.

TYPES OF HVDC SYSTEM

TWO 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.

TYPES OF HVDC SYSTEM

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.

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.

APPLICATIOS 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.

HVDC SYSTEM CONFIGURATIONS

HVDC links can be broadly classified into:

- Monopolar links
- Bipolar links
- Homopolar links
- Multiterminal links

MONOPOLAR LINK

- It uses one conductor .
- The return path is provided by ground or water.
- Use of this system is mainly due to cost considerations.
- A metallic return may be used where earth resistivity is too high.
- This configuration type is the first step towards a bipolar link.

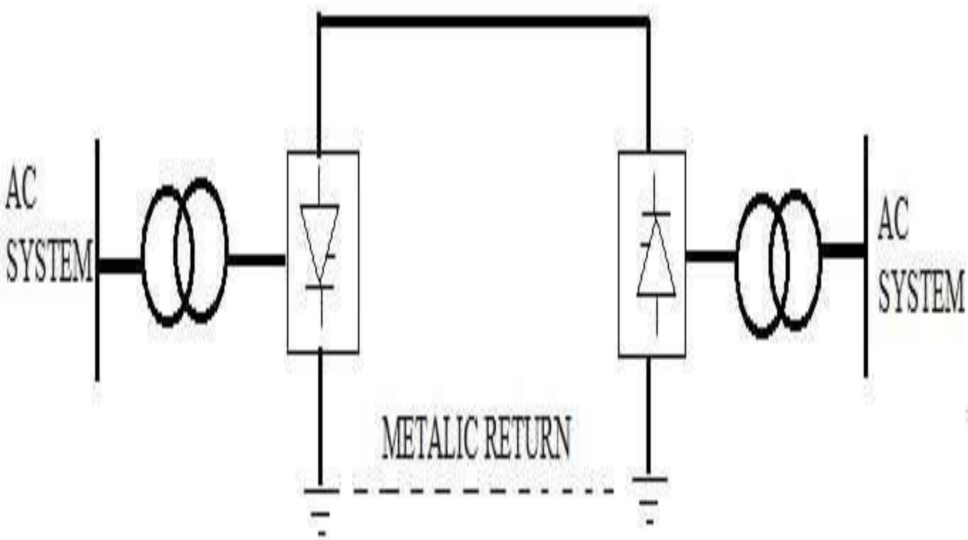
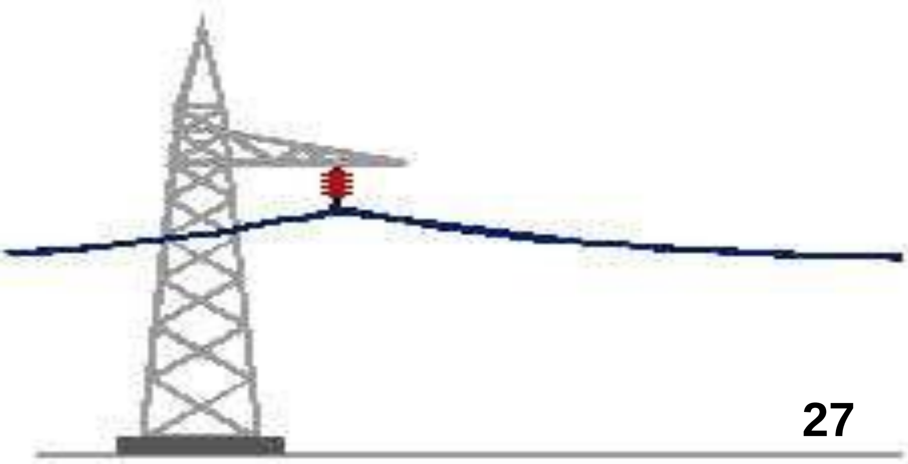
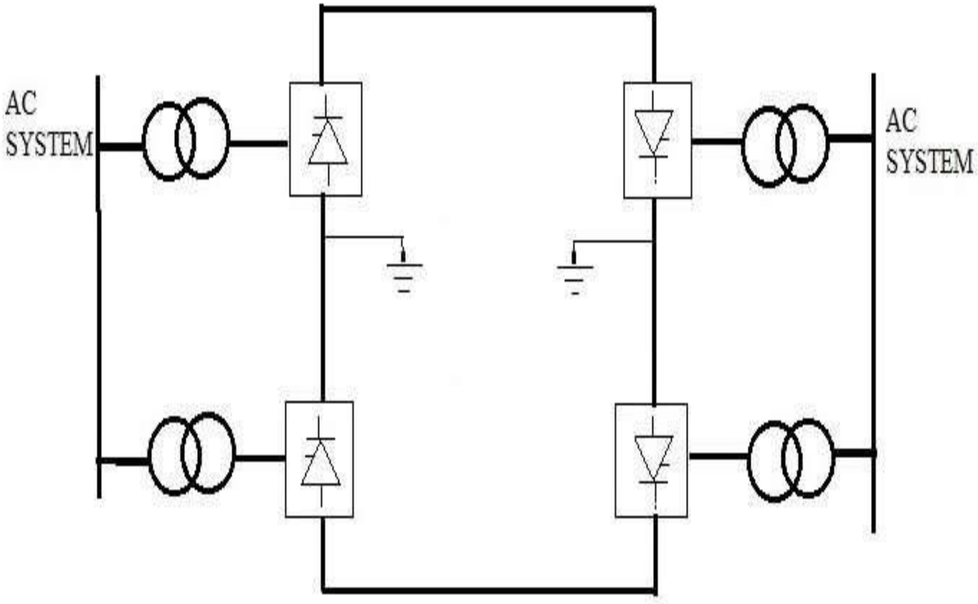


Fig 11: monopolar link



BIPOLAR LINK

- Each terminal has two converters of equal rated voltage, connected in series on the DC side.
- The junctions between the converters is grounded.
- If one pole is isolated due to fault, the other pole can operate with ground and carry half the rated load (or more using overload capabilities of its converter line).



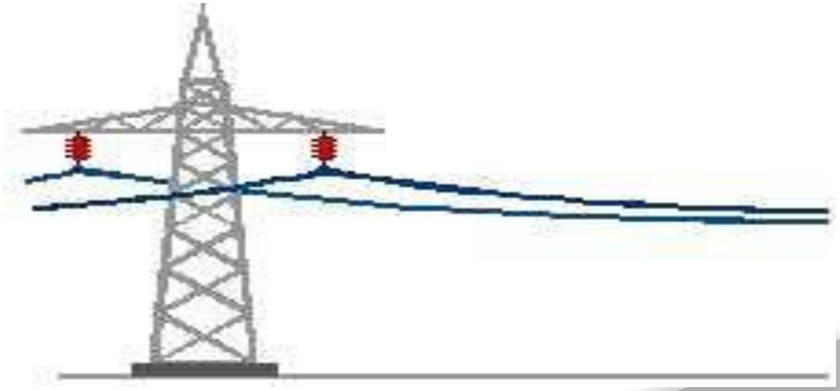


Fig 12: Bipolar link

HOMOPOLAR LINK

- It has two or more conductors all having the same polarity, usually negative.
- Since the corona effect in DC transmission lines is less for negative polarity, homopolar link is usually operated with negative polarity.
- The return path for such a system is through ground.

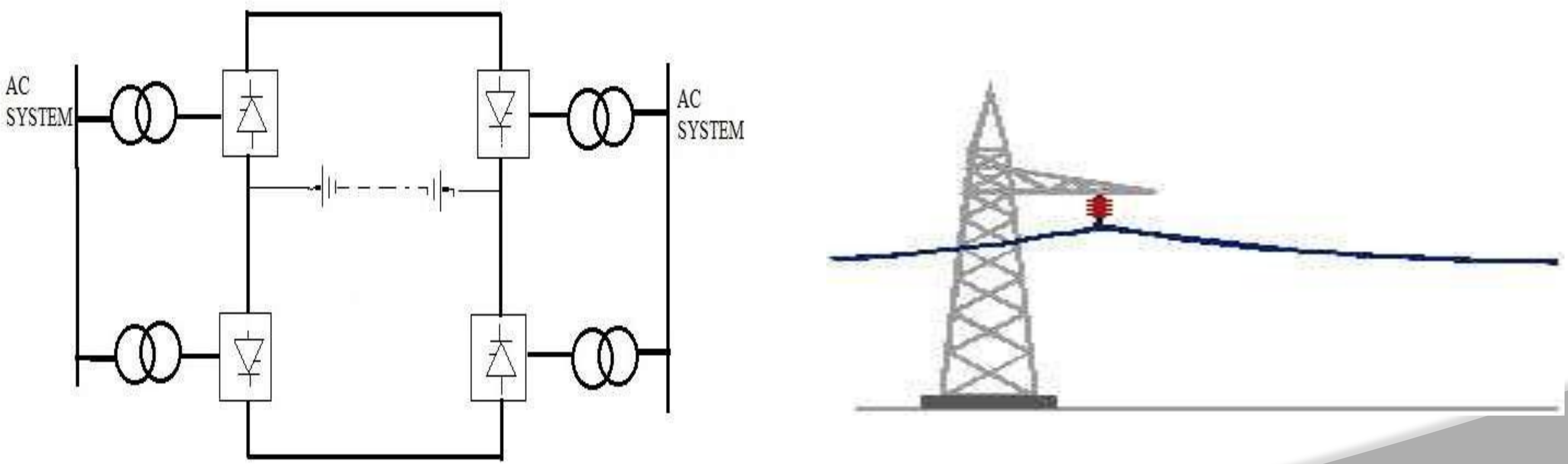


Fig 13: Homopolar link

DC AS A MEANS OF TRANSMISSION

- **DC Transmission has been possible with beginning of**
  - High power/ high current capability thyristor.
  - Fast acting computerized controls
- Since our primary source of power is A.C, The three basic steps are
  - Convert AC into DC (**rectifier)**
  - Transmit DC
  - Convert DC into AC (**inverter**)

DISDVANTAGES OF HVDC

- The disadvantages of HVDC are in conversion, switching and control.
- Expensive inverters with limited overload capacity.
- Higher losses in static inverters at smaller transmission distances.
- The cost of the inverters may not be offset by reductions in line construction cost and lower line loss.
- High voltage DC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching.
- HVDC is less reliable and has lower availability than AC systems, mainly due to the extra conversion equipment.

UNIT II

ANALYSIS OF BRIDGE CONVERTER

ANALYSIS OF GRATEZ CIRCUIT

The basic UNIT for HVDC converter is the three phase, full wave bridge circuit. This circuit is also known as a Graetz Bridge. The Graetz Bridge has been universally used for HVDC converters as it provides better utilization of the converter transformer and a lower voltage across the valve when not conducting, this voltage is called Peak Inverse Voltage called PIV and is important for selection of the Thyristor.

SIX PULSE RECTIFIER

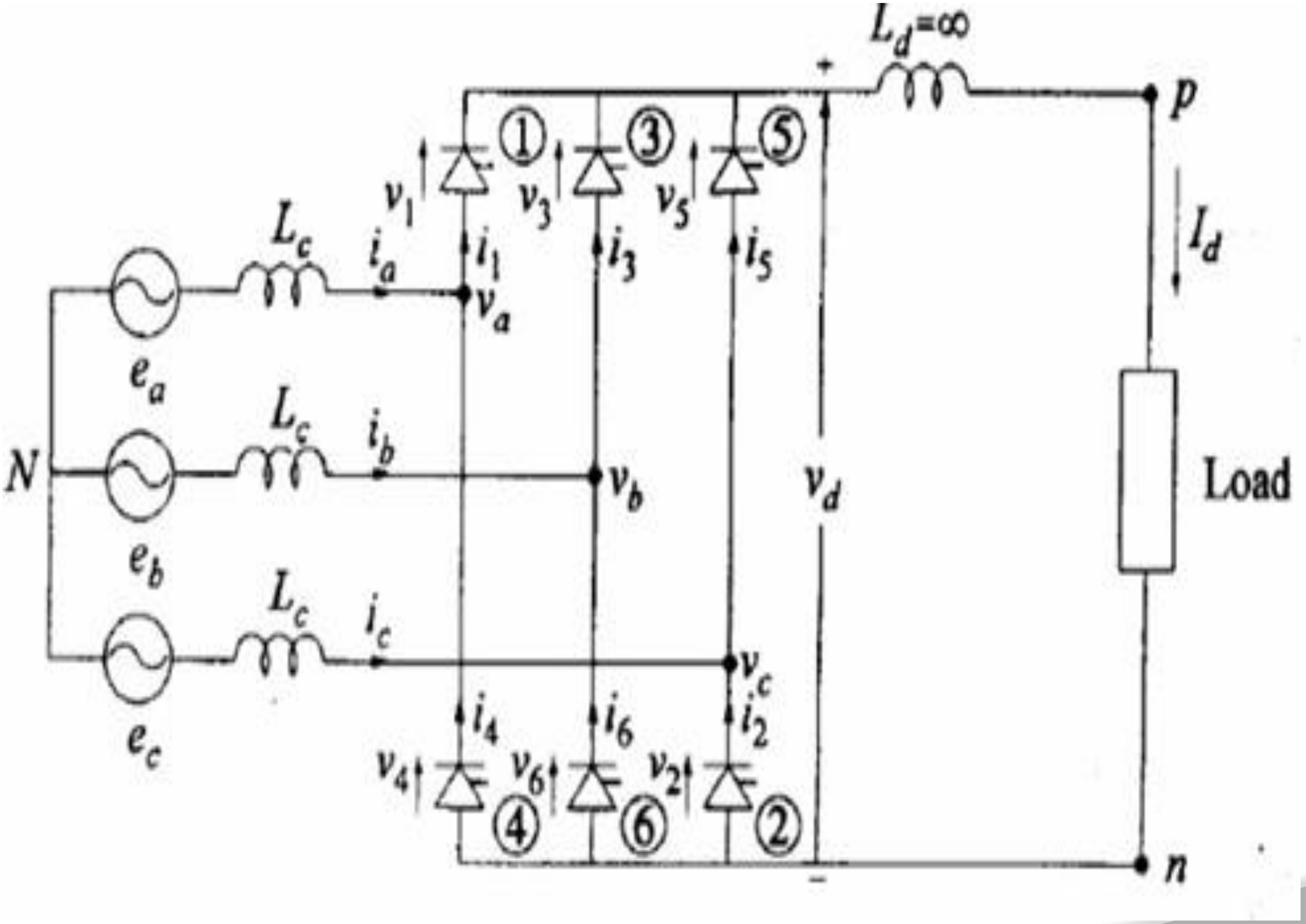


Fig 1: six pulse rectefier

ANALYSIS OF GRATEZ CIRCUIT

Let the instantaneous line – to – neutral source voltages be

$e_a = E_m \cos(\omega t + 60^\circ)$

$e_b = E_m \cos(\omega t - 60^\circ)$

$e_c = E_m \cos(\omega t - 180^\circ)$

Then the line-to-line voltages are

$e_{ac} = e_a - e_c = \sqrt{3} E_m \cos(\omega t + 30^\circ)$

$e_{ba} = e_b - e_a = \sqrt{3} E_m \cos(\omega t - 90^\circ)$

$e_{cb} = e_c - e_b = \sqrt{3} E_m \cos(\omega t + 150^\circ)$

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

ANALYSIS OF GRATEZ CIRCUIT

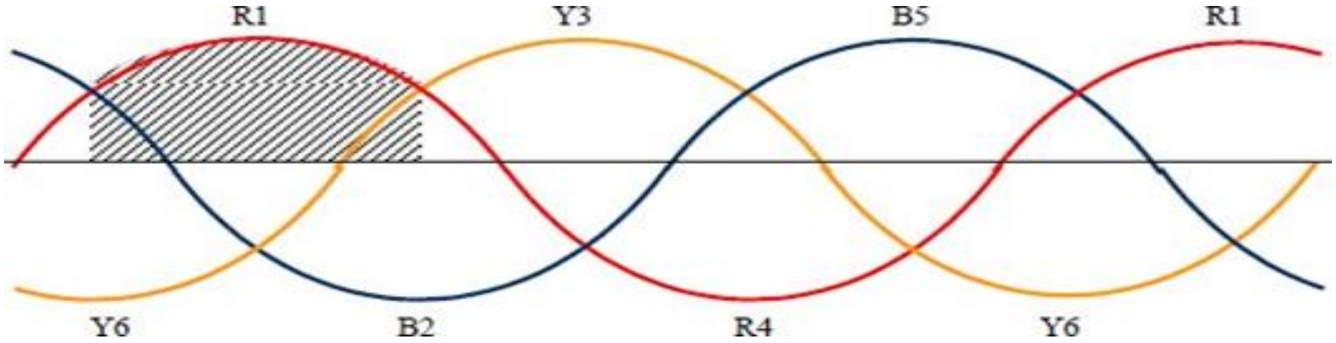


Fig 2: Thyristor voltage waveforms (α=0)

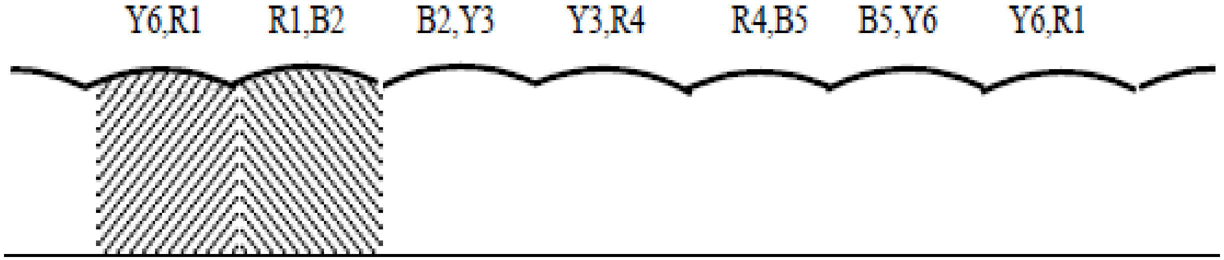


Fig 3: DC output waveforms (α=0)

ANALYSIS OF GRATEZ CIRCUIT

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

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

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

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

SIX PULSE RECTIFIER WAVEFORM

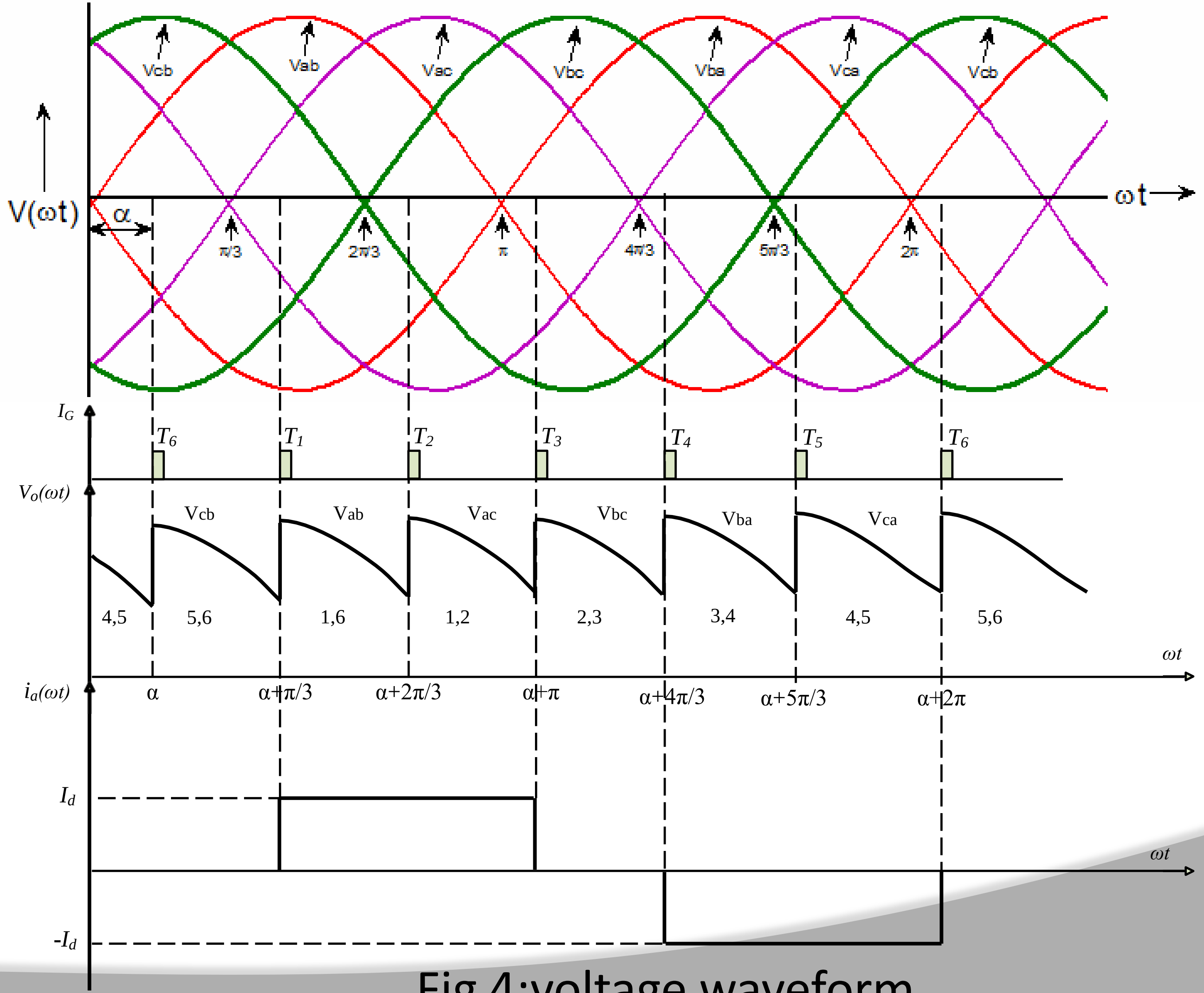


Fig 4:voltage waveform

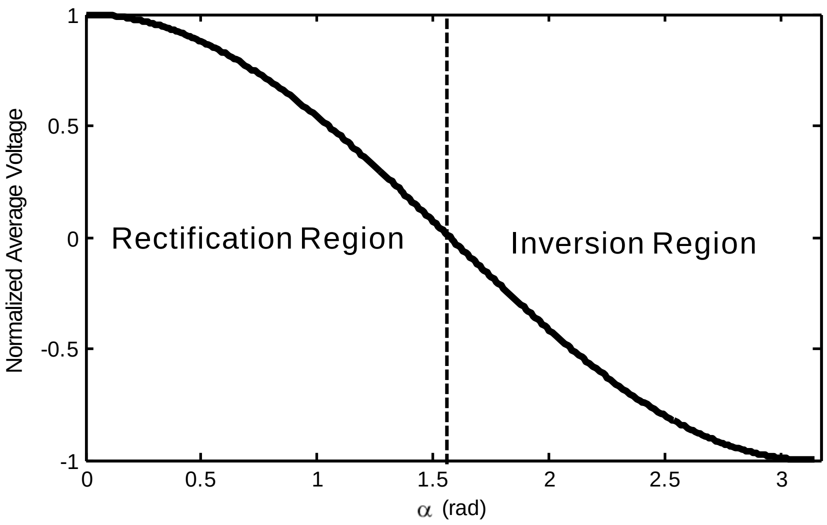
OPERATION OF SIX PULSE RECTIFIER

It can be seen from Fig that for $\alpha = {}^{\pi}/_{3}$ the rectified output voltage reaches zero crossing. If α is increased beyond ${}^{\pi}/_{3}$ i.e. $\alpha > {}^{\pi}/_{3}$, the load voltage becomses discontinous for resistive load where as for inductive load the negative voltage appears across load.

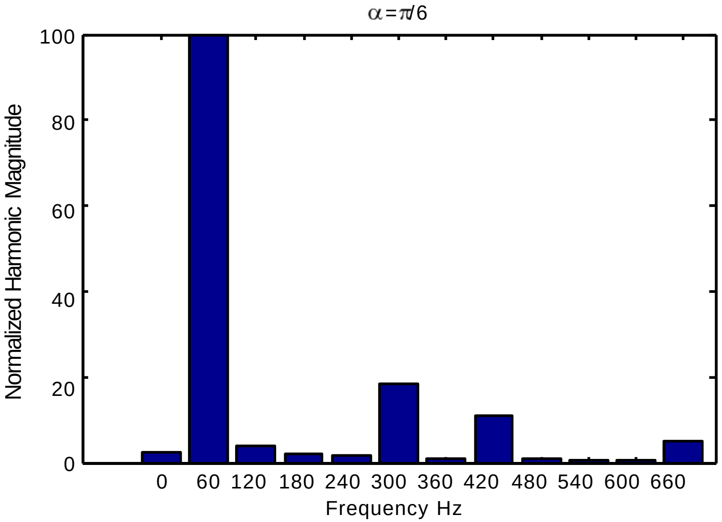
$$V_n = \frac{V_{dc}}{V_{dm}}\cos(\alpha)$$

Fig shows that by varying α between $0\ to\ {}^{\pi}/_{2}$ output varies between 1 & 0 i.e. rectification region and by varying α between ${}^{\pi}/_{2}\ to\ \pi$ output varies between 0 & -1 i.e. inversion region. Rectification region is represented by 1^{st} Quardant and inversion region by 4^{th} Quardant resulting in 2 Quardant operation.

$$P.F = 0.9\ \cos(\alpha)$$



Normalized Average (DC) Voltage as function of α



Specturm at alpha=pi/6

CONTROL ANGLE OR 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.

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

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

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

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

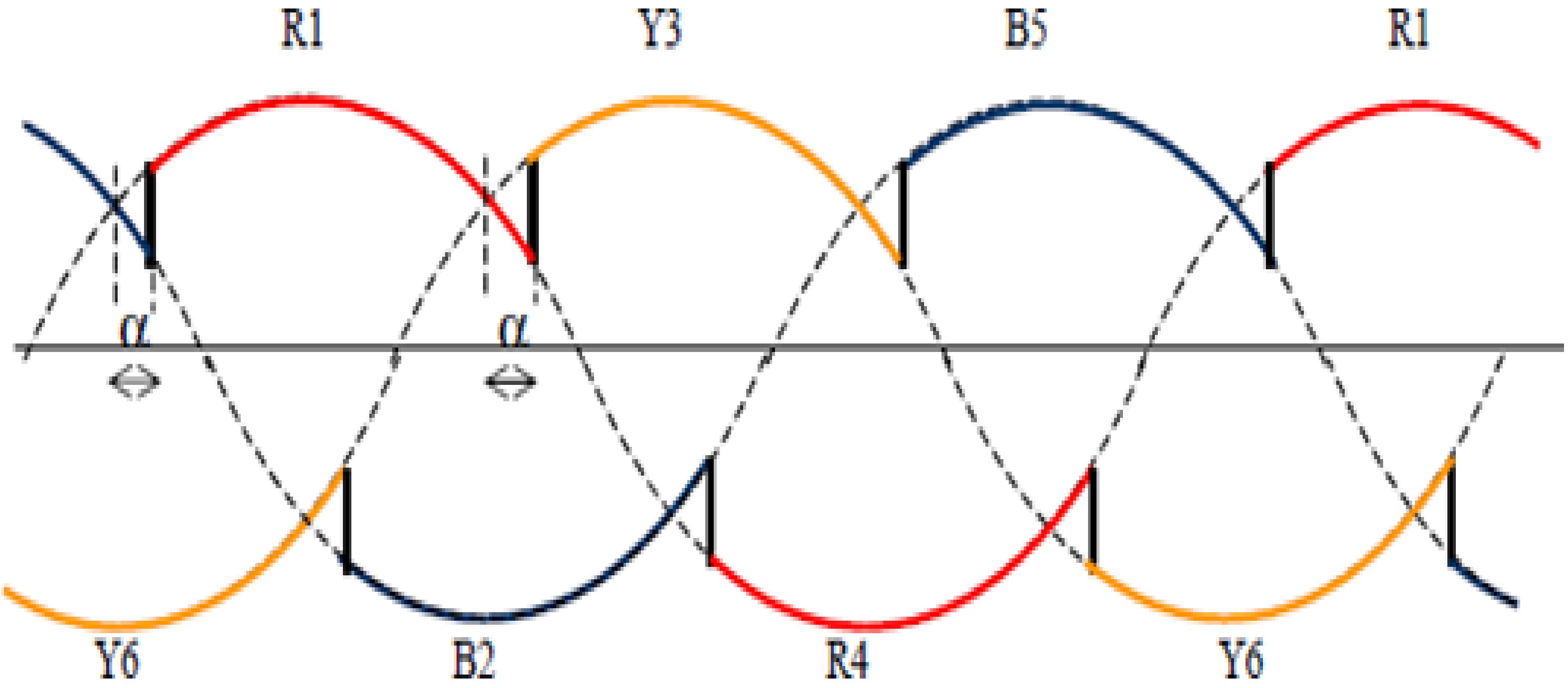


Fig 5: Thyristor voltage waveforms (with delay α)

COMMMUTATION 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.

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

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

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

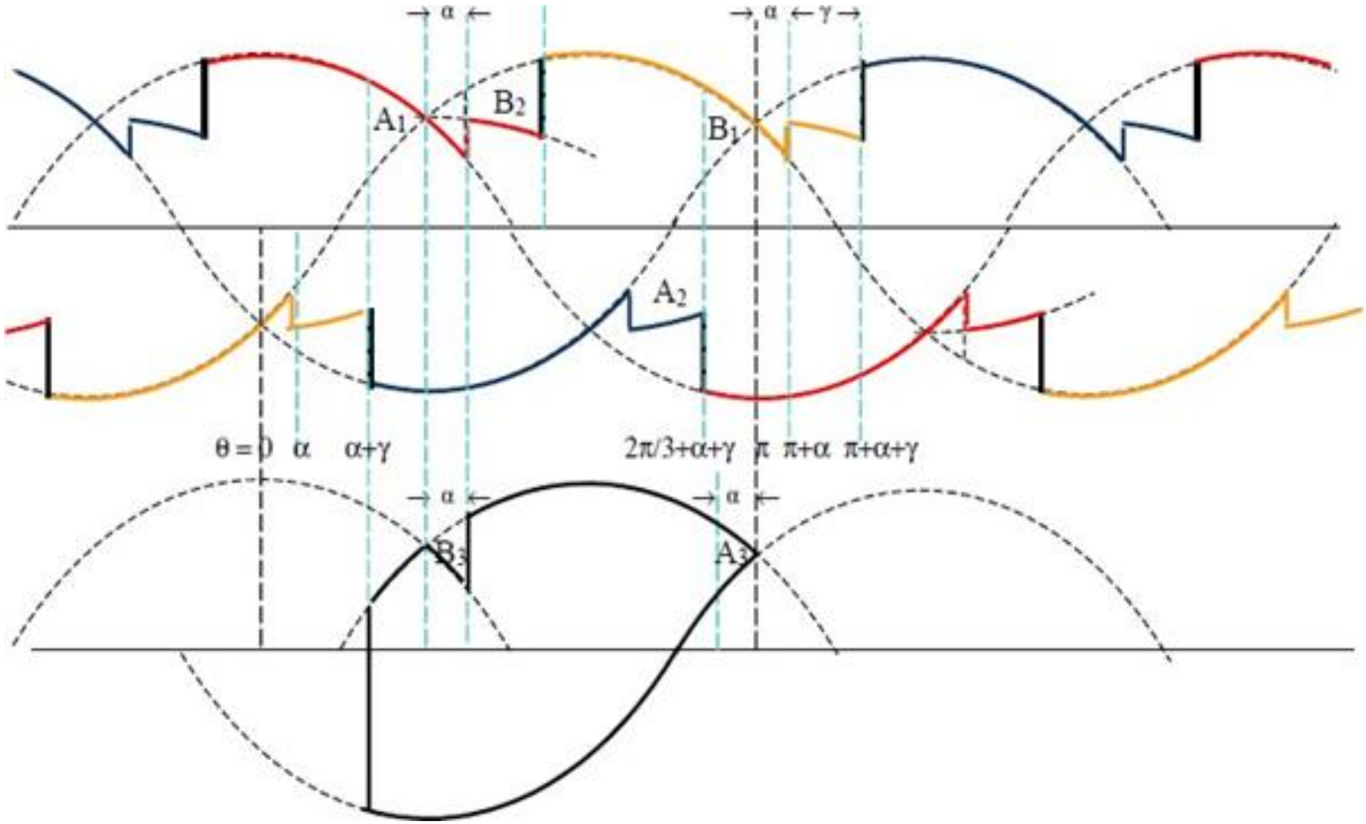


Fig 6: Thyristor voltage waveforms

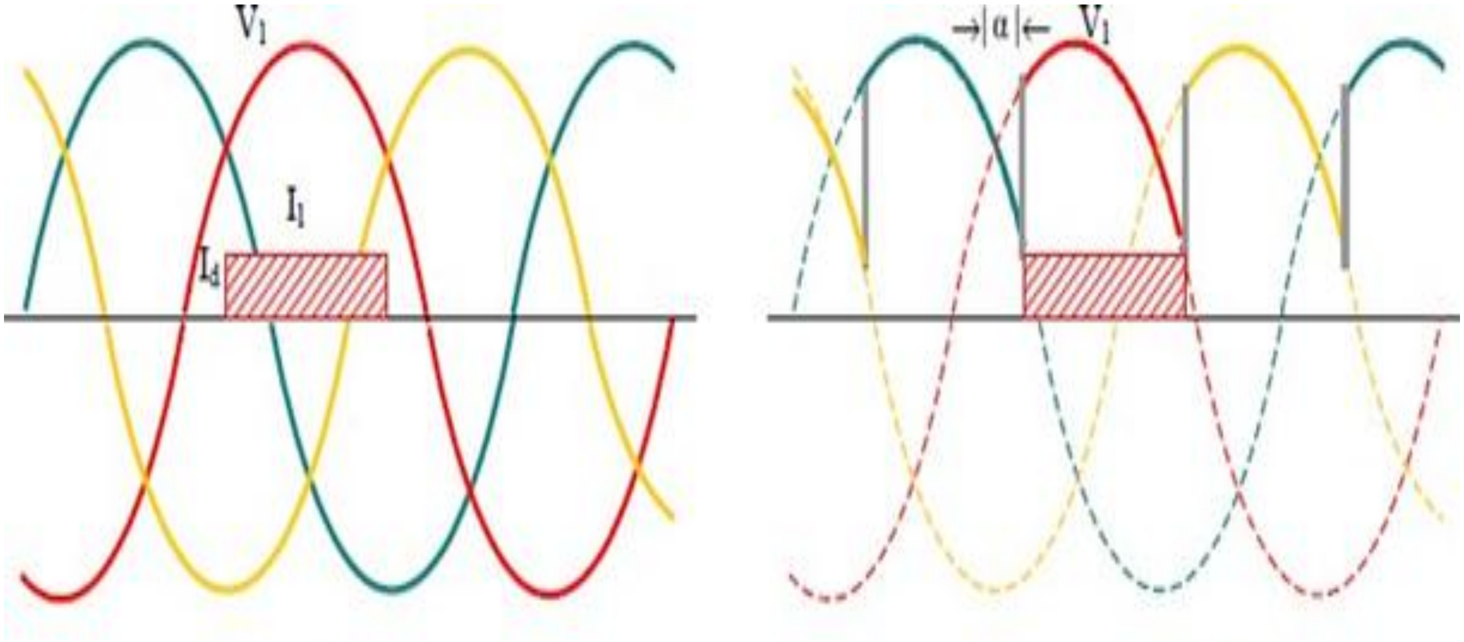
CURRENT WAVEFORM

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.

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

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

CUUERNT WAVEFORM



$\alpha = 0$

withα

Fig 7: Thyristor current waveforms

CURRENT WAVEFORM

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.

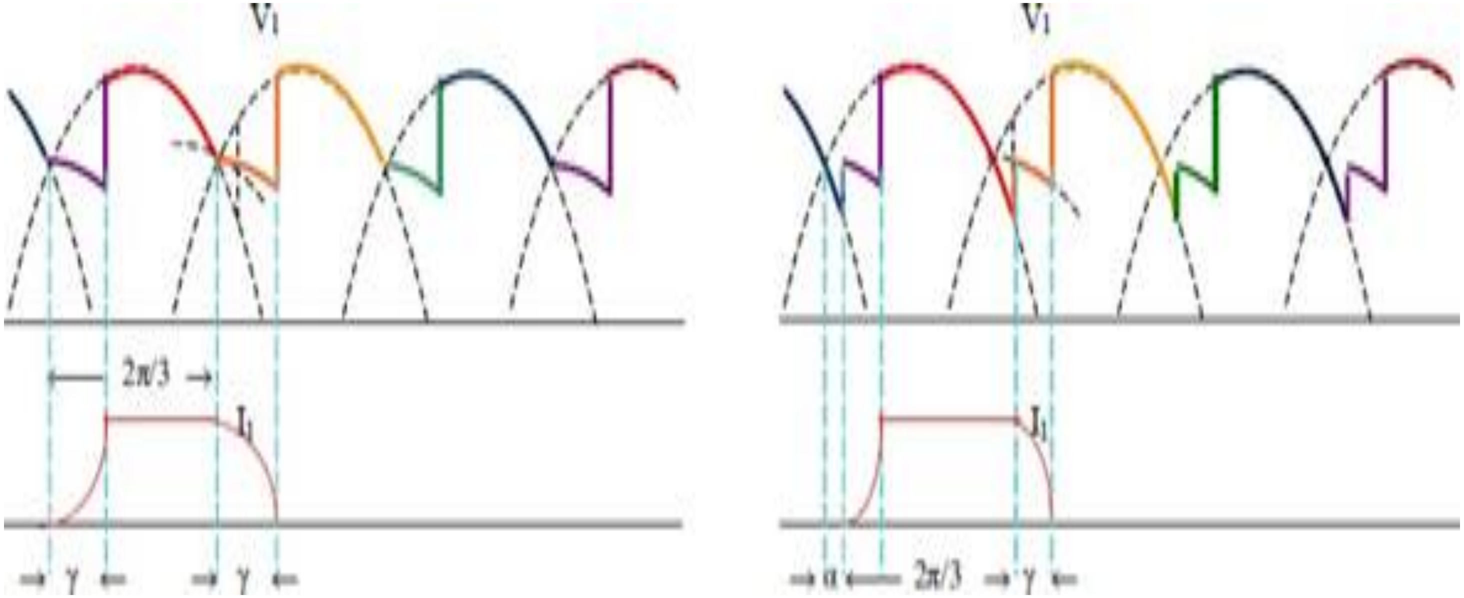


Fig 8: Thyristor current waveforms (commutation)

VOLTAGE WAVEFORM

The DC voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can analyze 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

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

VOLTAGE WAVEFORM

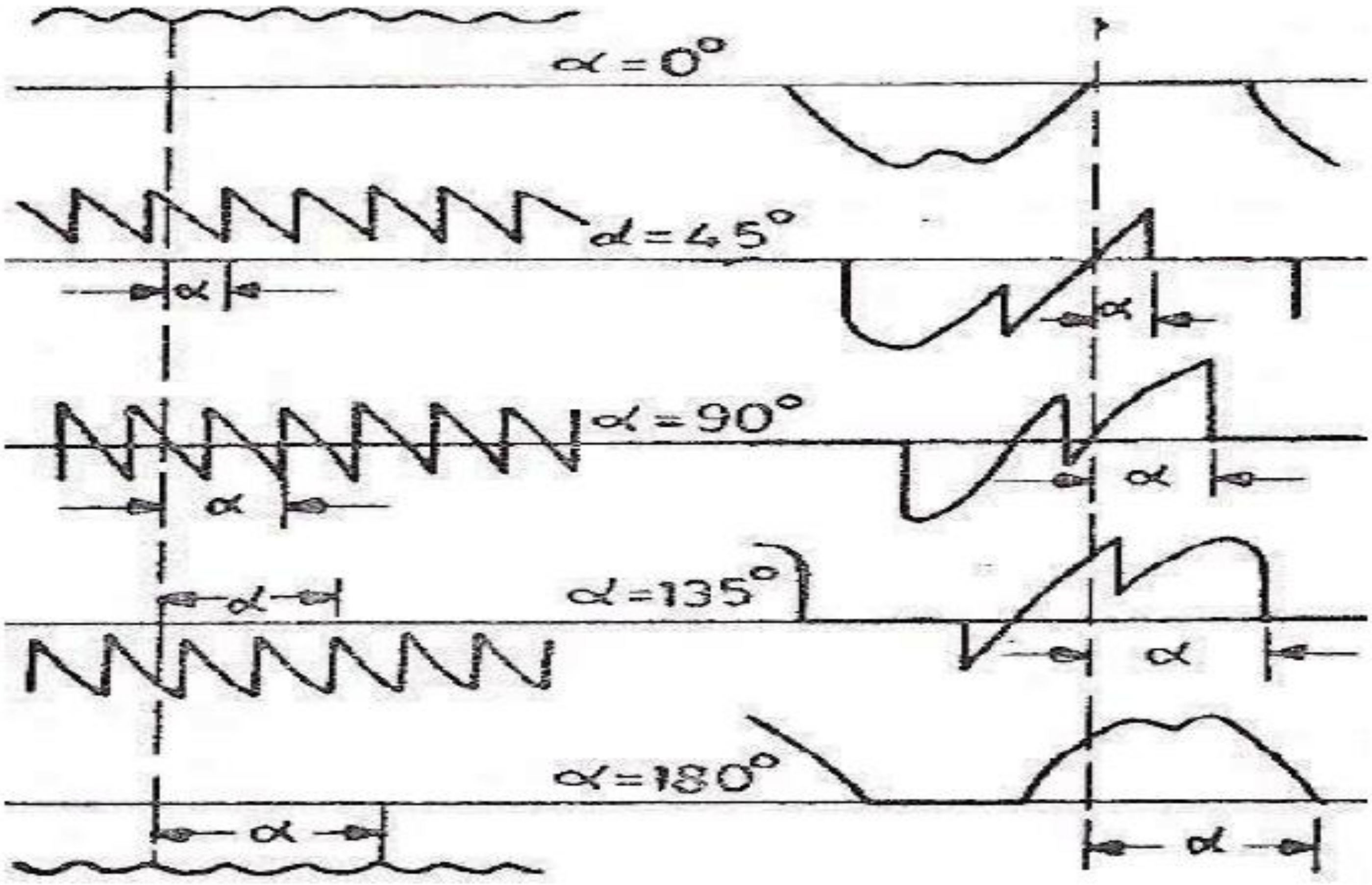


Fig 9: Thyristor voltage waveforms

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: $\beta < 60o$ and $\xi = \gamma$
  - Second Range: $60o < \beta < 90o$ and $\xi = 60o – \mu = \gamma\text{-}(\beta\text{-}60o\ )$
  - Third Range: $\beta > 90o$ and $\xi = \gamma – 30o$
- 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

12 PULSE CONVERETER

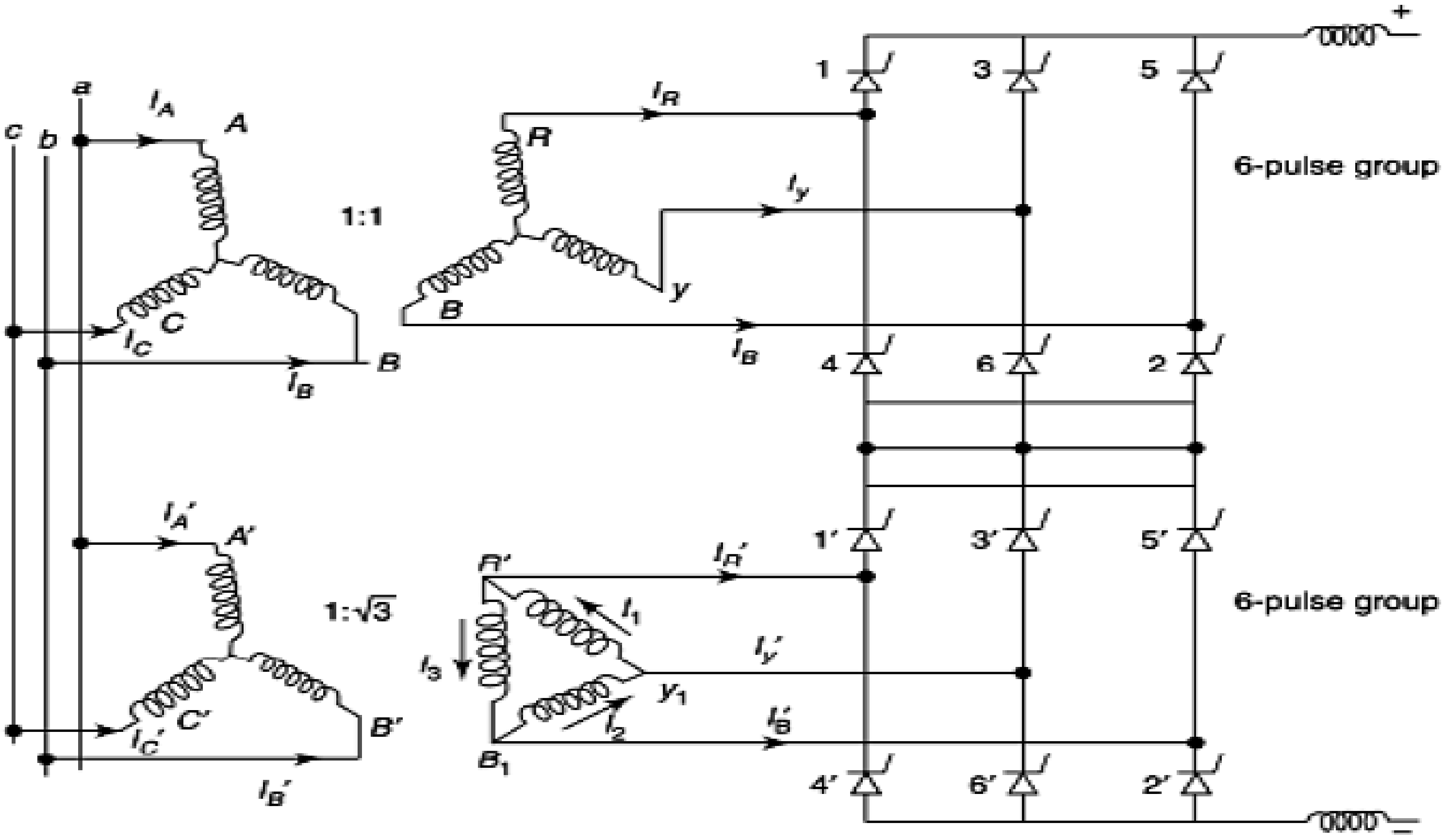
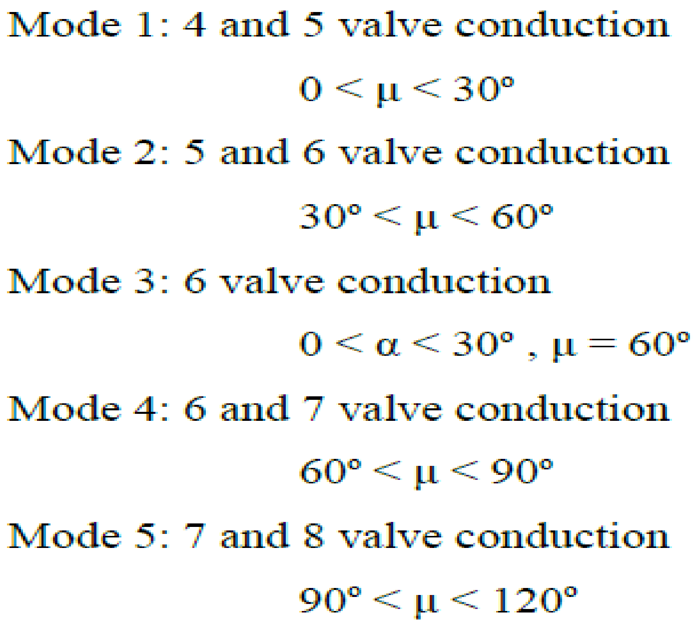


Fig 10: circuit diagram for 12 pulse converter

OPERATION 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



Mode 1: 4 and 5 valve conduction

$$0 < \mu < 30^\circ$$

Mode 2: 5 and 6 valve conduction

$$30^\circ < \mu < 60^\circ$$

Mode 3: 6 valve conduction

$$0 < \alpha < 30^\circ\ ,\ \mu = 60^\circ$$

Mode 4: 6 and 7 valve conduction

$$60^\circ < \mu < 90^\circ$$

Mode 5: 7 and 8 valve conduction

$$90^\circ < \mu < 120^\circ$$

CHARACTERISTICS OF 12 PULSE CONVERTER

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.

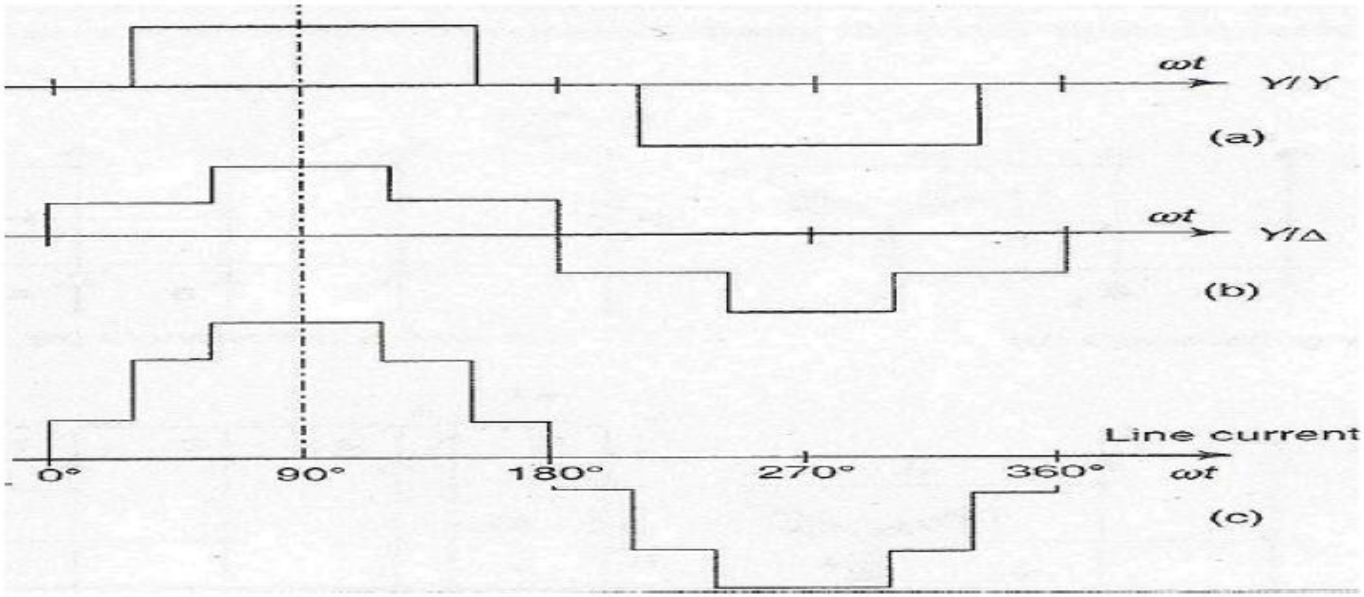


Fig 11: current waveforms for 12 pulse converter

UNIT III

HVDC CONTROL TECHNIQUES

CONTROL OF HVDC SYSTEM

Objectives of Control	• Efficient and stable operation. • Maximum flexibility of power control without compromising the safety of equipment.
Content	• Principle of operation of various control systems. • Implementation and their performance during normal and abnormal system conditions.

BASIC PRINCIPLE OF CNTROL

Direct current from the rectifier to the inverter

$$I_d = \frac{V_{dor}\cos\alpha - V_{doi}\cos\beta}{R_{cr} + R_l - R_{ci}}$$

- Power at the rectifier terminal

$$P_{dr} = V_{dr} I_d$$

- Power at the inverter terminal

$$P_{di} = V_{di} I_d = P_{dr} - R_L I_d^2$$

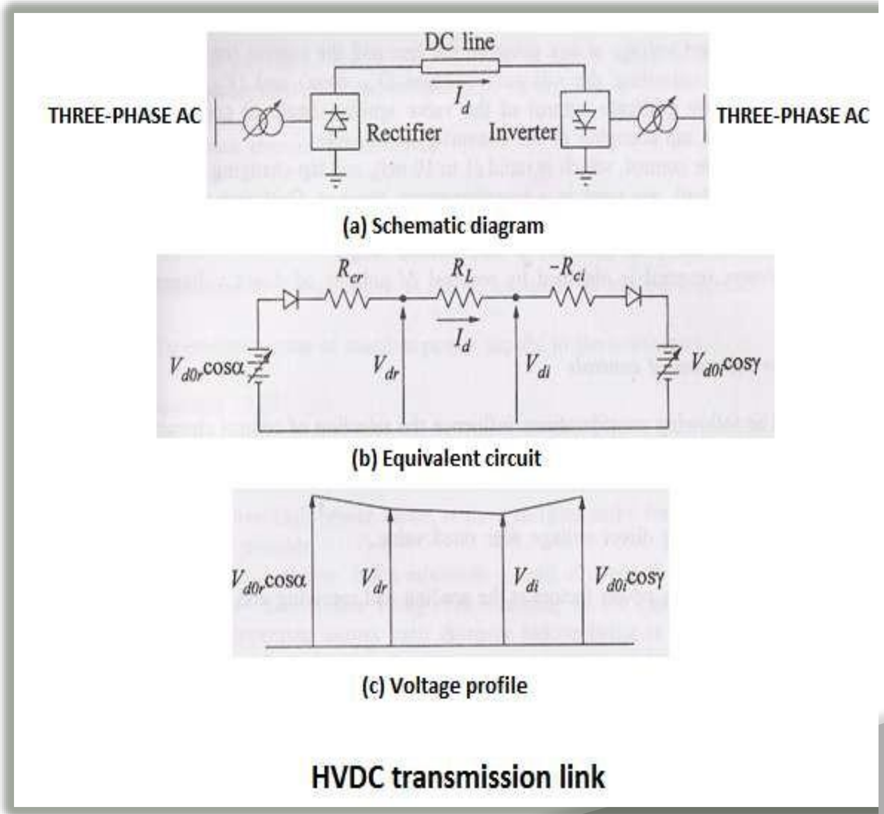


Fig 1: Schematic diagram of control

BASIC MEANS OF CONTROL

- Internal voltages $V_{dor} \cos\alpha$ and $V_{doi} \cos\beta$ can used be controlled to

Control the voltages at any point on the line and the current flow (power).

This can be accomplished by:

- Controlling firing angles of the rectifier and inverter (for fast action).
- Changing taps on the transformers on the AC side (slow response).

Power reversal is obtained by reversal of polarity of direct voltages at both ends.

CONTROL CHARACTERISICS

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.

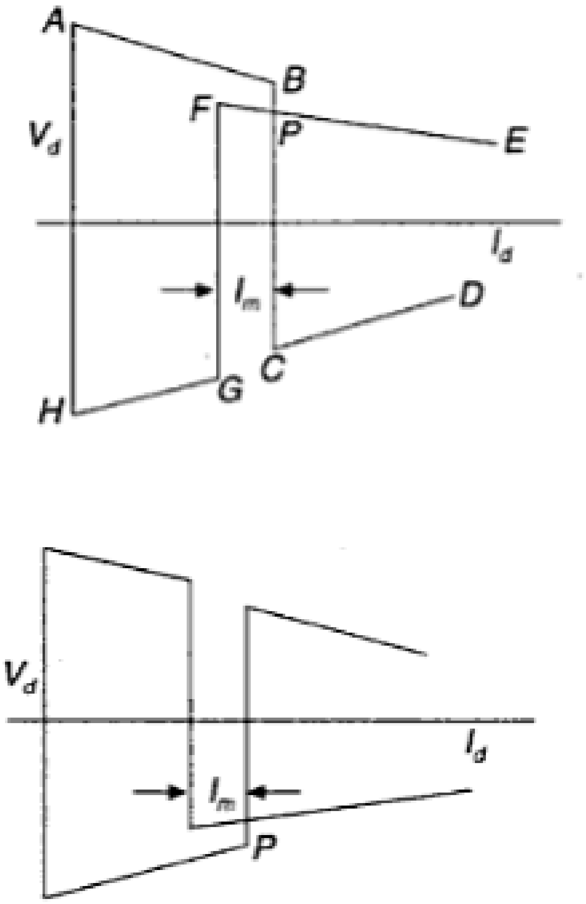


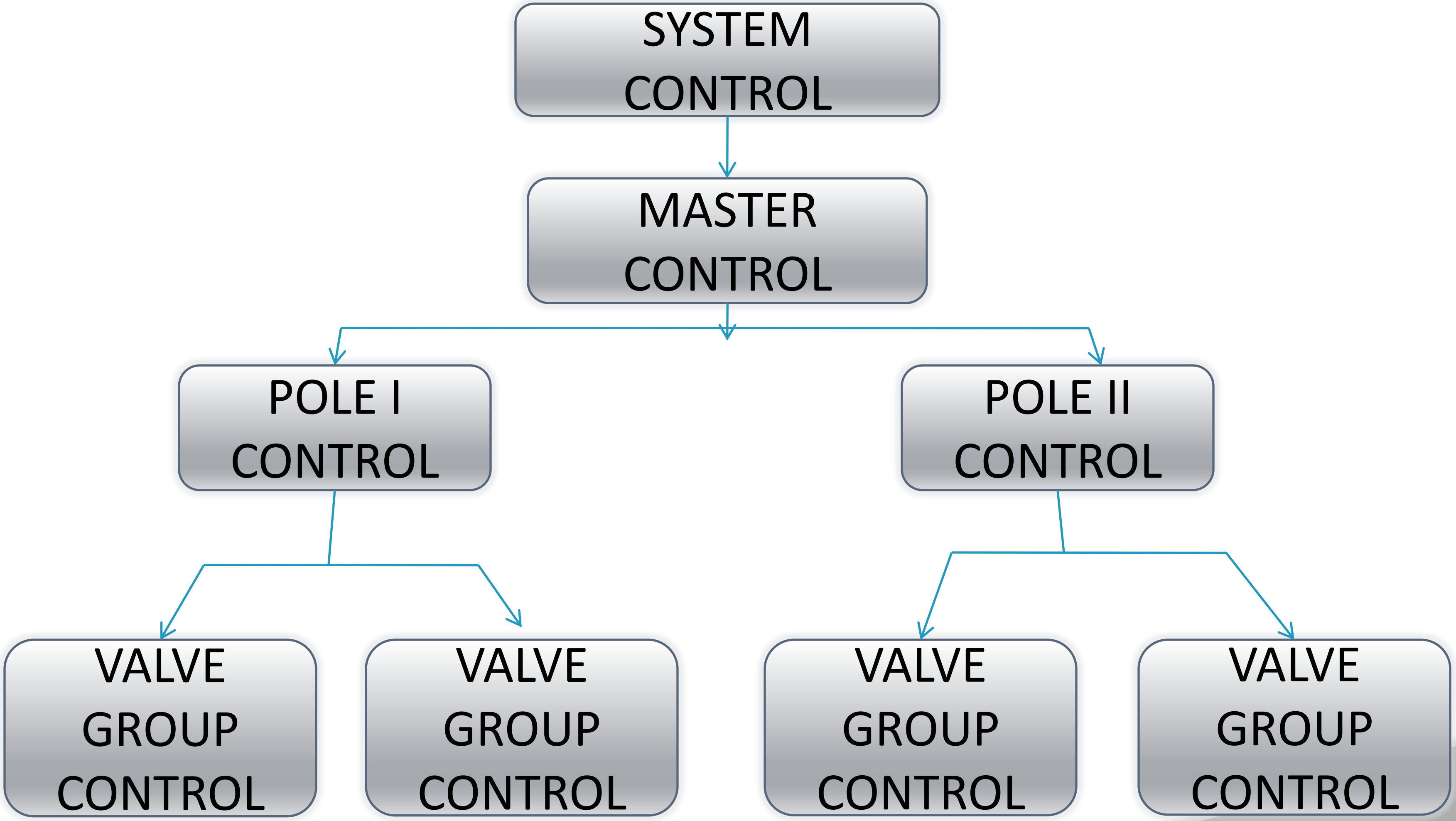
Fig 2: control characteristics

CONTROL CHARACTERISICS

- 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:

1. CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.
2. With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at the inverter.
3. 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 the rectifier.

SYSTEM CONTROL HIERARCHY



SYSTEM CONTROL

MASTER CONTROL

POLE I CONTROL

POLE II CONTROL

VALVE GROUP CONTROL

VALVE GROUP CONTROL

VALVE GROUP CONTROL

VALVE GROUP CONTROL

SYSTEM CONTROL HIERARCHY

- 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 protection circuits.

SYSTEM CONTROL HIERARCHY

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

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 conducting state.
- The two basic firing schemes are
  - Individual Phase Control (IPC)
  - Equidistant Pulse Control (EPC)

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

INDIVIDUAL PHASE CONTROL

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 α = 0o for that valve.

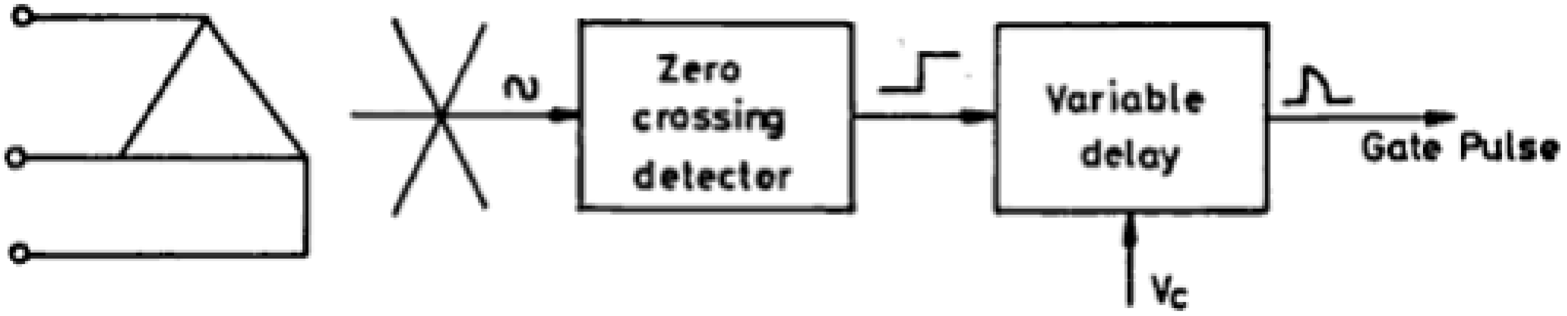


Fig 3: Constant α Control

INDIVIDUAL PHASE CONTROL

INVERSE COSINE CONTROL:

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

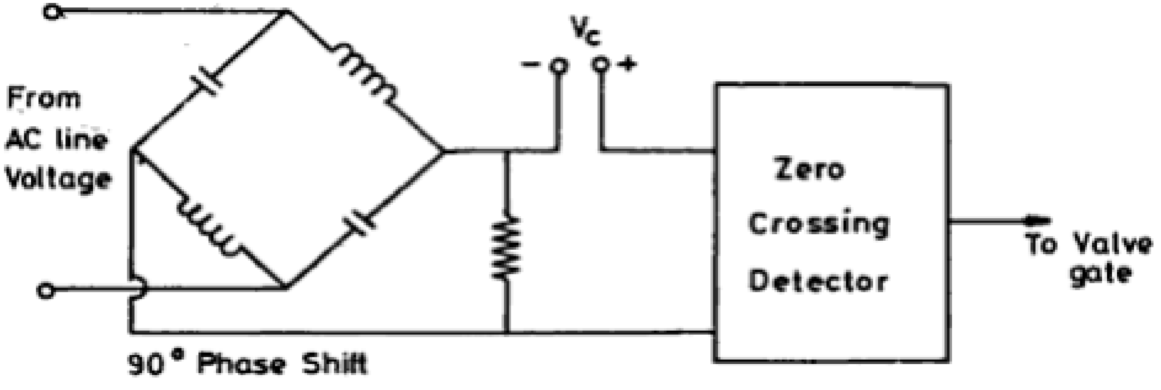


Fig 4: inverse cosine control

PULSE FREQUENCY CONTROL

A Voltage Controlled Oscillator (VCO) is used, the frequency of which is determined by the control voltage Vc 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 pfo where fo 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.

PULSE FREQUENCY CONTROL

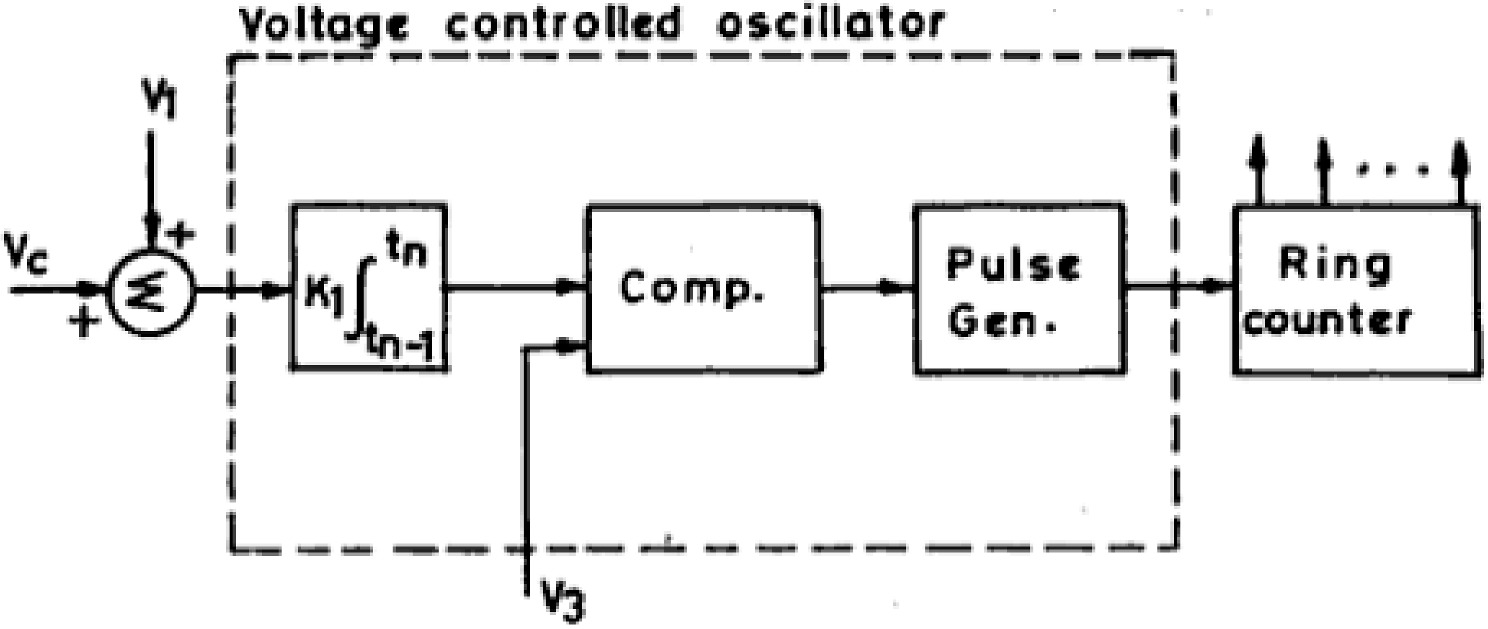


Fig 5: pulse frequency control

CURRENT AND EXTINCTION ANGLE CONTROL

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

CURRENT AND EXTINCTION ANGLE CONTROL

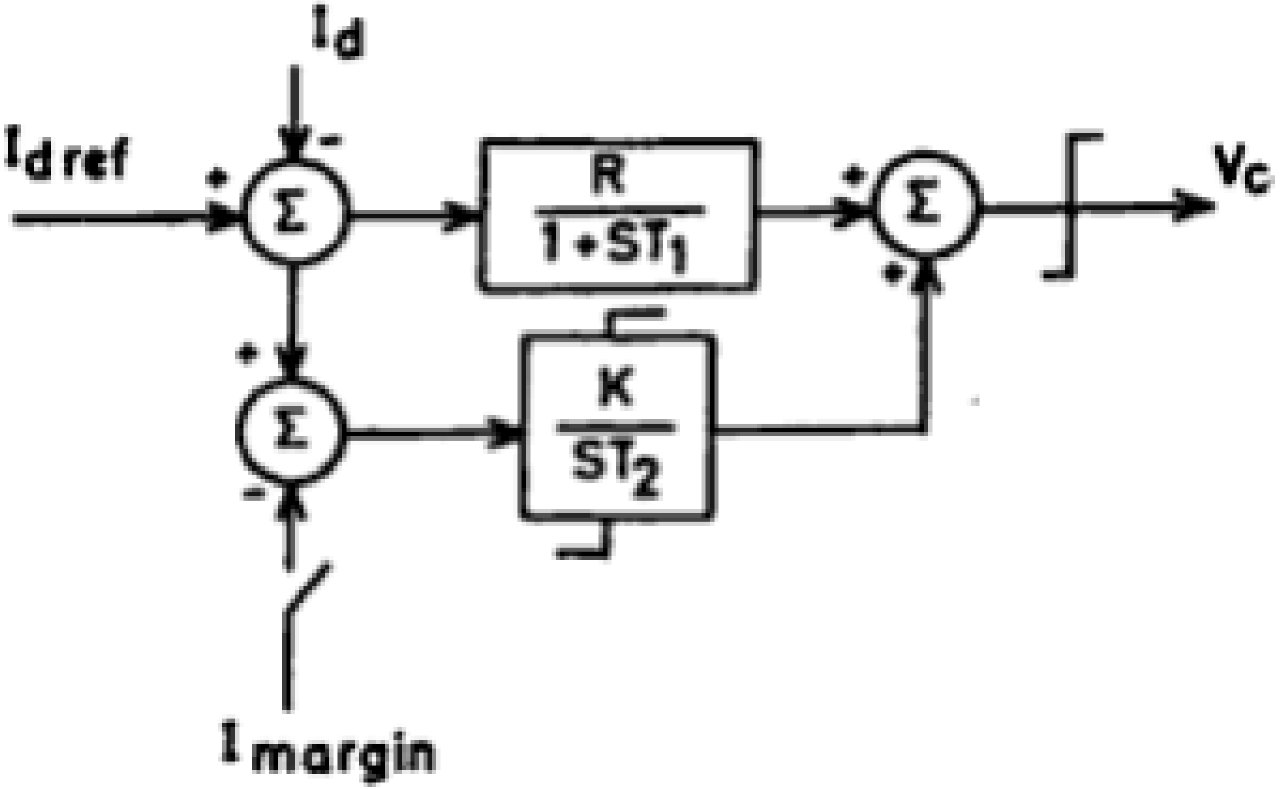
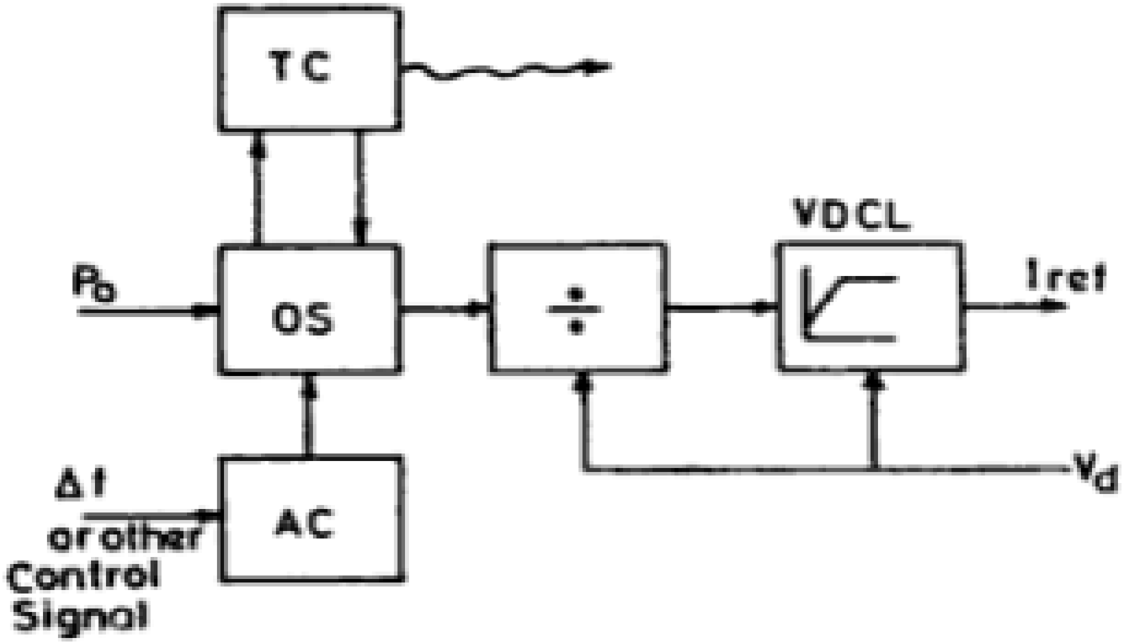


Fig 6: extinction angle control

POWE CONTROL

The current order is obtained as the quantity derived from the power order by dividing it by the direct voltage. The limits on the current order are modified by the voltage dependent current order limiter (VDCOL). The objective of VDCOL is to prevent individual thyristors from carrying full current for long periods during commutation failures. By providing both converter stations with dividing circuits and transmitting the power order from the leading station in which the power order is set to the trailing station, the fastest response to the DC line voltage changes is obtained without undue communication requirement.

POWER CONTROL



TC-Telecommunication equipment
OS-Order Setting unit

VDCL-Voltage dependent current limiter

Fig 7: Power Control

STARTING AND STOPPING OF DC LINK

Energization and Deenergization of a 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.

STARTING AND STOPPING OF DC LINK

- 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.

STARTING AND STOPPING OF DC LINK

- **Start-up with long pulse firing:**

1. De block inverter at about γ = 900
2. De block rectifier at α = 850 to establish low direct current
3. Ramp up voltage by inverter control and the current by rectifier control.

STARTING AND STOPPING OF DC LINK

Start-up with short pulse firing:

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.

UNIT IV

CONVERTER FAULTS AND PROTECTION

CONVERTER FAULTS

NATURE AND TYPE OF FAULT:

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

TYPES OF FAULTS

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

TYPES OF FAULTS

According to the origin of the malfunction, converter faults can be divided into 3 broad categories

- Faults due to malfunction of valves and controller
- Arc backs (back fire) in mercury arc valves
- Arc through(or fire through or short through)
- Quenching(arc quenching or arc chopping)
- Misfire
- Commutation failure in converters i.e failure to complete commutation before commutating emf reverses
- Short circuit within converter stations

ARC BACK

- This refers to the conduction in the inverse voltage period of valves and normally happens in rectifiers because the inverse voltage period in rectifiers are more.
- It is most common and severe malfunction in mercury valves and is random in nature. On an average it is one or two arc backs/ valve/month.
- Modern thyristors do not suffer from arc backs Factors that increase arc backs are High PIV High voltage jump, particularly of the jump of arc extinction.
- High rate of change of current at the end of conduction

ARC BACKS

- Over current Impurity of anode and grid High rate of rise of inverse voltage Factors I and 2 can be reduced by having low voltage and factors 3 and 4 can be reduced by having low current.
- These reduce power handling/valve and increase converter faults Factors 2 and 3 can be improved by having small (alpha, beta, gamma, del) but they are larger for control operation (momentarily)Factor 6 is minimized by having RC dampers across each valves. However factor 3 can be improved by high "u"
- This malfunction results in line to line short circuits and also sometimes three phase short circuits. It also generates some harmonics.

ARC THROUGH

- It occurs during the blocking period of the valve when the voltage across it is positive. Since the valve voltage is more positive in inverter, this malfunction is more common on inverter side. It is similar to commutation failure. This malfunction is mainly due to Failure of negative grid pulse Early occurrence of positive grid pulse Sufficiently high positive transient over voltage on grid or anode

PROBLEMS IN ARCH THROUGH

Problems:

- It reduces delay angle It introduces DC component in transformer cuurent. It changes harmonic components. Thus short circuit will persist till arc through is removed and bridge is bypassed.

MISFIRE

- Failure of valve to conduct during conduction period is misfire whereas arc through is the failure of valve to be blocked during schedule non conducting period.
- It can occur in rectifier or inverters but is more severe in inverters.
- It may be due to negative gate pulse or positive anode to cathode voltage or fault in valves
- The effect of misfire in inverters is same as commutation failure and arc through
- Suppose valve 6 and 1 are conducting and valve 2 fails to ignite. Now 3 will start conducting and there will be a DC short circuit which happens for small durations
- There is small jump in voltage at the beginning of short circuit an a large jump at the end of it.

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.

COMMUTATION FAILURE

- This fault, which is more common in the inverter, is the result of failure of incoming valve, due to insufficient extinction time, to take over the direct current before the commutating voltage reverses its polarity.
- Thereafter, the direct current is shifted back from incoming valve to outgoing valve.
- It is not due to malfunction of the valve, but due to AC DC condition outside the bridge. It is due to high DC current , low AC voltage (due to AC short circuit), late ignition or combination of these.
- Nearly all inverter valve faults lead to results similar to commutation failure.

COMMUTATION FAILURE

- The failure of two successive commutations in one cycle is double commutation failure.
- Let us take an example that valve 1 and 2 are conducting and 3 is to be ignited and is to take complete current of valve 1which is upper limb of converter.
- If current in incoming valve 3 diminishes to zero after full conduction, the current in valve 1 will continue to carry full Dc link current.
- Firing of valve 4 (in next sequence) will result in short across bridge, as both valve in same valve will conduct.
- If the commutation from valve 2 to 4 is successful then only valve 1 and 4 will conduct.

COMMUTATION FAILURE

- Firing of valve 5 (in sequence) will be unsuccessful since the voltage across it will be negative and 1 and 4 will continue to conduct.
- If successful commutation from 1 to 3 and back to 1 is completed before 4 fires and if the condition that caused first failure persists a second failure may occur in the commutation from 2 to 4 causing DC current back to 2.Now 1 and 2 will be conducting.
- After commutation failure, the succeeding commutation is carried out by CEA control and is usually sucessful.
- If caused by low AC voltage, the reappearance on normal voltage helps preventing the further failures.In the event that commutation failure persists, the bridge where it is happening should be bypassed or blocked.

PROTECTION SCHEMES

Desirable features of protection Protections of AC system

Selective Discriminative Reliable Speed Backup Protections of AC system

- Over voltage protection (using o/h wires, protective gaps, LA)
- Over current protection (using CB, fuses, relays, current limiting reactors)

PROTECTION OF HVDC SYSTEM

- Over voltage protection (similar to ac system with some differences)
- Over current protection (using some control of valves)
- Damper circuits
- DC reactors
- Over voltages in converter stations
- Due to disturbance originating on the AC side
- Due to disturbance originating on the DC side
- Due to internal faults in converter

TYPES OF EXTERNAL VOLTAGE IN HVDC

- Switching over voltages due to initiation and clearing of faults
- Temporary over voltages (lasting few secs) due to load rejection in weak AC systems
- Steep front over voltages due to lightning
- Disturbance in DC side
- Steep front surges due to lightning strokes(external)Switching surges due to ground fault on the pole producing over voltages in the normal pole
- voltage can also arise from current and voltage oscillations CAUSED BY SUDDEN JUMPS in converter voltage due to converter faults and commutation failures

TYPES OF EXTERNAL VOLTAGE IN HVDC

- Switching of DC filters and parallel connection of poles
- Switching surges originating from AC system, transmitted to the DC side.
- Series connection of valve groups multiplies the over voltages by the number of groups
- Sudden loss of load on rectifier
- Increased overshoot of DC voltage of bridge at the end of each commutation due to short overlap.

Disturbances due to internal converter faults

- Due to energization of DC lines
- Due to stay capacitances and inductances
- Due to converter faults
- Means of reducing the over voltages
- Lightening arrestors or surge diverters
- Plain gap and shield of O/H lines
- Converter control system
- Damping circuit
- DC reactors
- Surge capacitors

DC line arrestors

- The current through arrestor does not have natural zero to aid in resealing the arrester against sustained DC voltage
- Voltage is buffered by huge lumped inductance (through smoothing reactors and transformers)
- Special LA are built for DC

OVER CURRENT PROTECTION IN HVDC

- Main features of converter protection is that it is possible to clear faults by fast control action (less than 20 ms)
- Differential protection is employed because of its fast detection and selectivity
- Over current protection is used a s backup
- The level of over current required to trip must be higher than the valve group differential protection
- Pole differential protection is used to detect ground faults

DC REACTORS

- It limits di/dt rise to prevent commutation failure in inverter of one bridge when the voltage across other bridge collapses
- It reduces the incidence of commutation failure in inverters during AC dip
- It reduces harmonic voltage and current in DC linkIt reduces current ripples
- It limits crest of SC current in DC line

UNIT V

REACTIVE POWER MANAGMENT

INTRODUCTION TO HARMONICS

- 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.

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

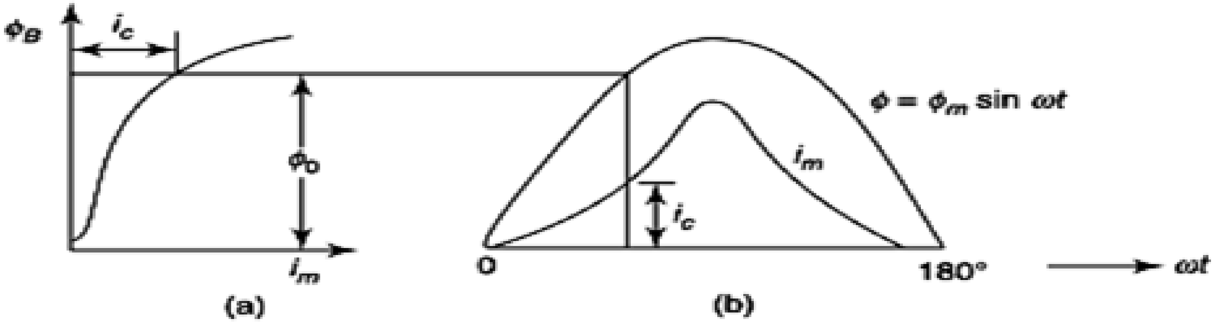
SOURCES OF HARMONICS

The three distinct sources of harmonics in HVDC systems are

- Transformer.
- AC Generator.
- Converter along with its control devices

TRANSFORMER AS SOURCE 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



Transformer magnetisation (without hysteresis)
(a) Magnetisation curve (b) Flux and magnetisation current waveforms

Fig 1: transformer magnetisation

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.

TYPES OF HARMONICS

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

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

DESIGN OF AC FILTERS

Harmonic distortion:

- Harmonic Distortion is given by,

$$D = \frac{\sum_{n=2}^{m} I_n Z_n}{E_1} \times 100$$

- **Telephone influence factor:**

An index of possible telephone interference and is given by,

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

where, Fn = 5 n f1 pn

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

DESIGN OF AC FILTERS

Total harmonic form factor (THFF):

- It is similar to TIF and is given by,

  $$F_n = (n\ f1 / 800)\ W_n$$

  where, W_n – weight at the harmonic order n, defined by the Consultative Commission on Telephone and Telegraph Systems (CCITT).

IT product:

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

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

TYPES OF AC FILTERS

- The various types of filters that are used are
  - Single Tuned Filter
  - Double Tuned Filter
  - High Pass Filter
    1. Second Order Filter
    2. C Type Filter

SINGLE TUNED FILTERS

Single Tuned Filter Single Tuned Filters are designed to filter out characteristic harmonics of single frequency.

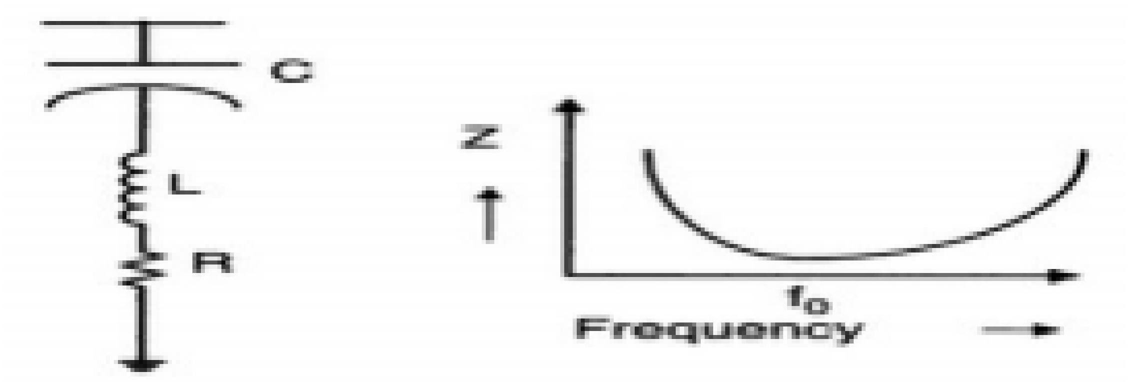


Fig 2: single tuned filter

DOUBLE TUNED FILTER

- The Double Tuned Filters are used to filter out two discrete frequencies, instead of using two Single Tuned Filters. Their main disadvantages are
  - only one inductor is subject to full line impulse voltage.
  - power loss at the fundamental frequency is considerably reduced.

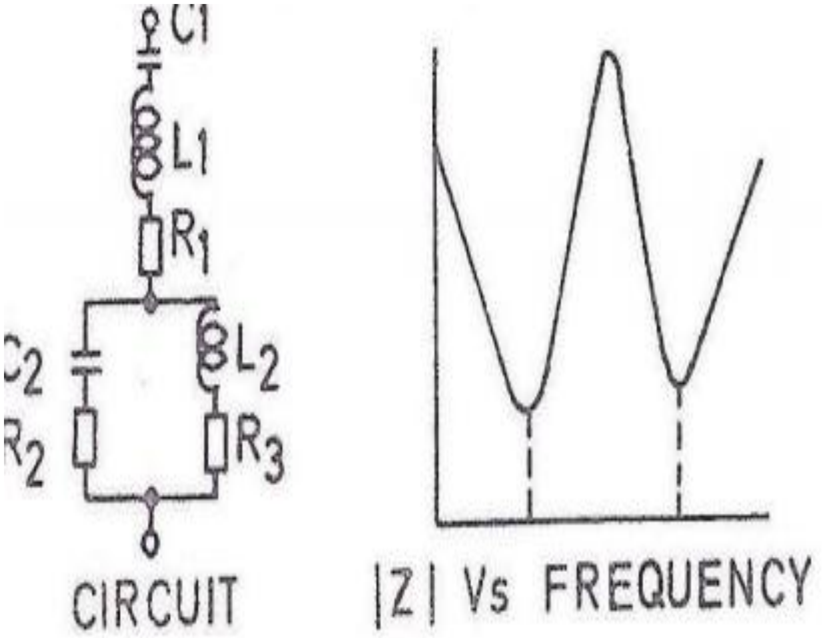


Fig 3: double tuned filter

HIGH PASS C TYPE FILTER

The losses at the fundamental frequency can be reduced by using a C Type Filter where capacitor C2 is in series with inductor L, which provides a low impedance path to the fundamental component of current. A converter system with 12 pulse converters has Double Tuned (or two Single Tuned) Filter banks to filter out 11th and 13th harmonics and a High Pass Filter bank to filter the rest of harmonics. Sometimes a third harmonic filter may be used to filter the non-characteristic harmonics of the 3rd order particularly with weak AC systems where some voltage unbalance is expected. All filter branches appear capacitive at fundamental frequency and supply reactive power

HIGH PASS C TYPE FILTER

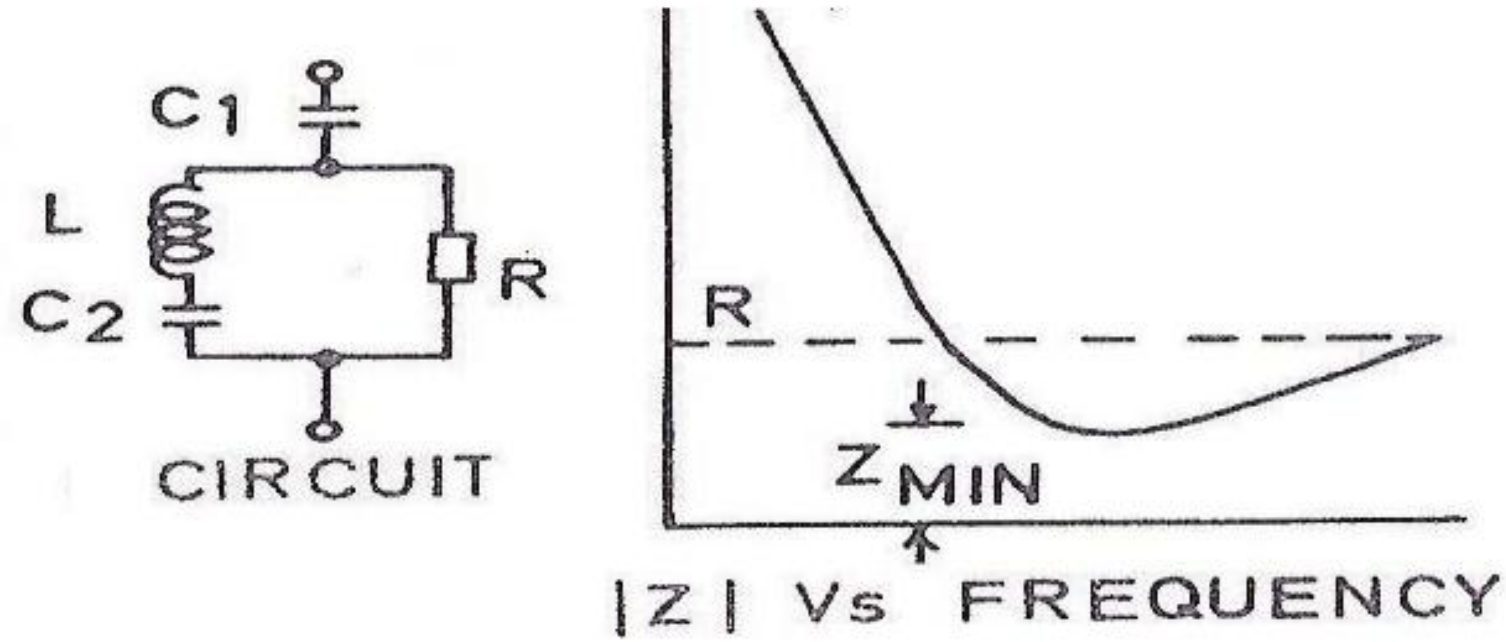


Fig 4: high pass C type filter

DC FILTERS

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.

DESIGN OF DC FILTERS

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.

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.

POWER FLOW ANALYSIS

Most of the solution techniques for AC/DC power flow are divided into two different approaches.

- The sequential method
- unified (or simultaneous) solution methods.

SEQUENTIAL METHOD

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.

UNIFIED METHOD

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.

REQUIREMENT OF RATINGS

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.

REQUIREMENT OF RATINGS

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.

REQUIREMENT OF RATINGS

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 converterbus.

THANK YOU