UNIT III

Basic concepts of DC Transmission

Transmission systems are necessary for

1) Bulk power Transfer from large group of gathering stations upto the main transmission network

2) For the system Interconnections

There are two types of Transmission based on supply

① AC Transmission

② DC Transmission.

Remote generation and system connections lead to search for efficient power Transmission at increasing power levels. The increase in voltage levels is not always feasible. The problems of AC Transmission particularly in long distance Transmission lead to ~~be~~ the development of DC transmission. However Generation & utilization ac, the dc Tr reauires converters at two ends, from AC to DC at the sending end and back to AC at the receiving end.

The HVDC transmission made a modest begining in 1954 when a 100KV 20MW DC link was established between swedish main land and the island of Getland until 1970, the Converter stations utilized mercury arc valves for rectification. The successfull use of thyristors for power control in industrial drives encouraged its operation in HVDC converters by the development of high power semiconductor devices.

The device voltage rating is now in the range of 10kV, and current rating upto 5kA (for 125mm device). The highest transmission voltage reached is ± 600kV.

Advantages of HVDC Transmission

1. Interconnections of systems using long length of cables in particular while crossing sea water.
2. Interconnections of systems operating at different frequencies (as synchronous tie)
3. Reduced Transmission lines
4. Rigid control over the magnitude & directions of power flow with easy
5. limiting the transfer of fault current
6. Damping out ~~os~~ oscillations and improving the stability Margins.

Comparision of AC & DC Transmission

The relative merits of the two modes of AC & DC should be compared based on the following facts.

1. Economics of Transmission
2. Technical performance
3. Reliability

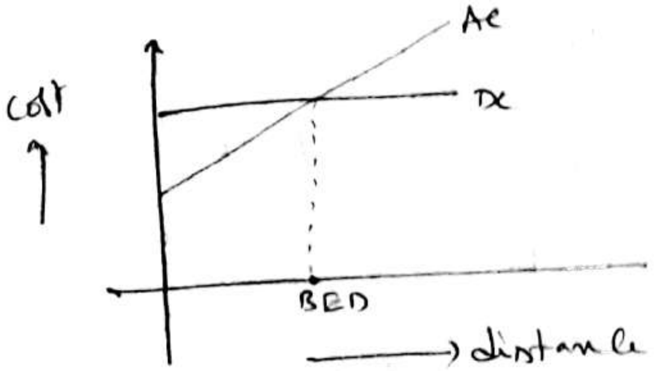
1. Economics of Transmission:-

DC Transmission of bulk power over long distances has certain distinct advantages over conventional AC Transmission such as following

1) In DC transmission, inductance and Capacitance of the line has no effect on the power Transfer capability of the line and the line drop. Also there is no leakage & charging current of the line under steady conditions.

2) A DC line requires only 2 Conductors where as an AC line requires 3 conductors in 3phase AC system. The cost of the terminal equipment is more in DC lines than in AC line. Break even distance is one at which the cost of the two systems is the same.

3. The choice of DC Transmission voltage for a given power has a direct impact on the total installation cost. The cost of losses is very important in the evaluation of energy losses cost and the time horizon for utilisation of DC system.



The Break even distance can vary from 500 to 800km in over head lines depending on the per unit line costs.

2. Technical performance

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

1) full control over power transmitted
2) The ability to enhance transient and small signal stability in associated networks
3) fast control to limit fault currents in DC lines. This makes it feasible to avoid DC breakers in two terminal DC links.

(a) comparision of single phase AC line and monopolar DC line

power Transmitted through DC line $P_d = V_d I_d$

power transmitted through AC line $P_{ac} = V_p I_p \cos\phi$

where V_d is DC voltage of the pole w.r.t ground.

V_p is ~~AC~~ rms line to ground voltage of AC system.

The ratio of DC power to AC power is

$$\frac{P_d}{P_{AC}} = \frac{V_d I_d}{V_p I_p \cos\phi}$$

Assume power factor $\cos\phi = 0.945$

$$V_d = \sqrt{2} V_p$$

(DC max) (AC max)

$$\frac{P_{dc}}{P_{AC}} = \frac{V_d I_d}{V_p I_p (0.945)}$$

$$= \frac{\sqrt{2} V_p I_p}{V_p I_p \, 0.945}$$

$$\boxed{\frac{P_{dc}}{P_{AC}} = 1.5}$$

Monopolar DC line can transmit 1.5 times the power an AC line can transmit for the same conductor size and system maximum voltage

(b) Comparision of DC line with 3ϕ AC line for power transfer capability

$$I_d = I_p$$

$$V_d = \sqrt{2} V_p$$

DC power $= P_d = 2 V_d I_d$

$$P_{AC} = 3 V_p I_p \cos\phi$$

$$\frac{P_{dc}}{P_{AC}} = \frac{2 V_d I_d}{3 V_p I_p \cos\phi}$$

$$\frac{P_{dc}}{P_{AC}} = \frac{2\sqrt{2}\, V_p I_p}{3 V_p I_p \, 0.945}$$

$$\boxed{\frac{P_{dc}}{P_{AC}} = 1}$$

The power Transmitted by a bipolar line is same as that of a 3ϕ AC line.

(c) comparision of a Bipolar DC system with a phase AC system for same insulation levels.

$$P_{AC} = 3 V_p I_p$$

$$P_{DC} = 2 V_d I_d$$

For equal losses

$$3 I_p^2 R = 2 I_d^2 R$$

$$\boxed{I_p = \sqrt{\tfrac{2}{3}}\, I_d}$$

since power transmitted is the same in both the Cases

$$3 V_p I_p = 2 V_d I_d$$

$$3 V_p \left(\sqrt{\tfrac{2}{3}}\, I_d\right) = 2 V_d I_d$$

$$3 V_p \sqrt{2/3} = 2 V_d$$

$$V_p = \frac{2 V_d}{\sqrt{6}}$$

$$V_p = \sqrt{2/3}\, V_d$$

$$V_d = \sqrt{3/2}\, V_p$$

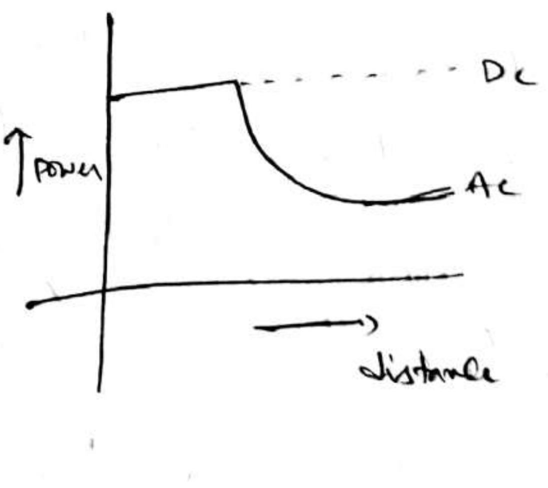
$$\frac{\text{DC insulation level}}{\text{AC insulation level}} = \frac{V_d}{\sqrt{2}\,V_p}$$

$$= \frac{\sqrt{3/2}\,V_p}{\sqrt{2}\,V_p}$$

$$= \frac{\sqrt{3}}{2} = 0.866$$

Stability limits

The power transfer of AC lines is dependent on the angle difference b/w the voltage phasors at the two ends. For a given power levels, this angle increases with distance. The power carrying capability of an AC line as a function of distance. Power carrying capability of DC lines which is unaffected by the distance of transmission and is limited only by the current carrying capability.



Voltage control

The voltage profile along the AC line is complicated by line charging and inductive voltage drops. When the lagging volt ampere produced by the line $I^2 X_L$ is equal to the leading voltampere produced by the line $\frac{V^2}{X_C}$ for a particular load such loads called surge impedence loading.

$$\frac{V^2}{X_C} = I^2 X_L$$

$$\left(\frac{V}{I}\right)^2 = \frac{X_L}{X_C} = \frac{L}{C}$$

$$Z_n = \frac{V}{I} = \sqrt{\frac{L}{C}}$$

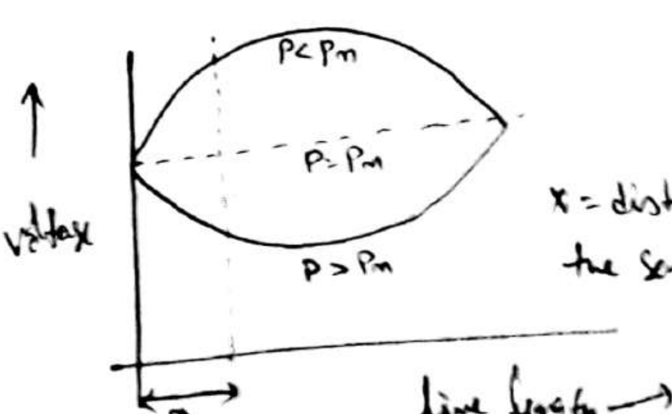
surge impedence loading $\boxed{P_n = \frac{V_1^2}{Z_n}}$

when load is equal to surge impedence loading on line voltage profile is flat line

when load is less than the surge impedence loading of the line voltage in the middle of the line rises

when ~~the~~ load is greater than surge impedance loading of the line voltage in the middle of the line decreases.

voltage variation along the line



x = distance from the sending end

Line compensation :-

AC line requires shunt and series compensation in long distance transmission, mainly to over come the problems of line charging & stability limitations series capacitors and shunt inductors used for this purpose. The increase in Power transfer capability and voltage control is possible through the use of shunt connected static var compensator (SVC).

Ground impedence

In AC Transmission the existance of Ground (zero sequence) currents cannot be permitted in steady state due to high magnitudes of ground impedence which will not only effect efficient power transfer. The Ground impedence is negligible for DC currents and a DC link can operate using one conductor with ground return.

3. Reliability

The reliability of DC Transmission system is good and comparable to that of AC systems. The performance of thyristor valve is much more reliable than mercury arc valves and further developments in devices, control and protection have improved the reliability level

There are 2 measures of overall system reliability

1. Energy availability
2. Transient reliability

(i) Energy availability

$$\text{Energy availability} = 100\left[1 - \frac{\text{Equivalent outage time}}{\text{Total time}}\right]$$

Equivalent outage time = Actual outage time x Fraction of system capacity lost due outage

(ii) Transient Reliability

This is a factor specifying the performance of HVDC systems during recordable faults on the ac systems

$$\text{Transient reliability} = \frac{100 \times \text{No of times HVDC system performance}}{\text{No. of recordable ac faults}}$$

Recordable ac system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault.

The energy availability on transient reliability of existing DC systems with thyristor valves is 95% or more.

Types of DC links

The type of an HVDC transmission system is identified on the basis of the arrangement of the pole and earth return.

Types of HVDC systems include

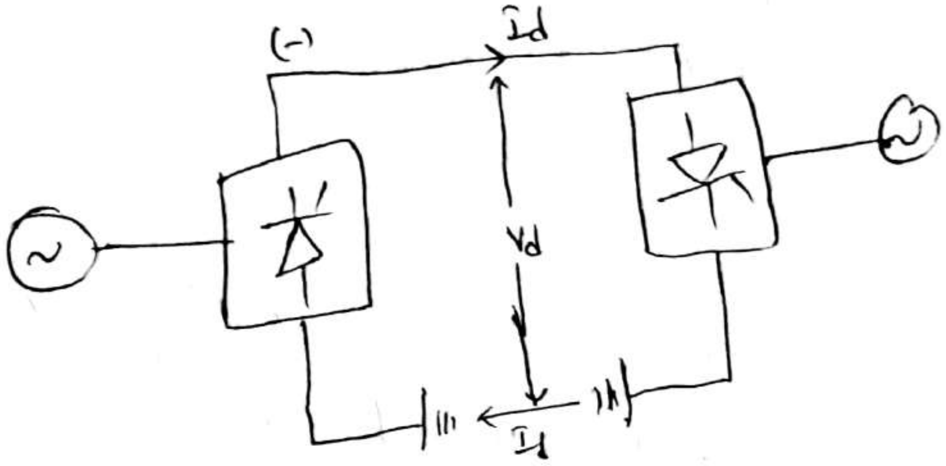
1. Monopolar link.
2. Homopolar link.
3. Bipolar link.
4. Back-Back HVDC coupling system
5. Multi terminal HVDC system

1. Monopolar link :-

This system has only one pole and return path is provided by permanent earth or sea. The pole generally has negative polarity with respect to the earth.

Monopolar system is used for operation of first stage of Bipolar system. The rated currents of the existing three monopolar transmission installations range from 200 to 1000 A.

The rating of a monopolar HVDC transmission system is equal to half of corresponding bipolar system rating. e.g long submarine cables longer than 25km and having power rating of about 250MW cable transmission HVAC is not technically feasible b/z of high charging currents with AC cables beyond thermal limit and bipolar cable is not justified for rating upto about 500 MW.



Mono polar link.

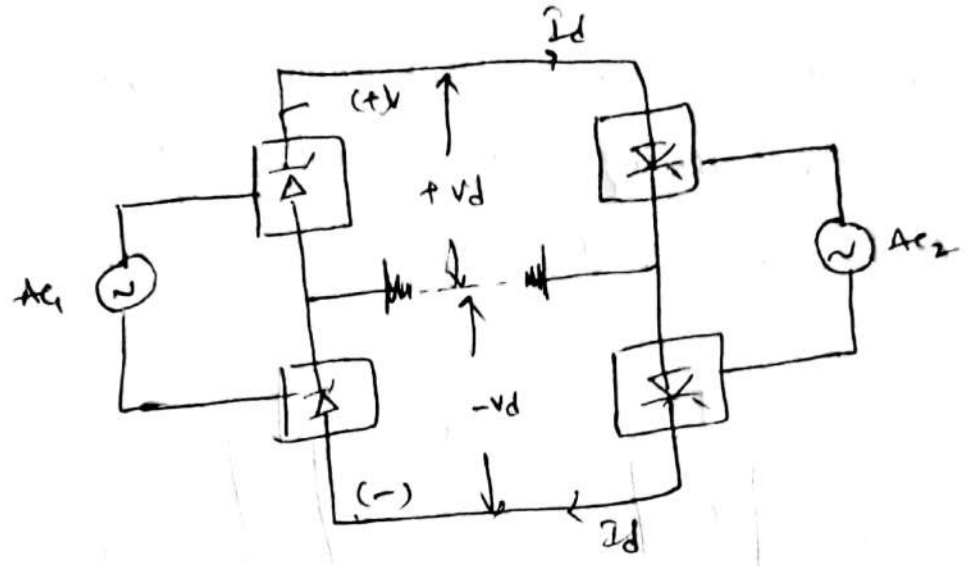
Bipolar DC link

This is most widely used for overhead long distance HVDC system for point-point power transfer.

The HVDC substation and HVDC lines has two poles, one positive and the other -ve with respect to other. The mid points of converter of each terminal station are earthed via electrode line and earth electrode.

During fault one one of the poles, the bipolar HVDC system is switched over automatically to monopolar mode therefore the service continuity is maintained.

The voltage between poles is twice that of the pole to the earth voltage. Therefore a bipole HVDC system is described as say ± 500kV Typical rating ±500kV,



Earth electrodes in a Bipolar system

The mid point of converters in each station is earthed with a suitable switching arrangement. This earthing is not the same as station earthing. This electrode earthing is through electrode earth installed 5 to 20 km from the HVDC substation.

Earth electrode An ~~arrange~~ array of conducting elements placed in the earth or sea which provide a low resistance path between the DC circuit and earth & which is capable of carrying continous current.

Earth electrode line

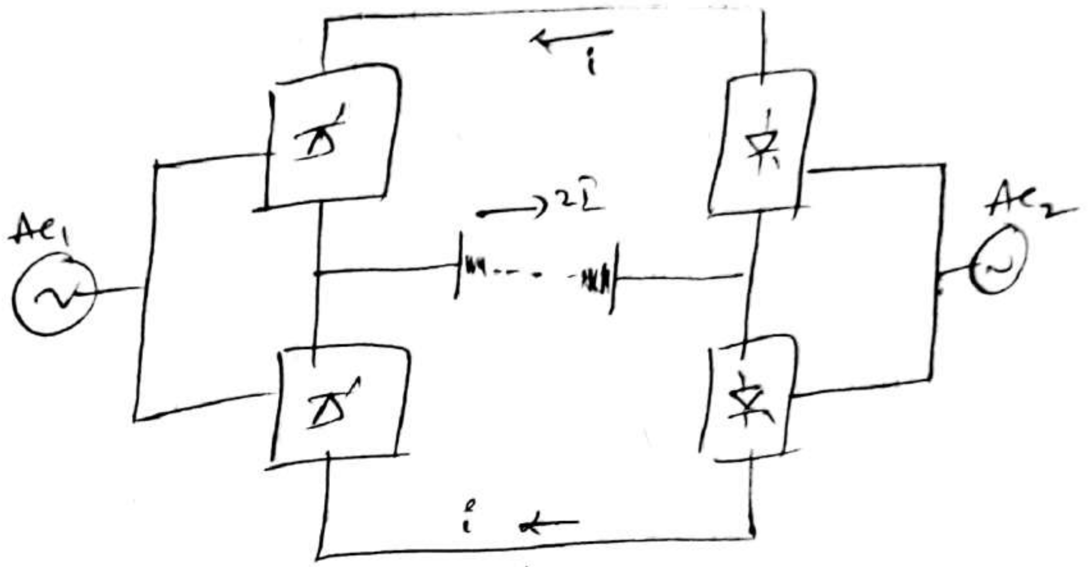
An insulated line b/w the HVDC substation and the earth electrode.

Homo polar DC link :-

In such a system 2 transmission poles are of the same polarity and the return is through permanent earth. Such a system may be used for the following

1. 2 homopolar overhead lines feeding to a common mono polar cable termination.

2. one overhead transmission tower carrying insulating strings supporting 2 homopolar transmission line conductors. such a system is not used more

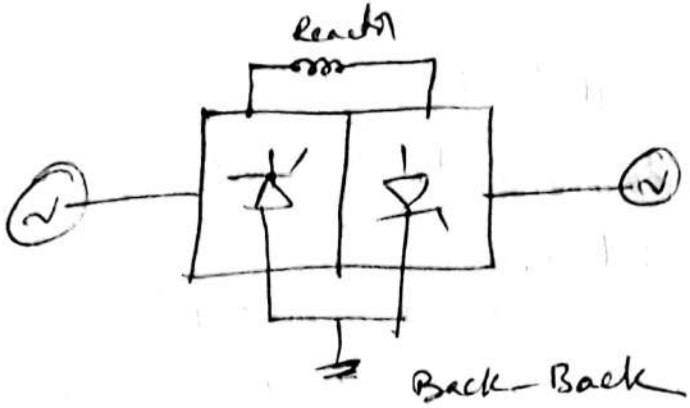


Back - Back HVDC Coupling system

HVDC coupling system is used for interconnection between geographically adjacent AC n/ws for the purpose of frequency conversion & for an asynchronous interconnection.

A strong AC networks can be interconnected by a weak n/w by a back to back interconnections. The back-back HVDC schemes are rated 500MW to 1500MW. 400MW B-B station can have thyristor converter ± 200kV with the voltage between ±DC connection equal to 400kV and current 1000A.

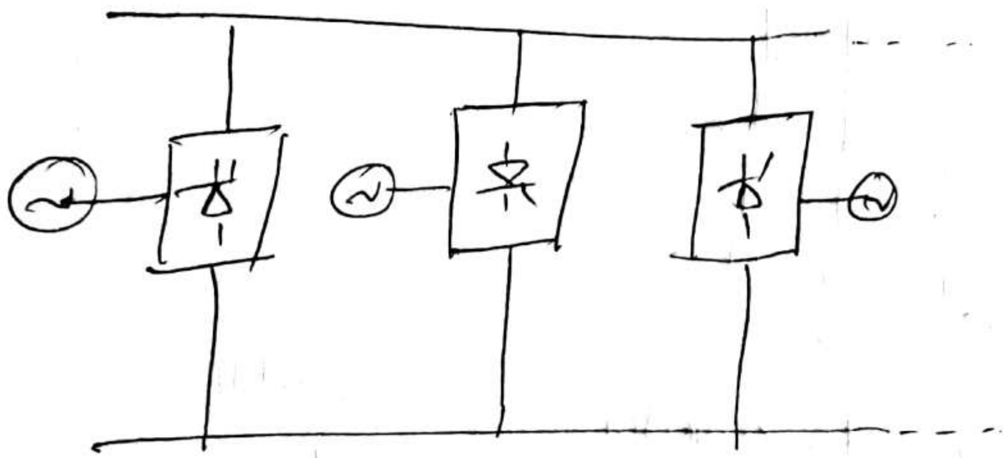
The rectifier and inverter are connected to form a DC loop 'There is no DC transmission line'. A DC smoothening reactor is connected in the DC loop. B-B coupling stations are generally designed for bipolar operation only and the return path is therefore not provided.



Back – Back

5. Multi terminal HVDC system (MTDC)

A multi terminal HVDC system interconnects 3 or more independently controlled AC networks each of the terminal substation has 12 pulse AC/DC converters. The 3 or more terminals are connected by HVDC interconnecting Tr line. The MTDC systems are of high cost and require complex controls

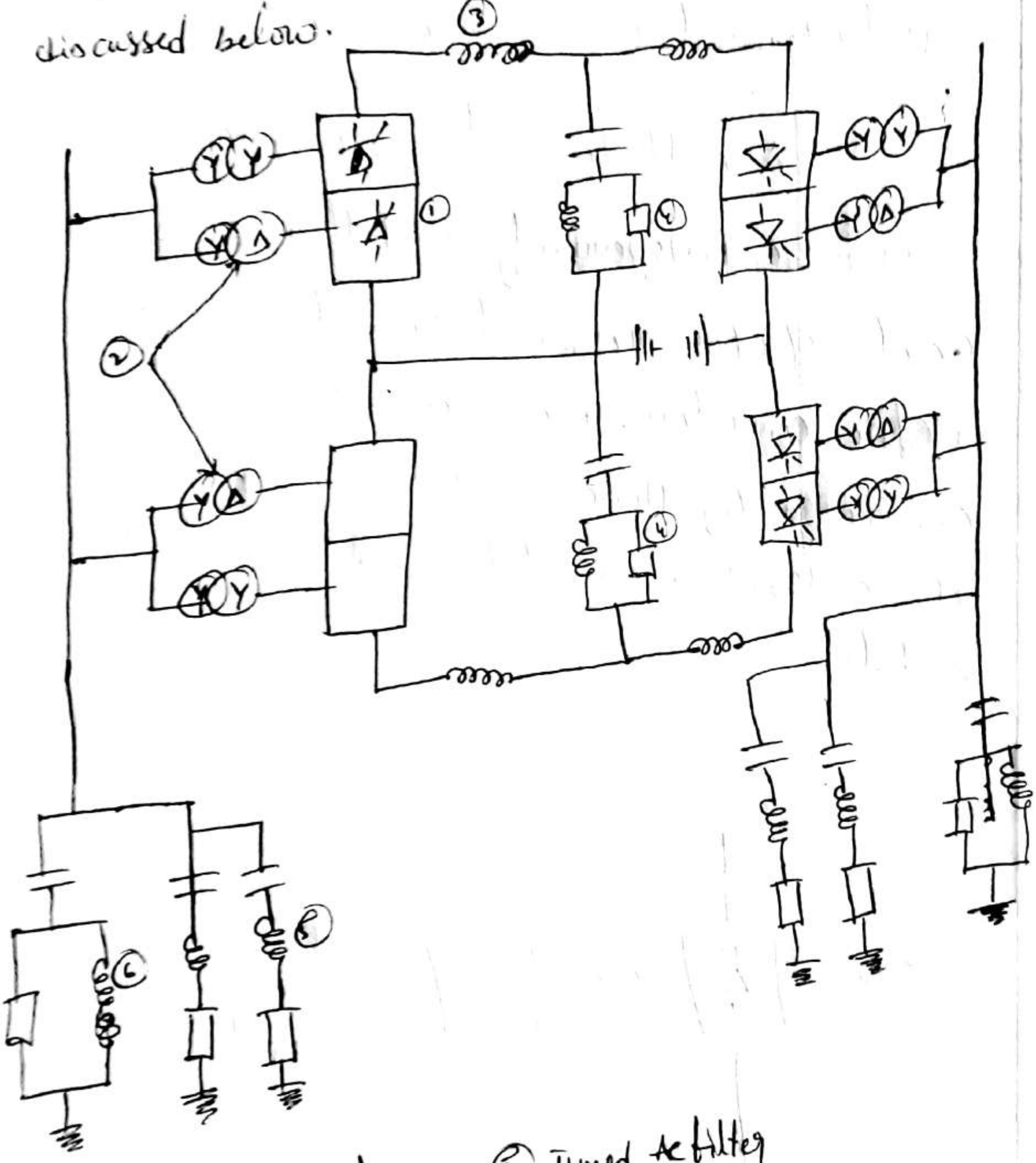


Bipolar Multi-terminal system.

Apparatus required for HVDC systems

The major components of a HVDC Transmission system are converter stations.

A typical converter station with 12 pulse converter unit per pole. The various components of a converter station are discussed below.



① 12 pulse converter

② Transformer

③ smoothing reactor

④ DC filter

⑤ Tuned AC filter

⑥ Hp AC filter.

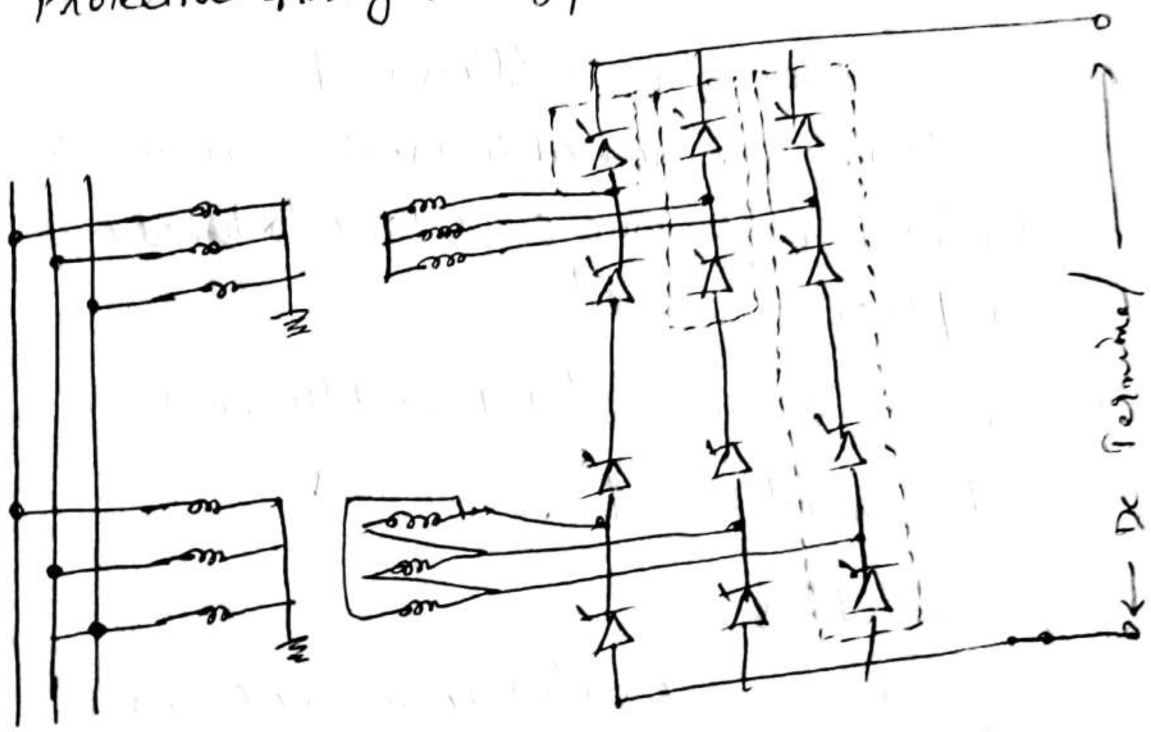
1. Converter

This usually consists of 2 3φ converter bridges, connected in series to form a 12 pulse converter unit. The total number of valves in such a unit are twelve. The valve can be packaged as a single valve, double valve or quadra valve arrangements. The converter is fed by converter transformer connected in Y/Y and star/delta arrangement.

The valves can be cooled by air, oil, water or freon, liquid cooling using deionized water is more efficient and results in the reduction of station losses.

The valve firing signals are generated in the converter control at ground potential and are transmitted to each of the thyristor through a fiber optic light guide system.

The valves are protected using snubber circuits protective firing and gapless surge arrestors.



12 pulse converter unit.

converter transformer

The converter transformer can have different configurations 1) 3ϕ 2 winding

2) single phase 3 winding

3) single phase 2 winding

The valve side windings are connected in star & delta with neutral point ungrounded on the AC side, the transformers are connected in parallel with neutral grounded.

The converter transformers are designed to withstand DC voltage stresses and increased eddy current losses due to harmonic currents

smoothing Reactor

A sufficiently large series reactor is used on DC side to smooth DC current and also for protection. The reactor is designed as a linear reactor & it is connected on the line side, neutral side or at intermediate location.

4 filters There are 3 types of filters used

1) AC filters These are used to provide low impedance, shunt paths for AC harmonic currents. Both tuned and damped filter arrangements

DC filters These are similar to AC filters and are used for the filtering of DC harmonics

High frequency filters

These are connected between the converter transformer and the station AC bus to suppress any high frequency currents.

Applications of DC Transmission system :-

1. long distance bulk power Transmission

2. underground or underwater Cables

3. Asynchronous interconnection of AC systems operating at different frequencies

4. control and ~~station~~ stabilization of power flows in AC ties in an integrated power system.

Disadvantages of DC Transmission

1) The difficulty of breaking DC currents which ~~not~~ results in high cost of DC breakers

2) Inability to use transformers to change voltage levels

3) High cost of conversion equipment.

4) Generation of harmonics which require AC & DC filters adding to the cost of converter stations.

5) complexity of control

Above disadvantages are overcome by

1) Development of DC breakers

2) Modular Construction of Thyristor valves

3) Increase in the ratings of ~~the~~ Thyristor cells that make up a valve

4) 12 pulse operation of converters

5) use of metal oxide, gapless arrestors

6) Application of digital electronics and fiber optics in control of converters

Planning for HVDC Transmission

The system planner must consider DC alternative in transmission expansion. The factors to be considered are (i) cost

(ii) Technical performance

(iii) Reliability

For submarine, cable transmission and interconnecting 2 systems of different nominal frequencies. The choice is DC Transmission. In other cases the choice is based on detailed Technical Economic consideration.

The consideration in the planning for DC depends on the application ① long distance bulk power transmission

② Inter connection between 2 adjacent systems

In the first application, the DC & AC alternatives are likely to have the same power carrying capability. Thus the cost comparision would form the basis for the selection of DC (or AC) Alternatives.

→ The second application, AC interconnection poses several problems thus the choice of DC interconnection will be based on the following assumptions

1) small fluctuations in the voltage and frequency do not affect the power flow

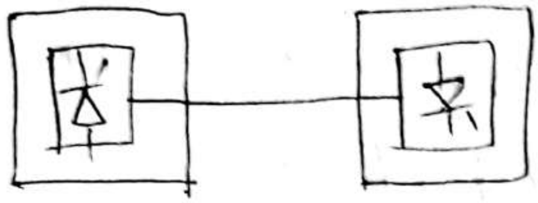
2) The system security can be enhanced by fast control of DC power

ASYNCHRONOUS Interconnections :-

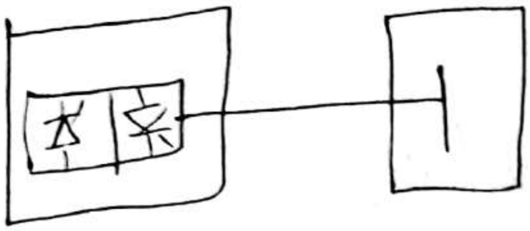
There are 3 possible configuration for interconnection

There are

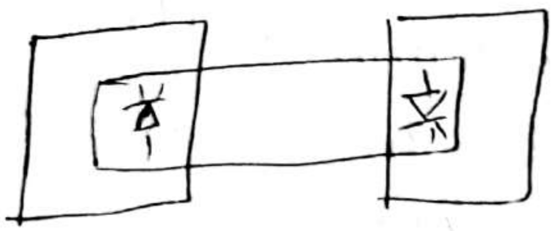
1) A 2 terminal transmission where each terminal is located at a suitable place and connected by a DC over head line or cable.



2) Back to Back HVDC station located some where within one of the network and an ac line from the other network to the common station.



3. A back to back station located close to the border between the two systems



In the choice between the first and second configuration it is to be noted that converter costs are less for the common coupling station and the AC line costs are greater than the DC line costs.

If the distance involved are less than 200km 2nd configuration is to be prefered.

If the short circuit ratio (SCR) is acceptable then the 3rd will be the most economic.

The following aspects also require a detailed study of the system interactions.

1) var requirements of converter stations and voltage stability

2) Dynamic over voltages

3) Harmonic generation & design of filters.

4) Damping of low frequency and subsynchronous torsional oscillations.

5) carrier frequency interference caused by spiky currents in valves due to discharge of stray capacitancy and snubber circuits.

choice of voltage level

For long distance bulk power transmission the voltage level is chosen to minimize the total costs for a given power level (P). The total costs include investment (C_1) and cost of losses (C_2). The investment costs ~~of losses~~ per unit length are modeled as

$$C_1 = A_0 + A_1 n V + A_2 n a \quad \text{— (1)}$$

where V is the voltage level w.r.t ground

n is the number of conductors

a is the total cross section of conductor

A_0, A_1 & A_2 are the constants.

The cost of losses per unit length is given by

$$C_2 = \frac{n\left(\frac{P}{nV}\right)^2 \rho T L p}{a} \quad \text{--- (2)}$$

where ρ - conductor resistivity

T = total operation time in a year

L = loss load factor = $\frac{\text{Avg power loss over a period of Time}}{\text{losses at the time of peak demand}}$.

from eq (2)

$$C_2 = \frac{n\left[\frac{P^2}{n^2V^2}\right]\rho T L p}{a}$$

$$C_2 = \frac{P^2 \rho T L p}{n V^2 a}$$

$$C_2 = \frac{\left(\frac{P}{V}\right)^2 A_3 \rho}{na} \quad \text{--- (3)} \qquad \text{where } A_3 = TLp$$

If sum of 3rd term C_1 & C_2 = 0

$$A_2 na + \frac{\left(\frac{P}{V}\right)^2 A_3 \rho}{na} = 0$$

$$na\left[A_2 + \frac{\left(\frac{P}{V}\right)^2 A_3 \rho}{(na)^2}\right] = 0$$

But $na \neq 0$ [Because n is the no of conductors, a is the area of cross section]

so $$A_2 + \frac{\left(\frac{P}{V}\right)^2 A_3 \rho}{(na)^2} = 0$$

$$A_2 = \frac{-\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{(na)^{\gamma}}$$

$$(na)^{\gamma} = \frac{-\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{A_2}$$

so $$(na)^{\gamma} = \frac{\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{A_2}$$

$P = +ve$ $\rho = +ve$

$V_2 = +ve$

so A_3 & A_2 are constants.

$$na = \sqrt{\frac{\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{A_2}}$$

$$\boxed{na = \left(\frac{P}{V}\right)\sqrt{\frac{\rho A_3}{A_2}}}$$

subtitute na value in C_1 and C_2

$$C_1 = A_0 + A_1 mv + A_2 na$$

$$= A_0 + A_1 mv + A_2 \left[\left(\frac{P}{V}\right)\sqrt{\frac{\rho A_3}{A_2}}\right]$$

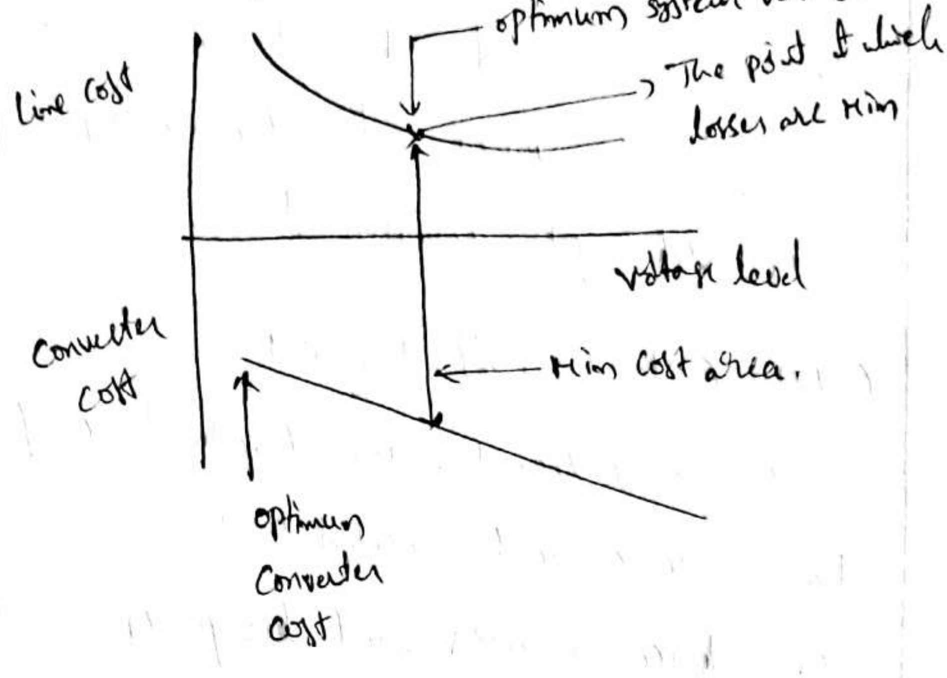
$$C_1 = A_0 + A_1 mv + \left(\frac{P}{V}\right)\sqrt{\rho A_3}\sqrt{A_2} \quad \text{— (4)}$$

$$C_2 = \frac{\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{na}$$

$$= \frac{\left(\frac{P}{V}\right)^{\gamma} \rho A_3}{\left(\frac{P}{V}\right)\sqrt{\frac{\rho A_3}{A_2}}}$$

$$C_2 = \left(\frac{P}{V}\right)\sqrt{\rho A_2 A_3} \quad \text{— (5)}$$

Based upon voltage level, line cost & converter ~~cost~~ ckt the optimum system voltage & optimal converter cost can be determined by back to back system.



Modern Trends in HVDC Technology

The continuing technological developments in the areas of power semiconductor devices, digital electronics, adaptive control, DC protection equipment have increased the pace of application of DC Transmission. The major contribution of these developments is to reduce the cost of converter stations while improving the reliability and performance.

Power semiconductors and values

The cost of the converters can come down if the no of devices to be connected in series and parallel can be brought down. The development of light triggered thyristors (LTT) should also improve the reliability of converter operation.

The rating of thyristors is increased by better cooling methods. Deionized water cooling has now became a standard and results in reduced losses in cooling. The power rating of converter (12 pulse) has increased upto 3000MW at 500KV.

GTO Gate turn off Thyristors are already available at 6KV and 4000A. The disadvantage of GTO's is the large gate current needed to turn off them. In contract IGBT device requires much less power and has high switching speeds.

Converter control

The development of microcomputer based converter control equipment has now made it possible to design systems with completly redundant converter control with automatic transfer between systems in case of malfunction.

Traditionally the DC is measured using Transducers of zero flux type based on magnetics, which are bulky and affected to problems during Transients. Recently hybrid-optical measuring systems are using. future developments will employ simplified construction through application of the fiber optic current measurement system based on faradays effect.

DC breakers

with the development and testing of prototype DC breakers, it will be possible to go in for tapping an existing a link or the development of new MTDC system. parallel, rather than series operation of converters is likely as it allows certain flexibility in the planned growth of a system.

Conversion of existing Ac lines

Conversion of existing AC circuits to DC in order to increase the power transfer limit.

operation with weak Ac system.

The strength of AC systems connected to the terminals of a DC link is measured in terms of SCR

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

If SCR < 3 It is a weak system.

constant reactive power control or AC voltage control have been suggested to overcome some of the problems with weak AC system. The use of static var systems is another alternative.

Limiting dynamic over voltages through converter control during load rejection is becoming a standard practice.

Active Dc filters

A hybrid filter ~~made up~~ made up of an active filter in series with the ~~pasive~~ passive filter has been developed to improve the filtering of harmonic currents flowing in HVDC lines.

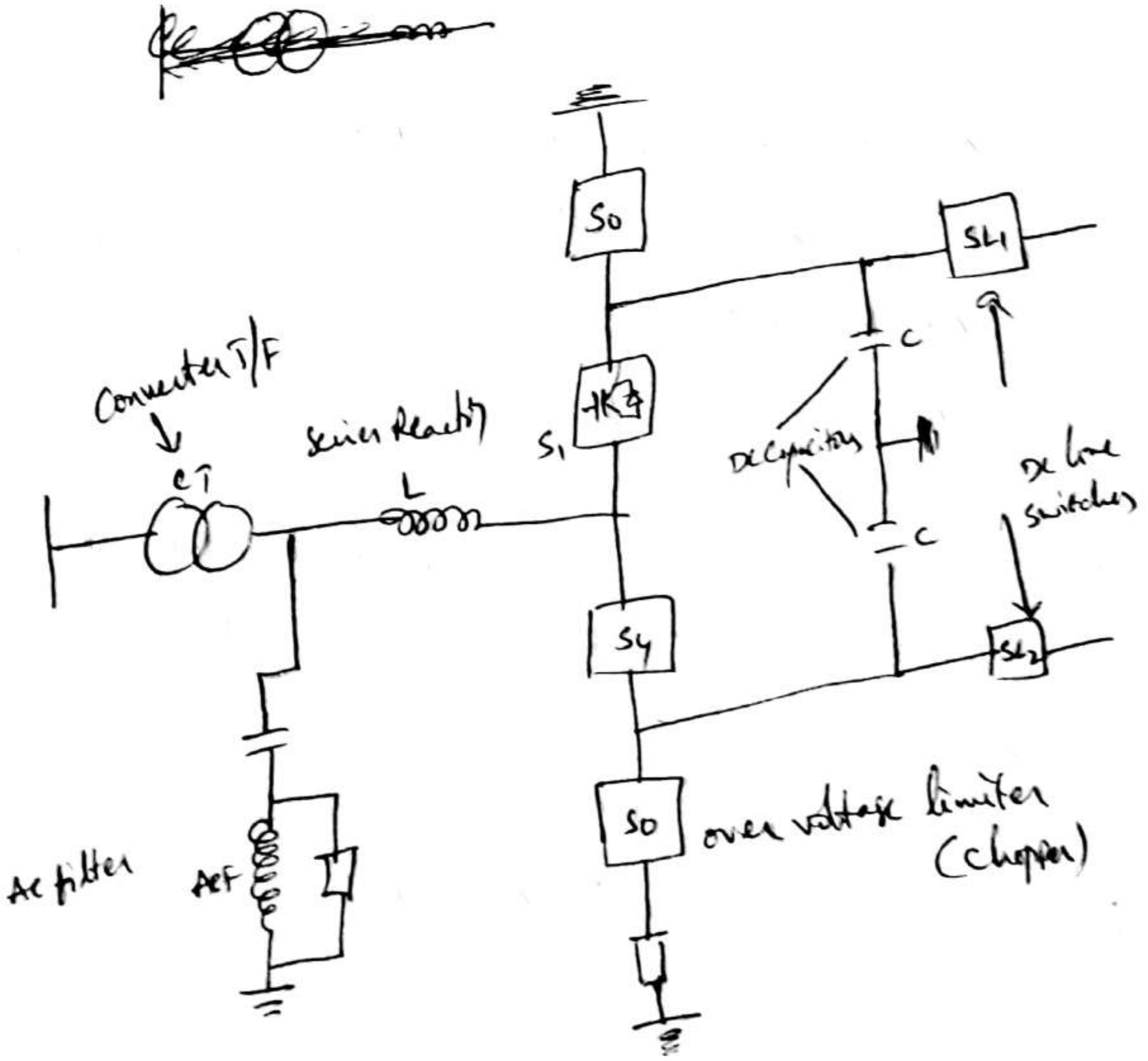
Capacitor commutated converter:-

It includes the connection of commutation capacitors in series with the valve side windings of the converter Transformer.

The advantage of CCC are

1) improved voltage stability when operating with weak AC system.
2) Reduced Risks of commutation failures
3) less load rejection overvoltages and reactive power requirement

VSC based HVDC Converter station.



" S_1, S_4 → IGBT valves in one phase"

A single line diagram of a VSC based HVDC converter station.

VSC based HVDC links are also applied for power transfer from off shore wind power plants and supply to off shore platforms. A single line diagram of a VSC station is shown above.

The major components at a converter station (excluding surge arrestor and circuit breakers) are shown in the diagram.

The series reactor is used to isolate the infected voltage by the VSC from the converter bus and limit the current harmonics.

The converter transformer is the normal AC transformer with only sinusoidal voltages and currents in steady state.

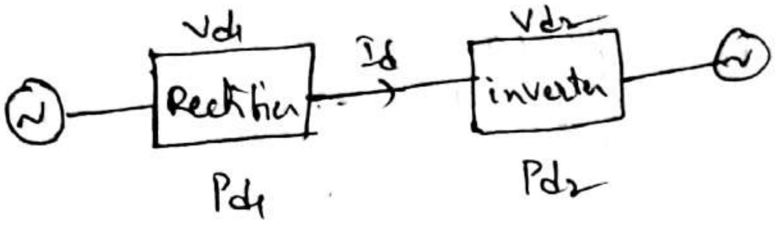
A seperate series connected R, & PLC filters can be used to eliminate very high frequencies

over voltage limiter (chopper) is required for fast discharge of the DC capacitor if the DC voltage exceeds the maximum DC bus voltage for deblocked converter.

IV Unit

Analysis of HVDC Converters

Power flow control in HVDC



The dc power 'Pd' in controller by adjusting the voltage between rectifier voltage 'Vd1' and inverter voltage 'Vd2' to get desired dc current 'Id'

$$I_d = \frac{V_{d1} - V_{d2}}{R}$$

where R = Resistance of DC Circuit

V_{d1} = o/p voltage at rectifier station

V_{d2} = o/p voltage at inverter Station

I_d = Flow of current in HVDC link

Here V_{d2} is controlled by inverter terminal

$I_{d1} = I_{d2} = I_d$ is controlled by rectifier terminal

The dc power at rectifier end is

$$P_{d1} = V_{d1} I_{dc}$$

$$= V_{d1}\left(\frac{V_{d1}-V_{d2}}{R}\right)$$

$$= \frac{V_{d1}^2}{R} - \frac{V_{d1}V_{d2}}{R}$$

The power supplied to DC line by rectifier terminal is proportional to square of direct voltage.

The dc power at inverter end is

$$P_{d2} = V_{d2} I_d$$

$$= V_{d2}\left(\frac{V_{d1}-V_{d2}}{R}\right)$$

$$= \frac{-V_{d2}^2}{R} + \frac{V_{d1}V_{d2}}{R}$$

The -ve sign of 1st term indicates that the power is received by inverter end.

Power loss in DC circuit

This is given by the difference between power of rectifier and power of inverter

$$\boxed{P_L = P_{d1} - P_{d2}}$$

$$= V_{d1}I_{d1} - V_{d2}I_{d2}$$

$$= (V_{d1} - V_{d2})\, I_d$$

$$= (V_{d1} - V_{d2})\frac{(V_{d1} - V_{d2})}{R}$$

$$P_L = \frac{(V_{d1} - V_{d2})^2}{R}$$

By increasing the difference between V_{d1} & V_{d2} the dc power flow and power loss increases

<u>power loss in the middle of DC line</u>

$$P_{dm} = \frac{P_{d1} + P_{d2}}{2}$$

$$= \frac{\left[\frac{V_{d1}^2}{R} - \frac{V_{d1}V_{d2}}{R}\right] + \left[-\frac{V_{d2}^2}{R} + \frac{V_{d1}V_{d2}}{R}\right]}{2}$$

$$\boxed{P_{dm} = \frac{V_{d1}^2 - V_{d2}^2}{2R}}$$

<u>power at sending end P_{d1}</u>

P_{d1} = Power in middle + $\frac{1}{2}$ total loss

$$= \frac{V_{d1}^2 - V_{d2}^2}{2R} + \frac{(V_{d1} - V_{d2})^2}{2R}$$

<u>Power at receiving end P_{d2}</u>

P_{d2} = Power in middle $- \frac{1}{2}$ Total loss

$$= P_{dm} - \frac{1}{2} P_L$$

$$\frac{V_{d1}^2 - V_{d2}^2}{2R} - \frac{(V_{d1} - V_{d2})^2}{2R}$$

General equation for DC power flow

$$P_d = \frac{V_{d1}^2 - V_{d2}^2}{2R} \pm \frac{(V_{d1} - V_{d2})^2}{2R}$$

Problem (i)

A bipolar 2 terminal HVDC link is delivering 1000 MW at ±500 kV at the receiving end, total losses in DC circuit are 60 MW calculate (i) sending end power (ii) power in the middle of line (iii) sending end voltage (iv) voltage at middle of line (v) Total resistance of the DC circuit

→ (i) sending end power = receiving end power + losses

= 1000 + 60

= 1060 MW

(ii) power in the middle = Receiving end power + ½ losses

P_{dm} = 1000 + 30

= 1030 MW

(iii) sending end voltage

$$I_d = \frac{P_{d2}}{V_d}$$

$$= \frac{1000 \times 10^6}{1000 \times 10^3} = 1000 \text{ Amps}$$

$P_{d1} = 1060 \text{ MW}$

$$V_{d1} = \frac{P_{d1}}{I_d} = \frac{1060 \times 10^6}{1 \times 10^3}$$

$= 1060$ KV pole-pole

$= \pm 530$ KV pole to earth

(iv) voltage at middle of line

$$V_{dm} = \frac{V_{d1} + V_{d2}}{2}$$

$$= \frac{1060 + 1000}{2} = 1030 \text{ KV}$$

$= \pm 515$ KV

(v) Total resistance

$$P_L = I_d^2 R$$

$$60 \times 10^6 = (1 \times 10^3)^2 R$$

$$R = 60\ \Omega$$

(2) A bipolar 2 terminal HVDC Transmission system has a 12 pulse converter per pole at each Terminal. The system has following data.

Rated dc voltage Vd = ±500 kV

Rated bipolar power = 1500 MW

Line Resistance/pole = 5Ω

DC voltage at Rectifier end = ±500 kV

Rectifier terminals feeds Rated power dc line

calculate (i) DC line current (2) DC line losses (3) inverter end DC voltage (4) DC power delivered to inverter end (5) DC voltage of 6 pulse converter at Rectifier end (6) DC voltage of 6 pulse converter at inverter end (7) Bipolar DC voltage of Rectifier (8) Bipolar DC voltage of inverter.

⇒ Rated power/pole $= \frac{1500}{2} = 750\,MW$

(i) Rated dc current $I_d = \frac{P_d}{V_d} = \frac{750 \times 10^6}{500 \times 10^3}$

$= 1500$ Amp

(2) DC line loss per pole

$P_L = I_d^2 R$

$= 1500^2 \times 5$

$= 11.25\,MW$

Rectifier end DC power P_{d1} = 750 MW per pole.

(3) DC voltage at inverter end/pole

$$V_{d2} = V_{d1} - I_d R$$
$$= 500 - 1.5 \times 5$$
$$= 492.5 \text{ kV}$$

(4) inverter end DC power

$$P_{d2} = P_{d1} - P_L$$
$$= 750 - 11.25$$
$$= 738.75 \text{ MW}$$

Bipolar DC power at inverter end $= 2 \times 738.75$
$= 1477.5$

⇒ DC voltage of 6 pulse bridge = 0.5 voltage of 12 pulse

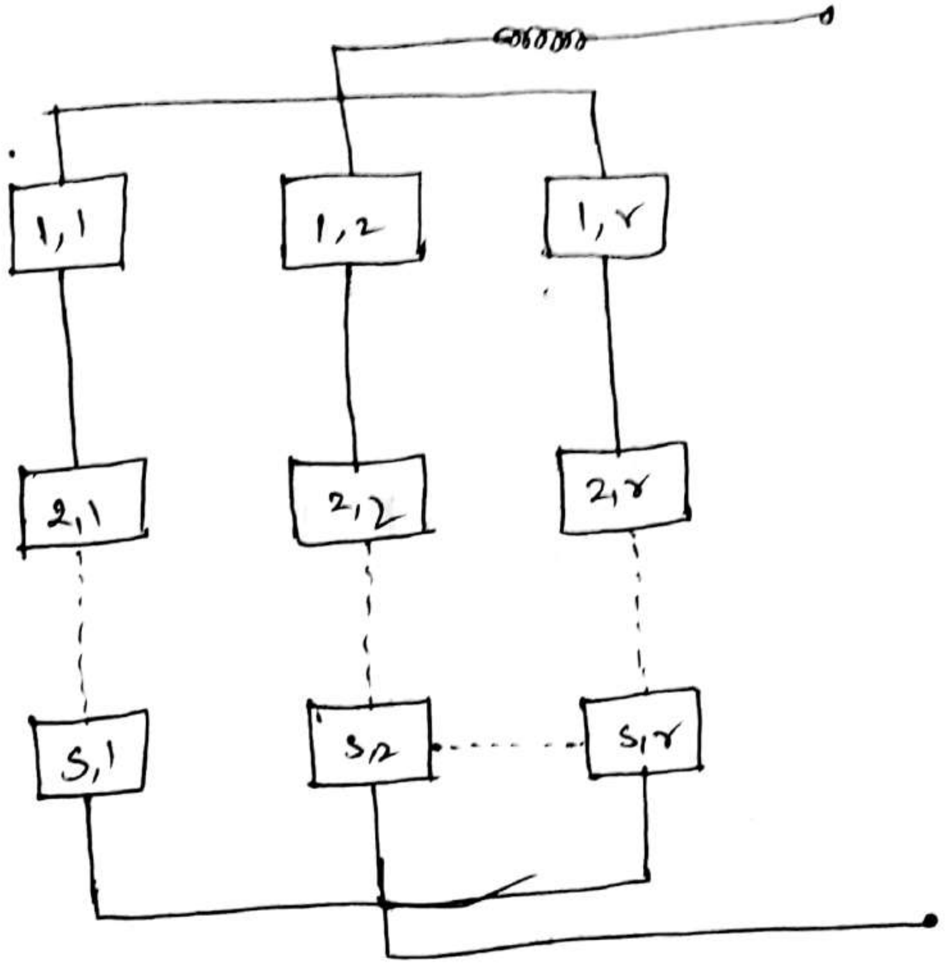
DC voltage of Rectifier 6 pulse bridge $= \frac{500}{2} = 250$

DC voltage of inverter 6 pulse bridge $= \frac{492.5}{2} = 246.25$

Bipolar voltage at inverter end $= 2V_{d2}$
$$= 2 \times 492.5$$
$$= 985 \text{ kV}$$

Rectifier end $= 2V_{d1}$
$$= 2 \times 500$$
$$= 1000 \text{ kV}$$

Choice of converter configuration.



The configuration for a given pulse number is selected in such a way that valve & Transformer utilization are maximum.

In general the converter configuration can be defined by basic commutation groups and the no of such groups series and parallel.

If there are 'q' valves in basic commutation group and 'r' of these are connected in parallel & 's' no of them connected in series then the pulse no is

$$p = qrs$$

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The valve ratings are specified in terms of peak inverse voltage. The ratio of peak inverse voltage to the average dc voltage in the index of valve utilization

$$V_d = \frac{Sq}{2\pi} \int_{-\pi/q}^{\pi/q} V_m \cos\omega t \, d\omega t$$

$$= \frac{Sq}{2\pi} V_m \, 2 \sin\left(\frac{\pi}{q}\right)$$

$$\boxed{V_d = \frac{Sq}{\pi} V_m \sin\left(\frac{\pi}{q}\right)}$$

when 'q' is even then max 'PIV' occurs when the valve with a phase shift of 'π' radians is conducting then

$$\boxed{PIV = 2 V_{max}}$$

when 'q' is odd then max PIV which occurs when the valve with a phase shift of $\left(\pi \pm \frac{\pi}{q}\right)$ then

$$PIV = 2 V_{max} \cos\left(\frac{\pi}{2q}\right)$$

valve utilization factor

$$= \frac{PIV}{V_{do}} = \frac{2\pi}{Sq \sin\left(\frac{\pi}{q}\right)} \quad \underline{q = even}$$

$$= \frac{\pi}{Sq \sin\left(\frac{\pi}{2q}\right)} \quad \underline{q = odd}$$

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T/F rating on valve side (S_{tv})

Valve current $I_v = \frac{I_d}{r\sqrt{q}}$

$S_{tv} = V I$

$= P \frac{V_m}{\sqrt{2}} I_v$

$= \frac{P V_{do} \pi}{\sqrt{2} \, sq \sin(\frac{\pi}{q})} \frac{I_d}{r\sqrt{q}}$

$= \frac{\pi}{\sqrt{2}} \frac{V_d I_d}{\sqrt{q} \sin(\frac{\pi}{q})}$ [P = qrs]

The Transformer ~~factor~~ utilization factor.

$T/F \ UF = \frac{S_{tv}}{V_{do} I_d}$

$$T.UF = \frac{\pi}{\sqrt{2}} \frac{1}{\sqrt{q} \sin(\frac{\pi}{q})}$$

The utilization factor is only a function of 'q' so the optimum value of 'q' which results max utilization for q=3

T.U.F is 1.485

=) The T/F utilization factor can be improved when two valves groups share a single T/F winding. In this case the current rating of winding can be increased by a factor of $\sqrt{2}$ while decreasing the no of windings with a factor of 2 hence

$$T.UF = 1.485 \times \frac{\sqrt{2}}{2}$$

$$= 1.047$$

when $q=3$

$$\text{valve rating} = \frac{\pi}{Sq \sin\frac{\pi}{2q}}$$

$$= 2.094$$

for a perticular pulse No

P	q	r	S	VUF (valve utilization factor)	T/F utilization factor
6	2	1	3	1.047	
	2	3	1	3.142	1.57
	3	1	2	1.047	1.485
	3	2	1	2.094	
	6	1	1	2.094	

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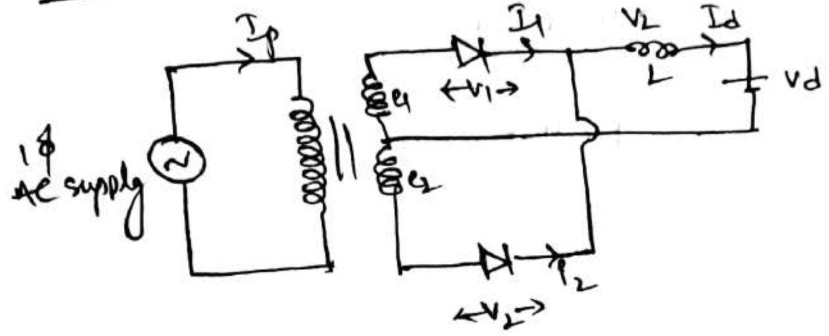
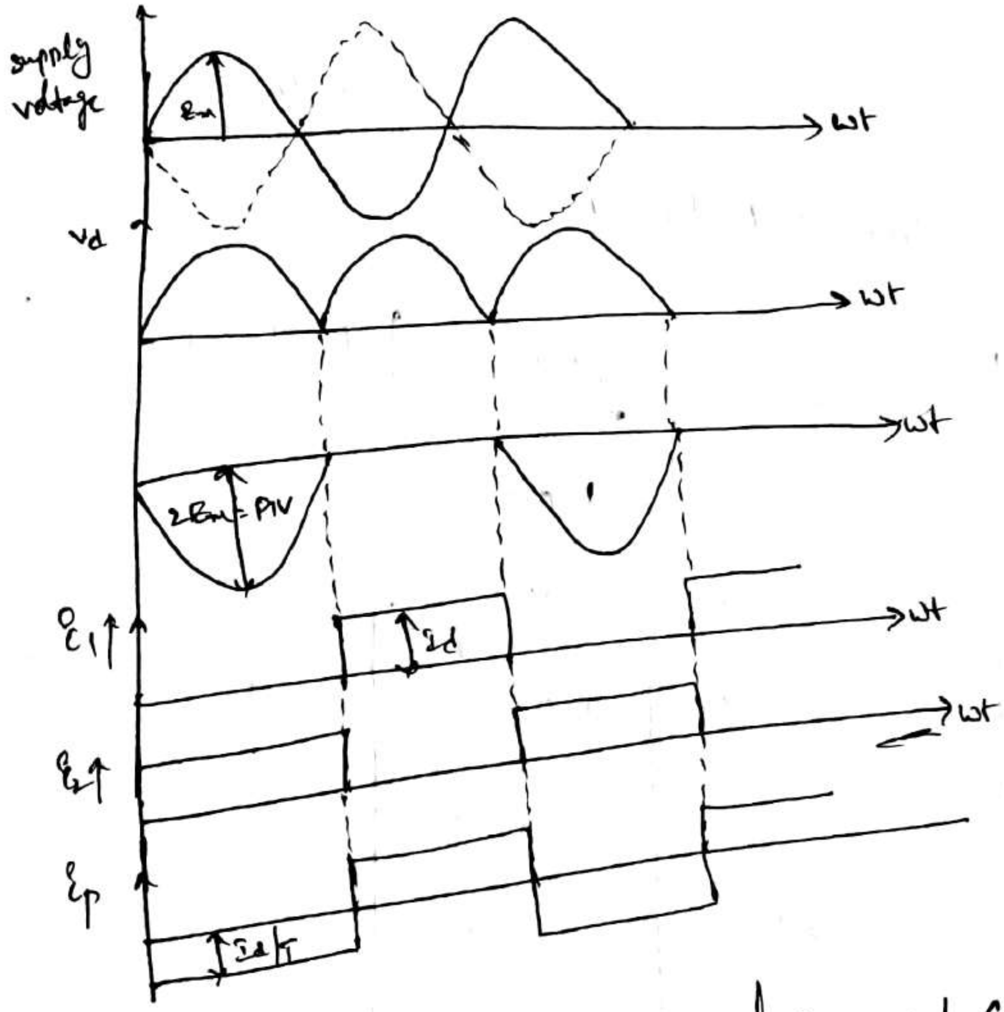
choice of best circuit for HVDC Converter

① 1-Φ FW Rectifier





In this circuit contains two valve, and center tap transformers. The line to neutral secondary voltages e_1 and e_2 having a phase difference of 180^0

During +ve half cycle valve 1 conducts and during -ve half cycle valve 2 conducts.

when valve 2 in conducting, the total secondary voltage appears across valve 1 is ~~e~~ e_1, similarly when valve 1 is conducting $e_2 - e_1$ appears across valve 2.

voltage

(i) Average voltage is

$$V_d = \frac{1}{\pi} \int_0^{\pi} E_m \sin\omega t \, d\omega t$$

$$= \frac{E_m}{\pi} \left[-\cos\omega t \right]_0^{\pi}$$

$$V_d = \frac{2E_m}{\pi}$$

$$\boxed{E_m = \frac{\pi}{2} V_d}$$

(ii) Peak inverse voltage

$$PIV = 2E_m$$

currents

$$I_{d\,avg} = \frac{I_d}{2}, \quad I_{d\,avg} = \frac{1}{2\pi} \int_0^{\pi} i_d \, d\omega t$$

$$\boxed{I_{d\,avg} \Rightarrow \frac{i_d}{2}}$$

$$I_{d\,rms} = \sqrt{\frac{1}{2\pi} \int_0^{\pi} i_d^2 \, d\omega t}$$

$$\boxed{I_{d\,rms} = \frac{i_d}{\sqrt{2}}}$$

VA rating of valve

VA rating of valve = PIV × I_{avg}

For 1-ϕ Full wave converter

$= 2\,PIV \times I_{avg}$

$= 2 \cdot 2 E_m \frac{I_d}{2}$

$= 2 \frac{\pi}{2} V_d I_d$

VA rating = 3.142 P_d

T/F rating

T/F 2ndry rating $= 2 \times I_{rms} \times E_{rms}$

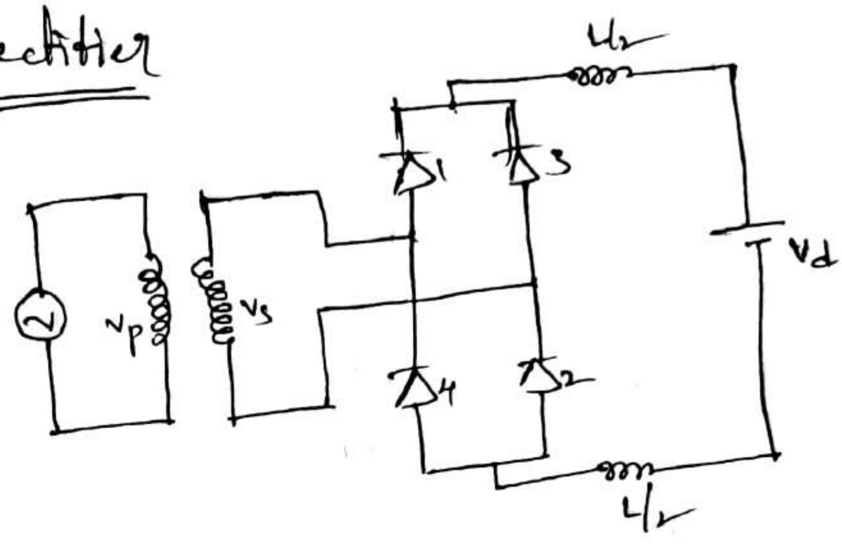
$= 2 \times \frac{I_d}{\sqrt{2}} \times \frac{\pi}{2\sqrt{2}} I_d$ $\qquad E_{rms} = \frac{E_m}{\sqrt{2}}$

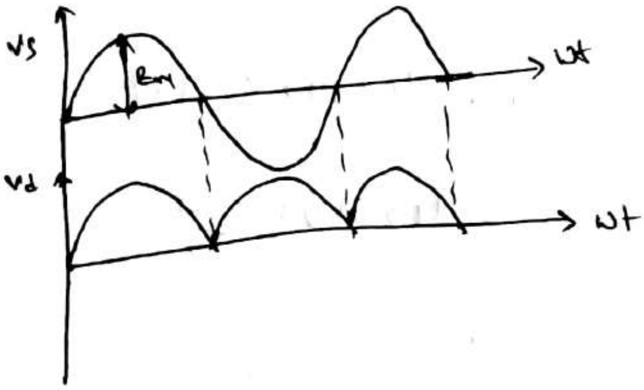
$= \frac{\pi}{2} V_d I_d$

T/F 2ndry rating = 1.571 P_d

IIly **T/F pry rating = 1.11 P_d**

Bridge Rectifier





During +ve half cycle of AC supply value 1 and 2 are conduct load side voltage is same as source. During -ve half cycle value 3 & 4 are conducting the load voltage.

~~and~~ The bridge circuit is more complecated than the full wave circuit because it has four values instead of two, the secondary winding is used more effectively and the PIV of each value has been halved for a given DC ~~voltage~~ output voltage.

Voltage

$$V_d = \frac{1}{\pi}\int_0^{\pi} E_m \sin \omega t \, d\omega t$$

$$V_d = \frac{2E_m}{\pi}$$

$$\boxed{E_m = \frac{\pi}{2} V_d}$$

$PIV = E_m$

currents

$$I_{d\,avg} = \frac{I_d}{2}$$

$$I_{d\,rms} = \frac{I_d}{\sqrt{2}}$$

value rating

VA rating of all values $= 4 \times PIV \times I_{d\,avg}$

$$= 4 \times \frac{\pi}{2} V_d \times \frac{I_d}{2}$$

$$= \pi I_d V_d$$

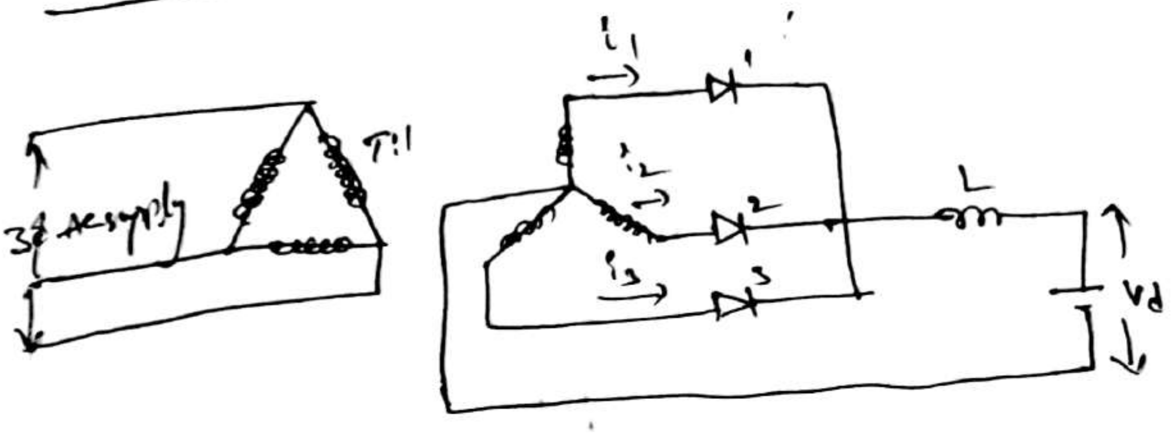
values rating $= 3.14 P_d$

T/F rating

VA rating of 2ndry winding =

Pry winding $= 1.11 P_d$

Three-phase rectifier



For large amount of power is required we go for 3φ rectifier.

In this circuit direct current in the secondary winding saturates the transformer cores. To avoid saturation Y connection is replaced by the zig-zag connection.

(i) Average voltage

$$V_d = \frac{1}{\frac{2\pi}{3}} \int_{30}^{150} E_m \sin\omega t \, d\omega t$$

$$= \frac{3\sqrt{3}}{2\pi} E_m$$

$$E_m = \frac{2\pi}{3\sqrt{3}} V_d$$

(ii) $PIV = \sqrt{3} E_m$

currents

$$I_{d\,avg} = \frac{1}{2\pi}\int_{30}^{150} i_d \, d\omega t$$

$$\boxed{I_{d\,avg} = \frac{I_d}{3}}$$

$$I_{d\,Rms} = \left[\frac{1}{2\pi}\int_{30}^{150} i_d^2 \, d\omega t\right]^{1/2}$$

$$= I_d/\sqrt{3}$$

VA rating of valves

= No of valves × PIV × Avg current

$$= 3 \times \sqrt{3}\, E_m \times \frac{I_d}{3}$$

$$= 3 \times \sqrt{3}\, \frac{2\pi}{3\sqrt{3}} V_d \times \frac{I_d}{3}$$

$$= \frac{2}{3}\pi\, V_d I_d \Rightarrow 2.094\, P_d$$

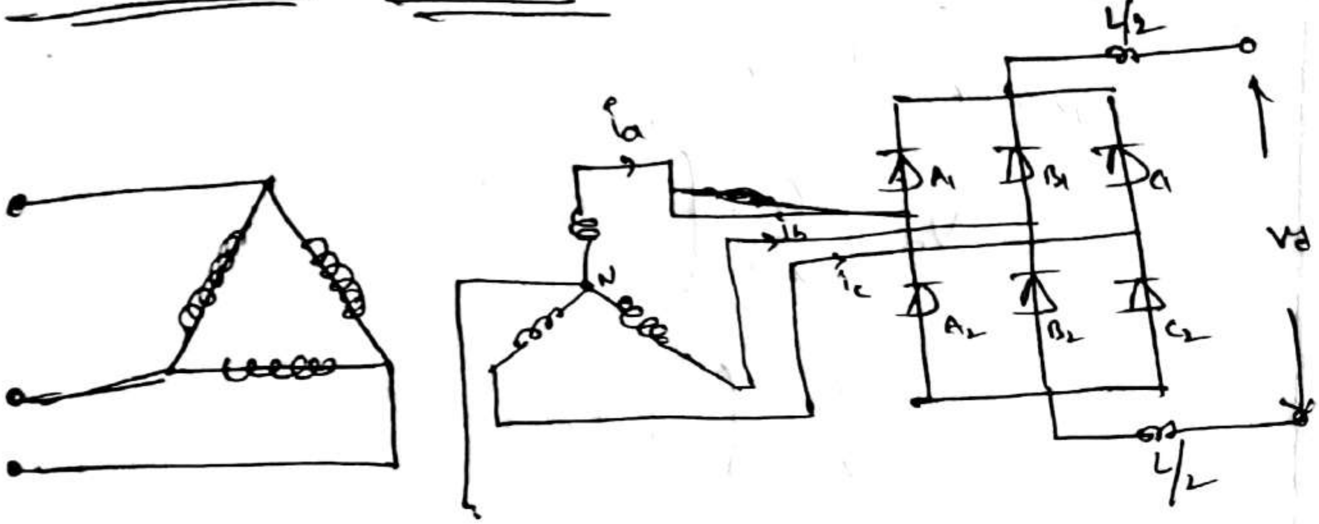
T/F rating 2ndry wdg

$$\rightarrow 3 \times I_{rms} \times E_{rms}$$

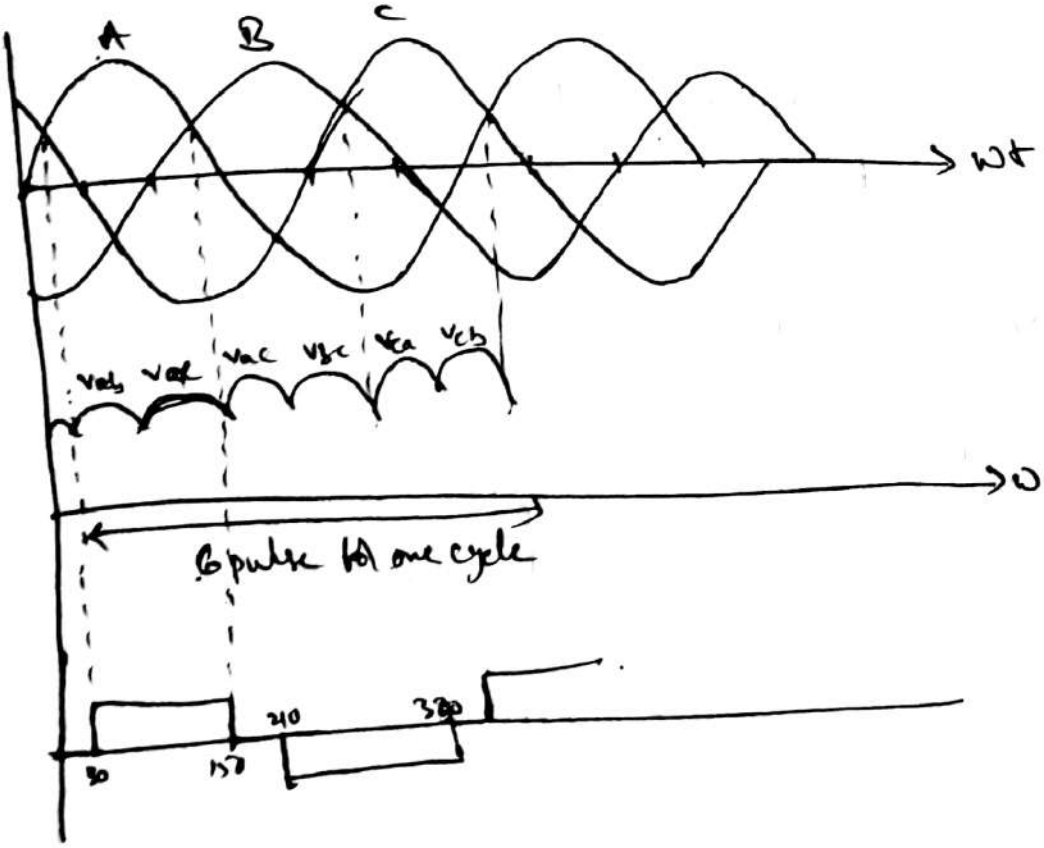
$$\Rightarrow 3\, \frac{I_d}{\sqrt{3}} \times \frac{\frac{2\pi}{3\sqrt{3}} V_d}{\sqrt{2}}$$

$$= 1.481\, P_d.$$

3φ Bridge Rectifier



In the 3φ mid point rectifier load voltage is equal to line to neutral voltage and it is line-line voltage. In this circuit upper group devise will conduct when supply voltage is most +ve where as lower group device will conduct when supply voltage is most -ve



voltages

Average voltage

$$V_d = \frac{6}{2\pi}\int_{30}^{90} V_{AB}\, d\omega t$$

$$= \frac{6}{2\pi}\int_{30}^{90} \sqrt{3} E_m \sin(\omega t + 30^\circ)\, d\omega t$$

$$V_d = \frac{3\sqrt{3} E_m}{\pi}$$

(or)

$$V_d = \frac{6}{2\pi}\int_{30}^{150} V_m \sin\omega t$$

$$= \frac{3}{\pi} V_m \left(\frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}\right)$$

$$= \frac{3\sqrt{3}}{\pi} V_m$$

$$\boxed{V_m = \frac{\pi}{3\sqrt{3}} V_d}$$

PIV = ~~$\sqrt{3}E_m$~~ $\sqrt{3} E_m$

currents

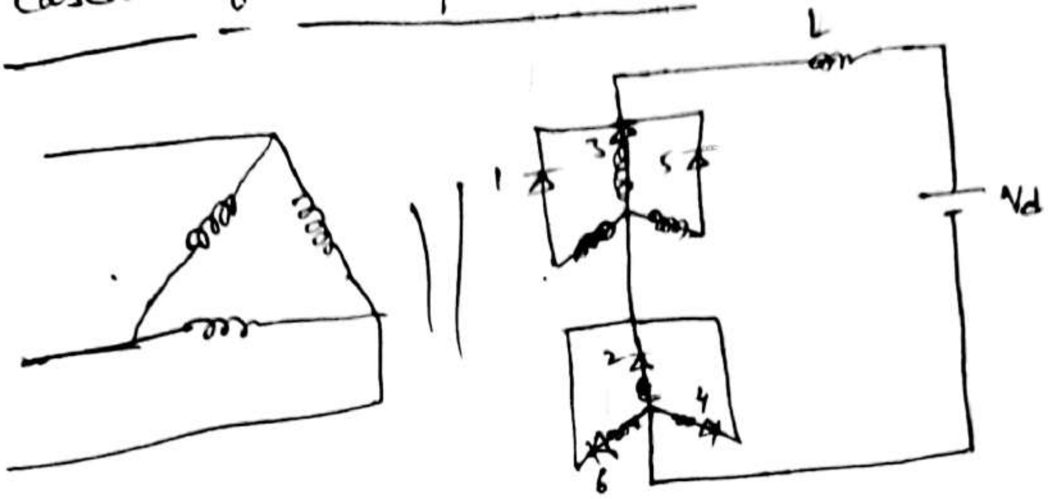
$$I_{avg} = \frac{1}{2\pi}\int_{30}^{150} I_d\, d\omega t$$

$$= I_d/3$$

$$I_{rms} = \frac{1}{2\pi}\left[\int_{30}^{150} I_d^2\, d\omega t + \int_{210}^{330} I_d^2\, d\omega t\right]^{1/2}$$

$$= \sqrt{\frac{2}{3}}\, I_d$$

Cascade of two 3ϕ Rectifiers



In this circuit consists of 6 valves, 2 groups each group consists of three valves. The T/F secondary is connected to double star with 180° phase difference b/w each Y connection.

Voltages

From 1st group of valves

$$V_{d1} = \frac{3}{2\pi}\int_{30}^{150} E_m \sin\omega t \, d\omega t$$

$$= \frac{3E_m}{2\pi}\left(\frac{\sqrt{3}}{2}+\frac{\sqrt{3}}{2}\right)$$

$$\boxed{V_{d1} = \frac{3\sqrt{3}E_m}{2\pi}}$$

similarly 2nd group of valves

$$V_{d2} = \frac{3\sqrt{3}}{2\pi}E_m$$

∴ Total average output voltage $\boxed{V_d = \frac{3\sqrt{3}E_m}{\pi}}$

$$E_m = \frac{\pi}{3\sqrt{3}} V_d$$

$PIV = \sqrt{3} E_m$

Currents

$$I_{d\,avg} = \frac{I_d}{3}$$

T/F 2ndary RMS current

$$= \sqrt{\frac{I_d^2 \frac{2\pi}{3}}{2\pi}}$$

$$= I_d/\sqrt{3}$$

From Primary side $= \sqrt{\frac{2}{3}} \frac{I_d}{T}$

VA Rating of valves

$$= 6 \times \sqrt{3} E_m \times I_d/3$$

$$= 6 \times \frac{\pi}{3} V_d \frac{I_d}{3}$$

$$= \frac{2}{3}\pi P_d \Rightarrow 2.094\, P_d$$

T/F rating

2ndary wdg rating $= 6 \times V_{rms} \times I_{rms}$

$$= 6 \times 0.428\, V_d \times 0.577 I_d$$

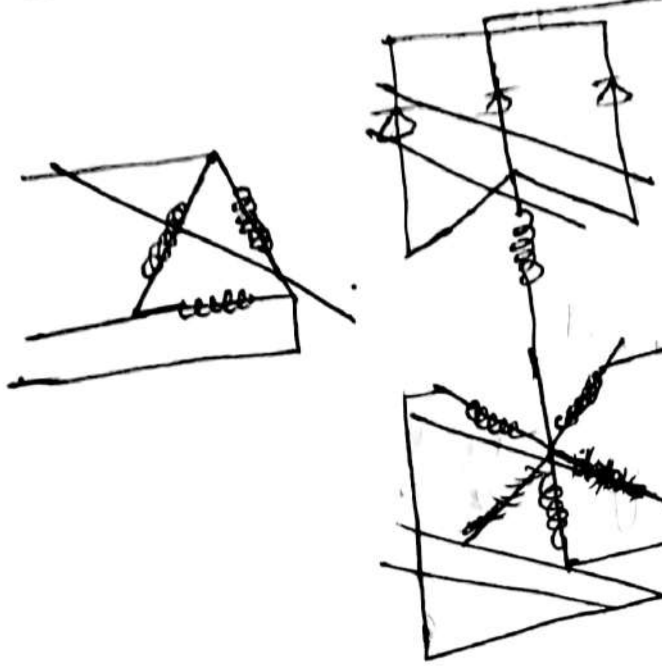
$$= 1.481\, P_d$$

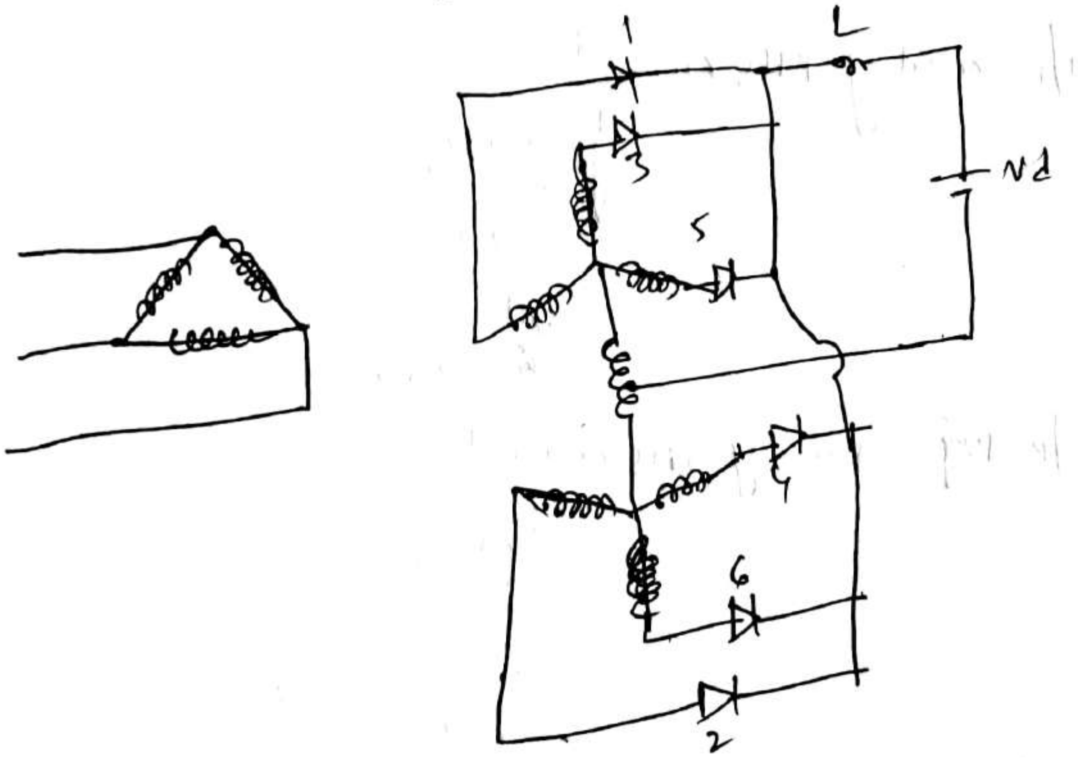
Pry wdg rating $= 3 \times 0.428\, V_d T \times 0.816 \frac{I_d}{T}$

$$= 1.047\, P_d.$$

Y-Y with inter phase T/F (or)

parallel connections with inter phase T/Fs





This circuit is same as previous one except two group of valves are connected through reactor. Interphase reactor is must because two groups are cannot be paralled directly

(i) Average voltage

$$V_d = \frac{3\sqrt{6}}{2\pi} E_m$$

(ii) PIV $= \sqrt{3} E_m$

(iii) value average current

$$I_{davg} = \frac{I_d}{2} \frac{1}{3}$$

$$= \frac{I_d}{6}$$

(IV) T/F secondary RMS current

$$= \sqrt{\frac{\left(\frac{I_d}{2}\right)^2 \frac{2\pi}{3}}{2\pi}}$$

$$= \frac{I_d}{2\sqrt{3}}$$

(V) T/F ~~Rg~~ primary RMS current

$$= \sqrt{\frac{\left(\frac{I_d}{T}\right)^2 \frac{2\pi}{3}}{\pi}}$$

$$= 0.408\, I_d/T$$

~~T/F~~

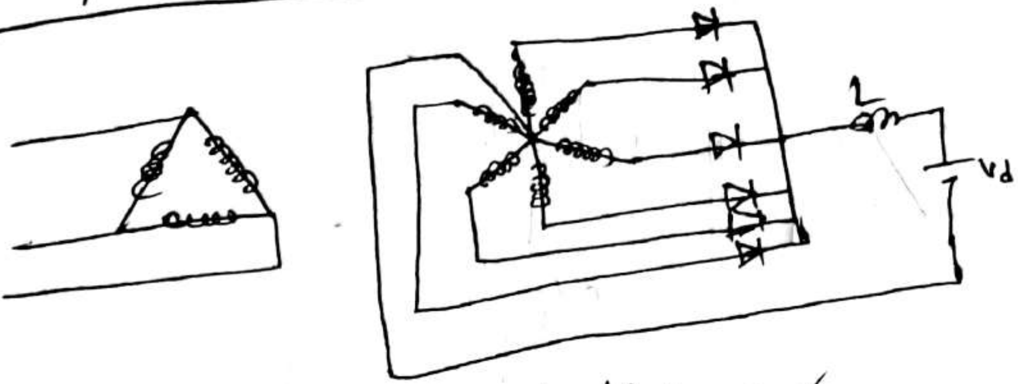
VA rating of all valves $=$ ~~3 ×~~ $6 \times \sqrt{3} E_m \times \frac{I_d}{6}$

$$= 2.094\, P_d$$

T/F 2ndry VA $= 6 \times \frac{\pi}{3\sqrt{3}} V_d \; \frac{I_d}{2\sqrt{3}}$

$$= 1.481\, P_d.$$

six phase connection



In this T/F utilization factor is poor

(i) Avg current $I_d = \frac{I_d}{6} \Rightarrow \left[\frac{1}{2\pi}\int_0^{\frac{\pi}{3}} I_d \, d\omega t\right]$

(ii) T/F 2ndry current $= \sqrt{\frac{I_d^2 \frac{2\pi}{6}}{2\pi}} = 0.408 \, I_d$

(iii) PIV $= 2E_m$

(iv) $V_d = \frac{6}{2\pi}\int_{-\pi/6}^{\pi/6} E_m \cos\theta \, d\theta$

$= 1.351 \, E_m$

(v) T/F 2ndry voltage $= \frac{E_m}{\sqrt{2}}$ = rms value

Value Ratting $\rightarrow 6 \times 2.094 V_d \times 0.167 I_d$

$= 2.094 \, P_d$

T/F rating

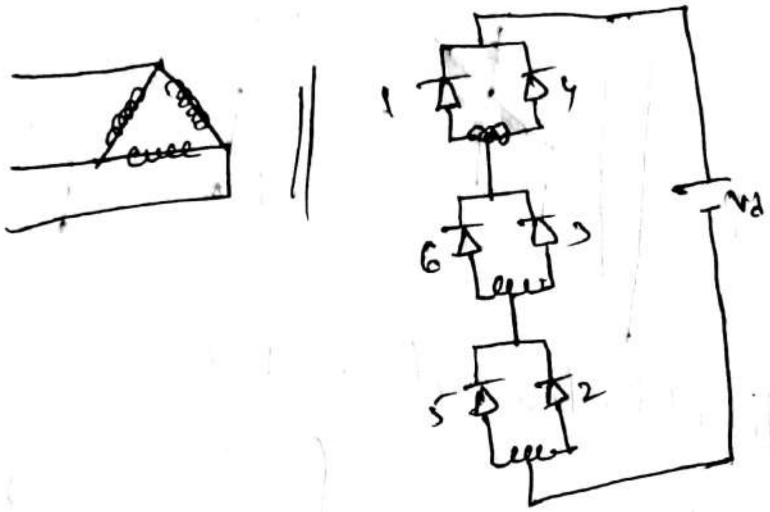
secondary VA rating $= 6 \times 0.74 V_d \times 0.408 I_d$

$= 1.811 \, P_d$

primary VA rating $= 3 \times 0.74 V_d T \times 0.577 \, I_d / T$

$= 1.981 \, P_d$ //

Cascade of 3, 1-ϕ FW Rectifier.



T/F utilization is poor.

- This circuit give a high DC voltage

voltage across each unit $= V_d = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} E_m \cos\theta \, d\theta$

$= \frac{2E_m}{\pi}$

for 3 units $V_d = \frac{6E_m}{\pi}$

$$\boxed{E_m = \frac{\pi}{6} V_d}$$

(i) for each value $V_d = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\omega t$

for each group $V_d = \frac{2}{2\pi}\int_0^{\pi} V_m \sin\omega t$

for 3 groups $V_d = \frac{6}{2\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$

$$\boxed{V_d = \frac{6}{\pi} E_m}$$

PIV = 2Em

currents

value average current

$$I_{d\,avg} = I_d/2$$

RMS value of current $= \sqrt{\dfrac{I_d^2 \pi}{2\pi}}$

$= 0.707\, I_d$

VA rating of valves

$\Rightarrow 6 \times \dfrac{I_d}{2} \times 2E_m$

$\Rightarrow 6 \times \dfrac{I_d}{2} \times 1.047 V_d$

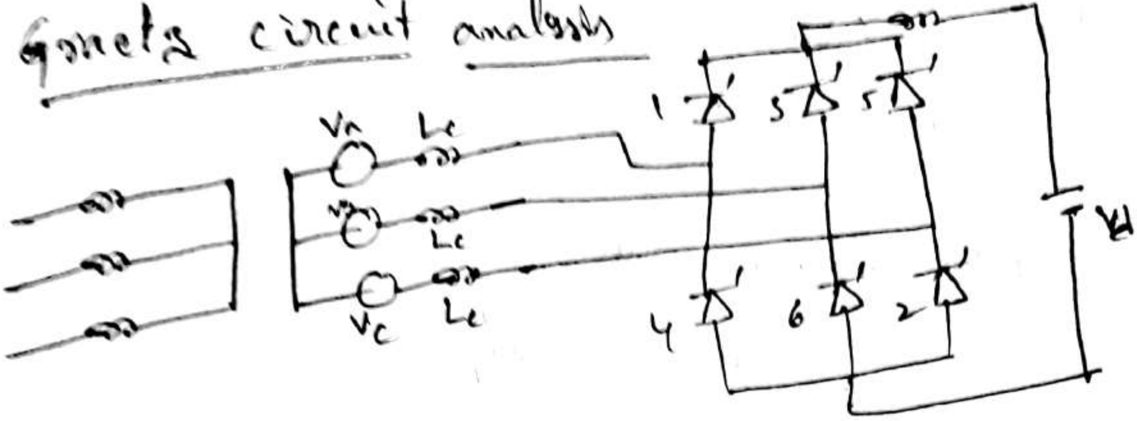
$\Rightarrow 3.142 P_d$

T/F 2ndry VA rating

$= 6 \times 0.37 V_d \times 0.707 I_d$

$= \underline{\underline{1.571 P_d}}$.

Graetz circuit analysis



with out over lap

Grate3 circuit which is operated with out over lap angle then the average o/p voltage is (when value 3, 2 are fired.)

$V_a = V_m \sin \omega t$

$V_b = V_m \sin(\omega t + 120)$

$V_c = V_m \sin(\omega t - 120)$

$V_d = V_b - V_c$ $\qquad V_{ba} = V_m \sin \omega t$

$= V_{bc}$ $\qquad V_{bc} = V_m \sin(\omega t + 60)$

$= V_m \sin(\omega t + 60)$

For a 6 pulse o/p the average value 6 times of one pulse then

$$V_d = 6 \left[\frac{1}{2\pi} \int_{\alpha}^{\alpha + 60} V_{bc} \, d\omega t \right]$$

$$= \frac{3}{\pi} \int_{\alpha}^{\alpha + 60} V_m \sin(\omega t + 60) \, d\omega t$$

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$\Rightarrow \frac{3}{\pi} V_m \left[\cos(\alpha + 60) - \cos(\alpha + 120) \right]$

$\Rightarrow \frac{3 V_m}{\pi} \cos\alpha$

$$V_d = V_{do} \cos\alpha$$

$V_{do} = \frac{3\sqrt{2}}{\pi} V_L$

when

$\alpha = 0^\circ$	$V_d = V_{do}$
90°	0
180	$-V_{do}$

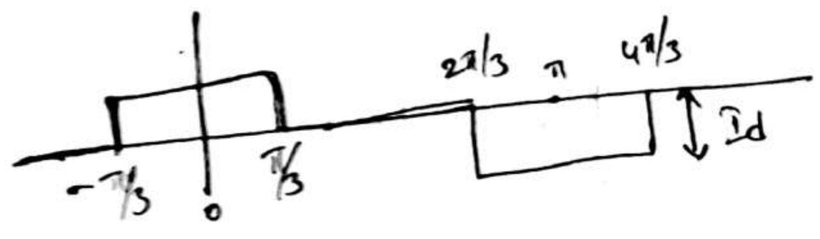
The dc voltage wave form it contains harmonics of its order. $h = np$

The rms value of 'h'th order harmonic in dc voltage is

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

<u>AC current wave form</u>

The AC current following through the values is



The rms value of current is

$$I = \sqrt{\frac{1}{2\pi}\left(\int_{-\pi/3}^{\pi/3} i_d^2\, d\omega t + \int_{2\pi/3}^{4\pi/3} i_d^2\, d\omega t\right)}.$$

$$= \sqrt{\frac{2}{3}}\, I_d$$

The rms value of fundamental component of current

$$I_1 = \frac{1}{\sqrt{2}} \frac{2}{\pi} \int_{-\pi/3}^{\pi/3} I_d \cos\theta\, d\theta$$

$$\boxed{I_1 = \frac{\sqrt{6}}{\pi} I_d}$$

The harmonics contained in the current wave form are of the order given by

$$h = np \pm 1$$ where n = integer, P = pulse no

For a 6 pulse bridge converter the order of Ac harmonics are 5, 7, 11, 13 and heigher order

Tuned filters are used for lower harmonics and high pass filter for the rest of heigher harmonics

⇒ The rms value of 'h'th order harmonic is given by

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

Power factor

The power supplied by converter

$$P_{ac} = \sqrt{3}\, V_L I_L \cos\phi$$

The DC power must match the AC power by ignoring the losses in converter.

$$P_{ac} = P_{dc}$$

$$\sqrt{3} V_L I_L \cos\phi = V_d I_d$$

$$\sqrt{3} V_L \frac{\sqrt{6}}{\pi} I_d \cos\phi = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha\, I_d$$

$$\Rightarrow \quad \cos\phi = \cos\alpha$$

The reactive power requirements are increased from zero

when $\alpha = 90^0$ $\cos\phi = 0$ only reactive power is consumed

The wave forms are.

Graetz circuit with over lap

Due to the leakage inductance of the converter T/F and the impedence in the supply N/W the current in a valve can not change suddenly and commutation from one valve to the next can not be instantanious.

Ex The valve 3 is fired current transfers from valve 1 to 3 during which both valves are conducting this period is called overlap and duration is over angle 'u' of commutation angle $\left[\alpha + \frac{u+\gamma}{\beta} = \pi\right]$

=> For each interval of period the supply devided into two sub intervals.

=> Depending upon overlap ~~and duration is over lap~~ angle 'u' the operation of converters devides into 3 modes.

Mode 1 2 & 3 valve conduction $u \leq 60^\circ$

In this mode at 1st interval 3 valves conducted then after 2 valves are conducted.

Mode 2 3 valve conduction mode $u = 60^\circ$

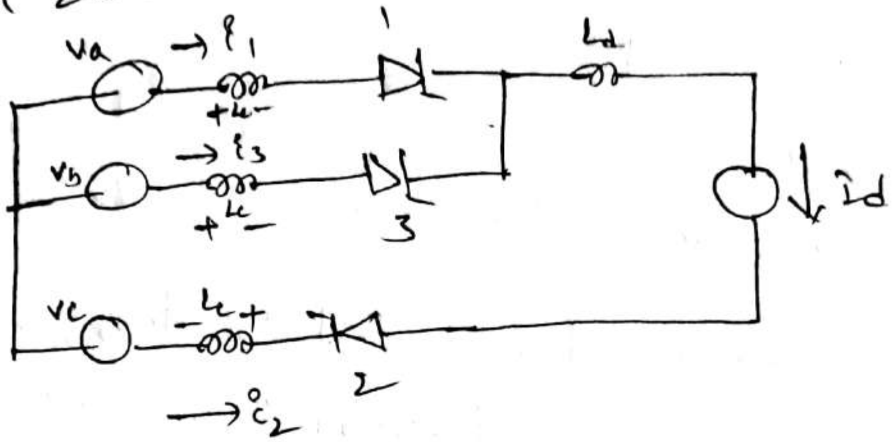
In this always 3 valves are conducted.

Mode 3 3 & 4 valve conduction $u > 60$

In this 1st interval 4 and next interval 3 valves are conducted.

Mode 1 $\mu < 60$

The equivalent circuit of the converter when 2 & 3 valves are conducted.



From circuit

$$v_b = L_c \frac{di_3}{dt}, \quad v_a = L_c \frac{di_1}{dt}$$

$$v_b - v_a = L_c \left(\frac{di_3}{dt} - \frac{di_1}{dt} \right)$$

$$v_{ba} = L_c \left[\frac{di_3}{dt} - \frac{di_1}{dt} \right]$$

$$V_m \sin\omega t = L_c \left[\frac{di_3}{dt} - \frac{di_1}{dt} \right]$$

Illy

$$i_1 = i_d - i_3$$

$$\frac{di_1}{dt} = \frac{-di_3}{dt}$$

so

$$V_m \sin\omega t = L_c \left[\frac{di_3}{dt} - \frac{di_1}{dt} \right]$$

$$= 2L_c \frac{di_3}{dt}$$

$$di_3 = \frac{1}{2L_c} V_m \sin\omega t \, dt$$

$$\boxed{i_3 = \frac{V_m}{2\omega L_c} \left[-\cos\omega t \right]}$$

where $\alpha \leq \omega t \leq \alpha + \mu$

$\omega t = \alpha, \ \mu = 0 \qquad i_3 = 0$

$\omega t = \alpha + \mu$ then $i_d = i_3 = \frac{V_m}{2\omega L_c}\left[\cos\alpha - \cos(\alpha+\mu)\right]$

$$i_d = i_s\left[\cos\alpha - \cos(\alpha+\mu)\right] \qquad i_s = \frac{V_m}{2\omega L_c}$$

<u>Average direct voltage</u>

~~$V_d = \frac{6}{2\pi}\left[\int_{\alpha}^{\alpha+\mu} \frac{-3}{2} V_c \, d\omega t + \int_{\alpha+\mu}^{\alpha+60} (V_b - V_c)\, d\omega t\right]$~~

under over lap condition.

$$V_a + V_b + V_c = 0$$

$$V_a + V_b = -V_c$$

$V_a - L_c\frac{di_1}{dt} = V$, $V_b - L_c\frac{di_3}{dt} = V$, $i_1 + i_3 = i_d$

$\frac{di_1}{dt} = -\frac{di_3}{dt}$

$\Rightarrow \quad V_a + V_b = 2V$

$$V = \frac{V_a + V_b}{2}$$

$$V_d = V - V_c$$

$$= \frac{V_a + V_b}{2} - V_c$$

$$= \frac{-V_c}{2} - V_c$$

$$\boxed{V_d = \frac{-3}{2} V_c}$$ when 3 valves conducted.

$$V_d : 6\left[\frac{1}{2\pi}\left\{\int_{\alpha}^{\alpha+\mu} \cdot\frac{3}{2}v_c\, d\omega t + \int_{\alpha+\mu}^{\alpha+60} v_b - v_c\, d\omega t\right\}\right]$$

$$\Rightarrow \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu} -\frac{3}{2}v_c\, d\omega t - \int_{\alpha}^{\alpha+\mu}(v_b - v_c)\,d\omega t + \int_{\alpha}^{\alpha+\mu}(v_b - v_c)\,d\omega t + \int_{\alpha+\mu}^{\alpha+60}(v_b - v_c)\,d\omega t\right]$$

$$\Rightarrow \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60}(v_b - v_c)\,d\omega t - \int_{\alpha}^{\alpha+\mu}\left(\frac{3}{2}v_c + v_b - v_c\right)d\omega t\right]$$

$$\Rightarrow \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60} v_{bc}\, d\omega t - \int_{\alpha}^{\alpha+\mu}\frac{2v_b + v_c}{2}\, d\omega t\right]$$

$$\Rightarrow \frac{3}{\pi}\left(\int_{\alpha}^{\alpha+60} v_{bc}\, d\omega t - \int_{\alpha}^{\alpha+\mu}\left(\frac{v_b - v_a}{2}\right)d\omega t\right]$$

$$\Rightarrow \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60} v_{bc}\, d\omega t - \int_{\alpha}^{\alpha+\mu}\frac{v_{ba}}{2}\, d\omega t\right]$$

$$\Rightarrow \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60} V_m \sin(\omega t + 60)\,d\omega t - \int_{\alpha}^{\alpha+\mu}\frac{V_m \sin\omega t}{2}\, d\omega t\right]$$

$$\Rightarrow V_{do}\cos\alpha - \frac{3}{2\pi}\int_{\alpha}^{\alpha+\mu} V_m \sin\omega t\, d\omega t$$

$$\Rightarrow V_{do}\cos\alpha - \frac{V_{do}}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

$$\Rightarrow \frac{V_{do}}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right], \quad I_d = I_s\left(\cos\alpha - \cos(\alpha+\mu)\right)$$

$$\frac{V_{do}}{2}\cos\alpha + \frac{V_{do}}{2}\left(\cos\alpha - \frac{I_d}{I_s}\right)$$

$$V_{do}\cos\alpha - V_{do}\frac{I_d}{2 I_s}$$

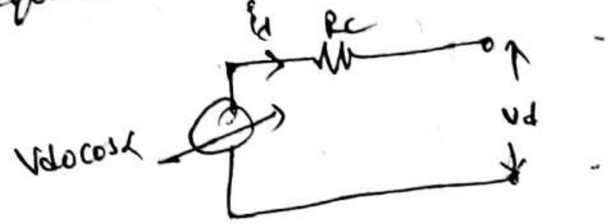
$$\Rightarrow V_{do}\cos\alpha - \frac{3\omega L_c}{\pi} I_d$$

$$\boxed{V_d = V_{do}\cos\alpha - R_c\, I_d}$$

The average o/p voltage of the converter when it works as rectifier is

$$V_d = V_{do}\cos\alpha - R_c I_d$$

The equivalent circuit of the rectifier end is



when the converter acts as inverter then the average o/p voltage is

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

$$= -\frac{V_{do}}{2}\left[\cos(\pi-\beta) + \cos(\pi-\gamma)\right]$$

$$= \frac{V_{do}}{2}\left[\cos\beta + \cos\gamma\right]$$

In terms of β

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

$$= \frac{V_{do}}{2}\left[\cos\beta - \left(\cos\alpha - \frac{I_d}{I_s}\right)\right]$$

$$= \frac{V_{do}}{2}\cos\beta - \frac{V_{do}}{2}\cos\alpha + \frac{3\omega L_c}{\pi} I_d$$

$$\boxed{V_{dr} = V_{do}\cos\beta + R_c I_d}$$

equivalent circuit

In terms of γ

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

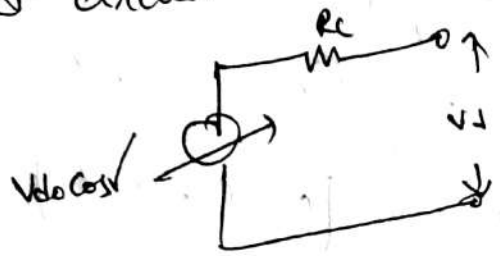
$$= \frac{V_{do}}{2}\left[\cos\gamma - \cos\beta\alpha\right]$$

$$= \frac{V_{do}}{2}\left[\cos\gamma - \frac{I_d}{I_s} - \cos(\alpha+\mu)\right]$$

$$= \frac{V_{do}}{2}\left(2\cos\gamma - \frac{I_d}{I_s}\right)$$

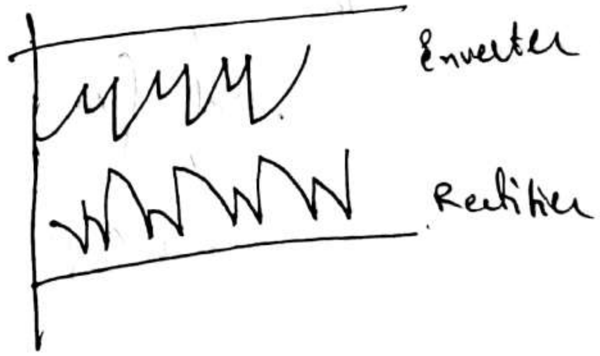
$$\boxed{V_{di} = V_{do}\cos\gamma - R_c I_d}$$

equivalent circuit

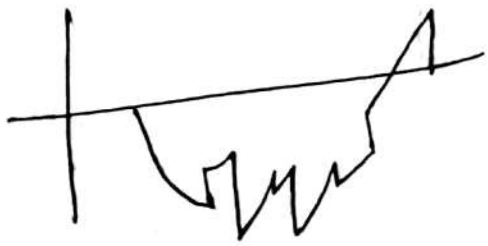


wave forms $\alpha = 15^0$ $\mu = 15^0$

Inverter o/p



voltage across valve.



AC current & DC voltage harmonics

The fundamental component of the AC current derived for the case with no overlap is not valid.

⇒ The expression for the current can be derived from fourier series analysis

$$I_P = \left[I_{P1}^2 + I_{P2}^2 \right]^{1/2}$$

$$I_{P1} = I_P \cos\phi = \frac{\sqrt{6}}{\pi} I_d \left[\frac{\cos\alpha + \cos(\alpha+\mu)}{2} \right]$$

$$I_{P2} = I_P \sin\phi = \frac{\sqrt{6}}{\pi} I_d \left[\frac{2\mu + \sin 2\alpha - \sin 2(\alpha+\mu)}{4\left[\cos\alpha - \cos(\alpha+\mu)\right]} \right]$$

From the two expressions

$$\tan\phi = \frac{2\mu + \sin 2\alpha - \sin 2(\alpha+\mu)}{\cos 2\alpha - \cos 2(\alpha+\mu)}$$

The harmonics in AC current are reduced from the values calculated with no overlap

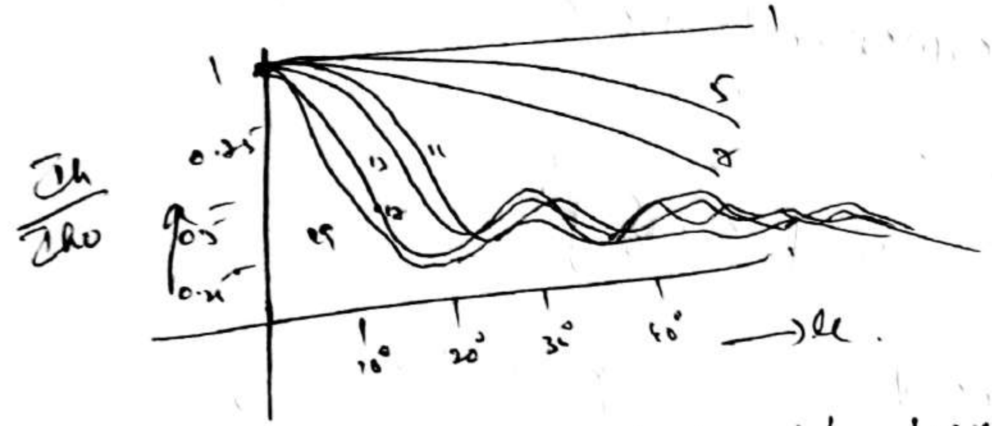
The reduction factor is given by

$$\frac{I_h}{I_{h0}} = \frac{1}{2x} \left[H^2 + K^2 - 2HK\cos(2\alpha+\mu) \right]^{1/2}$$

where $H = \frac{\sin(h+1)\mu/2}{(h+1)}$, $K = \frac{\sin(h-1)\mu/2}{(h-1)}$

$x = \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right]$

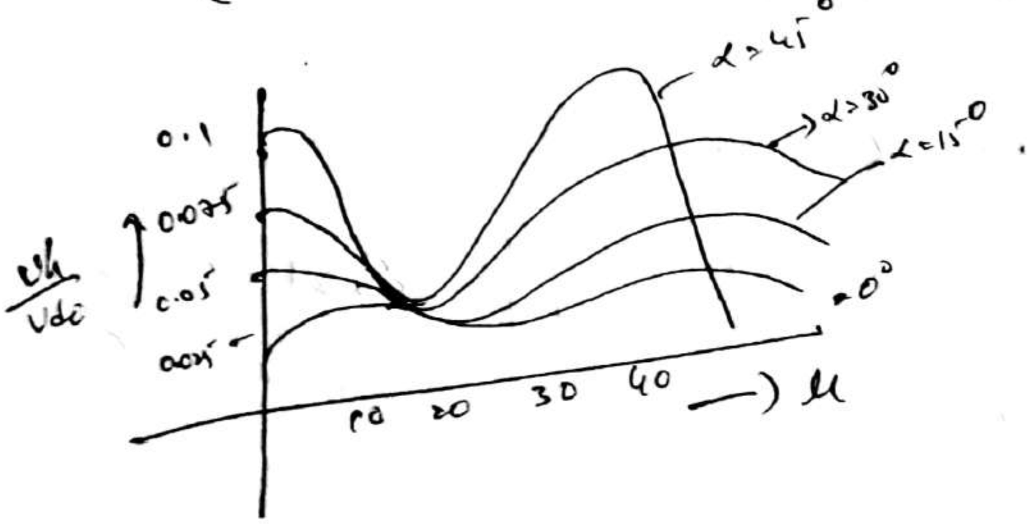
$I_{ho} = \frac{\sqrt{6}}{\pi} \frac{I_d}{h}$ = harmonic component with no overlap.



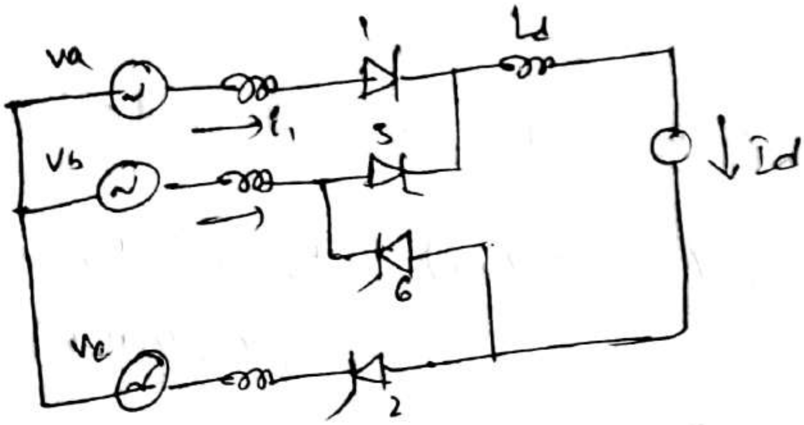
The harmonics especially of higher order decreases sharply with increasing values of 'μ' and the reduction factor lies in the range of 0.1 to 0.2.

The harmonics in dc voltage are also alter due to overlap $\frac{V_h}{V_{do}} = \left[\frac{1}{2}\left[F^2+G^2-2FG\cos(2\alpha+\mu)\right]\right]^{1/2}$

$F = \frac{\cos(h+1)\mu/2}{(h+1)}$, $G = \frac{\cos(h-1)\mu/2}{(h-1)}$



3 and 4 valve Conduction mode



when the overlap angle exceeds 60^0 the minimum no of valves conducting are 3 and 4 when the commutation process started, the previous commutation process not completed.

=) when valve 3 is fired the valves 1, 6, and 2 are conducting

$\alpha \leq \omega t \leq \alpha + u - 60$

$$i_1 = i_s \sin(\omega t + 60) + A$$

$$i_6 = i_d - i_2$$

$$= i_d - i_s \sin \omega t + C$$

The constant A can be determined from initial conditions

$$i_1(\omega t = \alpha) = i_d = i_s \sin(\alpha + 60) + A$$

=) ~~Constant~~ constant C can be determined from the final condition

$$i_6(\omega t = \alpha + u - 60) = i_d - i_s \sin(\alpha + u - 60) + C$$

For $\alpha+\mu-60 \le \omega t \le \alpha+60^\circ$

$$i_1 = I_s \cos\omega t + B$$

The constant B can be determined from continuity equation

$$i_1(\omega t = \alpha+\mu-60) = I_s \sin(\alpha+\mu) + A$$
$$= I_s \cos(\alpha+\mu-60) + B$$

From symmetry

$$i_1(\omega t = \alpha+60) = i_6(\omega t = \alpha)$$

$$I_s \cos(\alpha+60)+B = I_d - I_s \sin\alpha + C$$

From all these values

$$I_d = \frac{I_s}{2}\left[\cos(\alpha-30) - \cos(\alpha+\mu+30)\right]$$

Average DC voltage

$$V_d = \frac{3}{\pi}\int_{\alpha+\mu-60}^{\alpha+60} -\tfrac{3}{2} v_c \, d\omega t + 0 \Rightarrow$$ 4 values, $v_c = -V_m \cos\omega t$

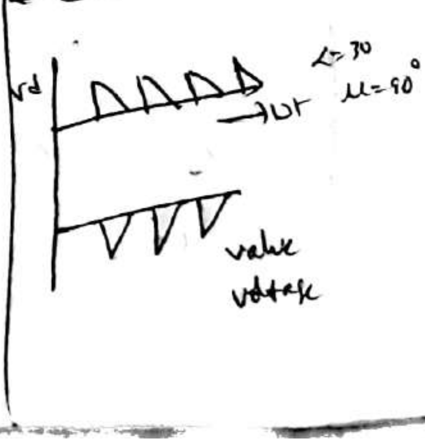
$$= \frac{3}{\pi}\frac{3}{2}V_m\left[\sin(\alpha+60) - \sin(\alpha+\mu-60)\right]$$

$$= \frac{\sqrt{3}}{2} V_{do}\left[\cos(\alpha-30) + \cos(\alpha+\mu+30)\right]$$

$$= V_{do}\left[\sqrt{3}\cos(\alpha-30) - \frac{3I_d}{2I_s}\right]$$

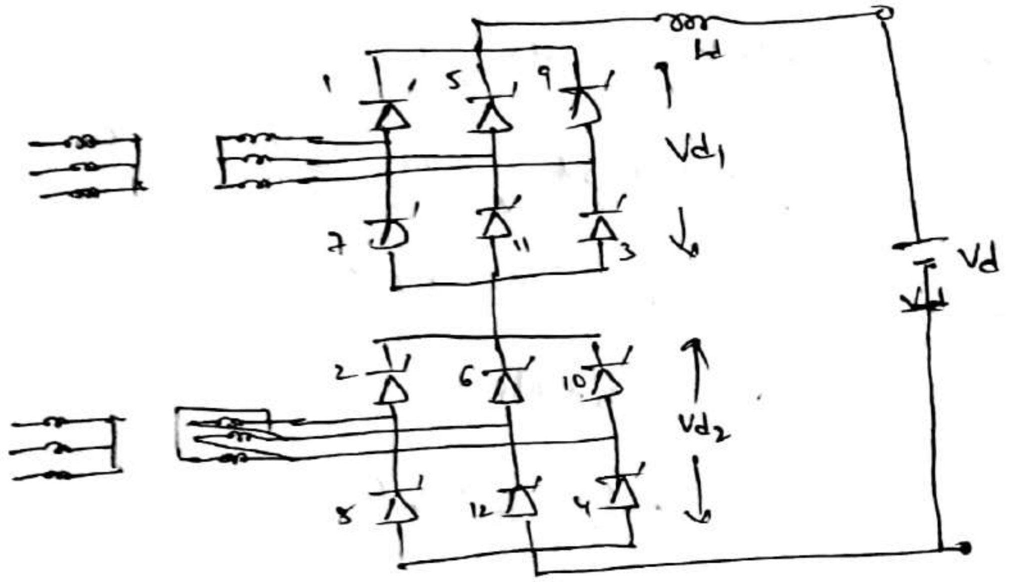
$$\boxed{V_d = \sqrt{3}\, V_{do}\cos(\alpha-30) - 3R_c I_d}$$

wave forms



12 pulse converter

To reduce the voltage ripple on the DC side of the converter and current harmonics generated on the AC side. This is accomplished by using high pulse no converter by high pulse converter.



A 12 pulse converter is obtained by connecting of two 6 pulse bridge converter series

=) The AC supply is from T/F having two 2ndry one is Y connected other is Δ connected are supplying 3φ voltages to the bridges with a phase displacement of 30° $\left(\frac{2\pi}{12}\right)$ hence two six pulse o/ps are symmetrically displaced to give an overall 12 pulse o/p

$$\frac{N_{S1}}{N_P} = 1 , \quad \frac{N_{S2}}{N_P} = \sqrt{3}$$

N_{S1}, No of Turns in 2ndry Y connected T/F

N_{S2} No of Turns in 2ndry Δ connected T/F

N_P : primary No of Turns

The total o/p voltage is the sum of the individual converter o/p voltages

$$V_d = V_{d_1} + V_{d_2}$$

In order to make two converter o/p voltages are same the turns ratio is necessary between the windings of Δ & Y connected 2ndaries.

$$V_{d_1} = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \quad , \quad V_{d_2} = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha$$

Average DC voltage of 12 pulse converter is

$$V_d = V_{d_1} + V_{d_2}$$

$$= \frac{6\sqrt{2}}{\pi} V_L \cos\alpha$$

$$V_d = \frac{6 V_m}{\pi} \cos\alpha$$

If source inductance is considered there are 5 modes of operation in 12 pulse converter

Mode 1 – $0 < \mu < 30$ – 4, 5 valves conducted

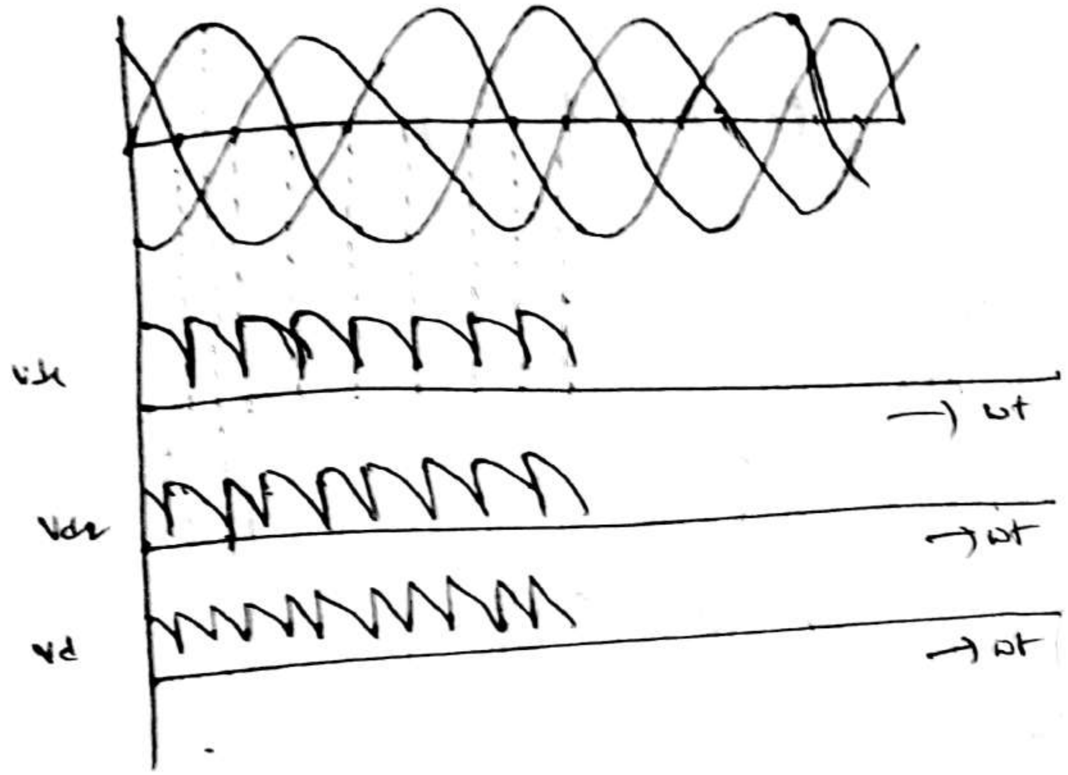
Mode 2 – $30 < \mu < 60$ – 5 & 6 valves conducted

Mode 3 – $0 < \alpha < 30, \mu = 60$ – 6 valves conducted

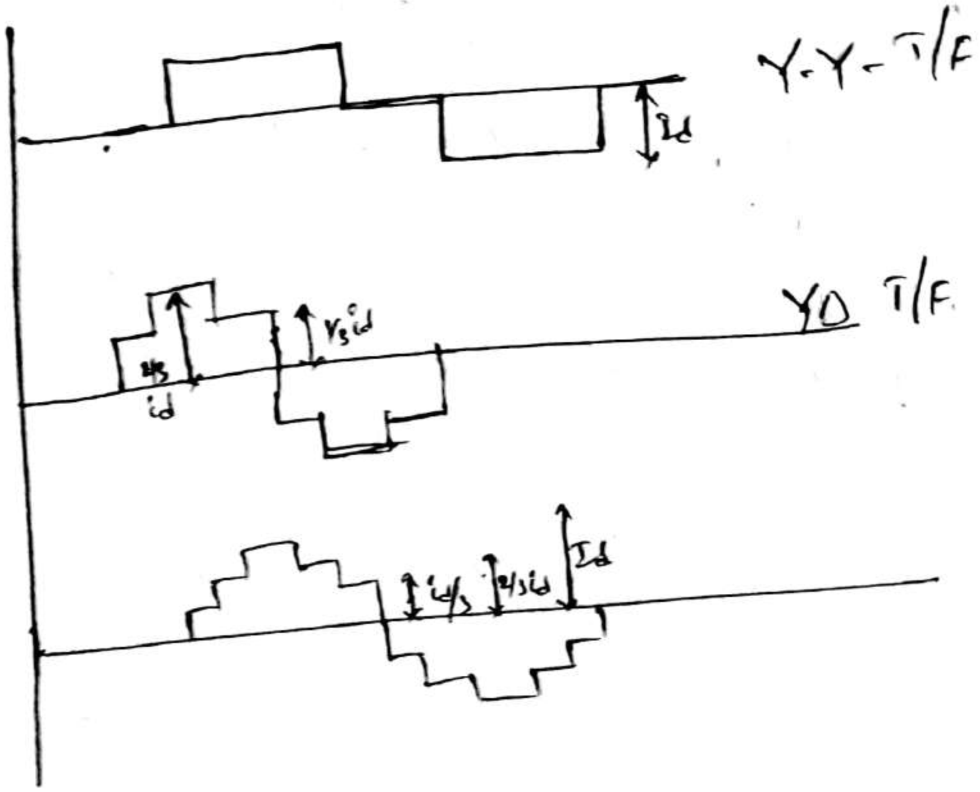
Mode 4 – $60 < \mu < 90$ – 6 & 7 valves conducted

Mode 5 – $90 < \mu < 120$ – 7 & 8 valves conducted.

o/p voltage wave forms



current wave forms



Bridge characterstics

The relation ship b/w Vd, Id is called characteristic of converter.

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

$$\frac{V_d}{V_{do}} = \frac{1}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right]$$

$$\bar{V}_d = \frac{1}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right]$$

$$\boxed{\bar{V}_d = \cos\left(\alpha+\frac{\mu}{2}\right)\cos\left(\frac{\mu}{2}\right)}$$

Note

$\cos A + \cos B$

$2\cos\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right)$

$\cos A - \cos B$

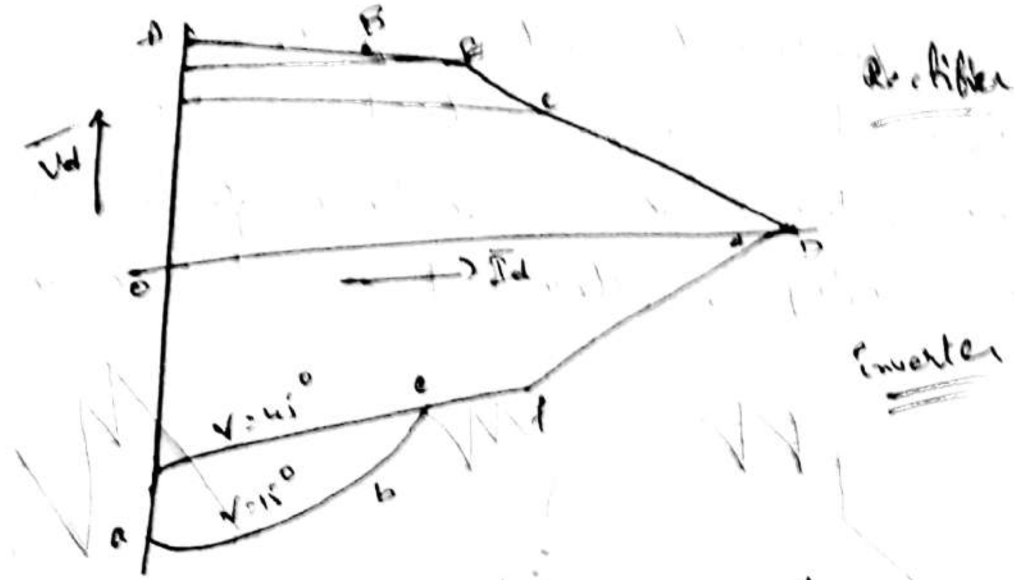
$2\sin\left(\frac{A+B}{2}\right)\sin\left(\frac{B-A}{2}\right)$

IIly $\bar{I}_d = \frac{I_d}{2 I_s} = \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right]$

$$\boxed{\bar{I}_d = \sin\left(\alpha+\frac{\mu}{2}\right)\sin(\mu/2)}$$

Mode 1 & 3 the characterstics are linear and for Mode 2 the characterstics are eliptical i.e $\mu = 60$ the characterstics are eliptical

$$\left[\frac{\bar{V}_d}{\cos\mu/2}\right]^2 + \left[\frac{\bar{I}_d}{\sin\mu/2}\right]^2 = 1$$



For different values of α, μ the values of $\overline{I_d}$, $\overline{V_d}$ are

point	α	μ	$\overline{I_d}$	$\overline{V_d}$
A	0	0	0	1
B	0	60	0.25	0.75
C	30	60	$\sqrt{3}/4$	$\sqrt{3}/4$
D	30	120	$1/\sqrt{3}$	0
E	15	60	$\frac{1}{2\sqrt{2}}$	$\frac{\sqrt{3}}{2\sqrt{2}}$

The point E corresponding to max power o/p of rectifier the ~~corresponding~~ coordinates of A, B, C, D, E on boundary.

Inverter characteristics are similar to the rectifier. The operation of inverter requires a minimum commutation margin angle during which the voltage across the valve is -ve hence operating region of an inverter is different from that for a rectifier.

Mode 1 $\mu < 60^0$

① $\beta < 60$ $\quad \gamma = \gamma_0 = 30$

$\bar{V_d} = \cos\gamma_0 - \bar{I_d}$

② $60 < \beta < 90$ $\quad \xi_0 = 60 - \mu$

elliptical characteristics

③ $90 < \beta < 90^\circ + \xi_0$, $\quad 60 - \xi_0 \leq \mu \leq 60$

$\bar{V_d} = \cos(\gamma_0 + 30) - \bar{I_d}$

Mode 2 $\mu > 60$

$\beta > 90^\circ + \gamma_0$

$\bar{V_d} = \sqrt{3}\cos\gamma_0 - 3\bar{I_d}$

for different values of γ, α, the values of $\bar{I_d}$, $\bar{V_d}$ calculated and graph drawn above

point	γ	α	$\bar{I_d}$	$\bar{V_d}$
a	15	0	0	-0.966
b	15	45	0.233	0.474
c	45	60	0.483	-0.224
d	45	120	0.558	0
e	22.5	45^0		

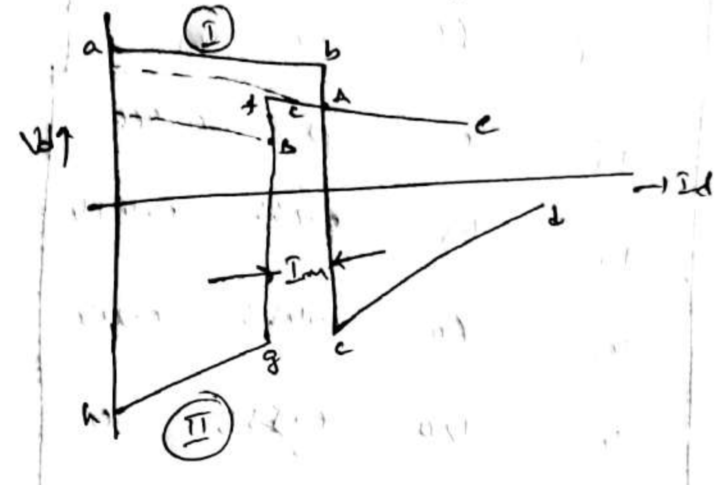
The point 'e' is the maximum power supplied by the inverter.

In normal operation $\bar{I_d}$ is 0.08 to 0.1

In order to control converter is linear operation is important.

Converter control characteristics

The control characteristics of both stations are



which shows DC voltage of the station II versus DC current. each station characteristic has three parts as given below

station I	station II	Type
ab	hg	minimum α
bc	gf	Constant current
cd	fe	minimum γ.

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

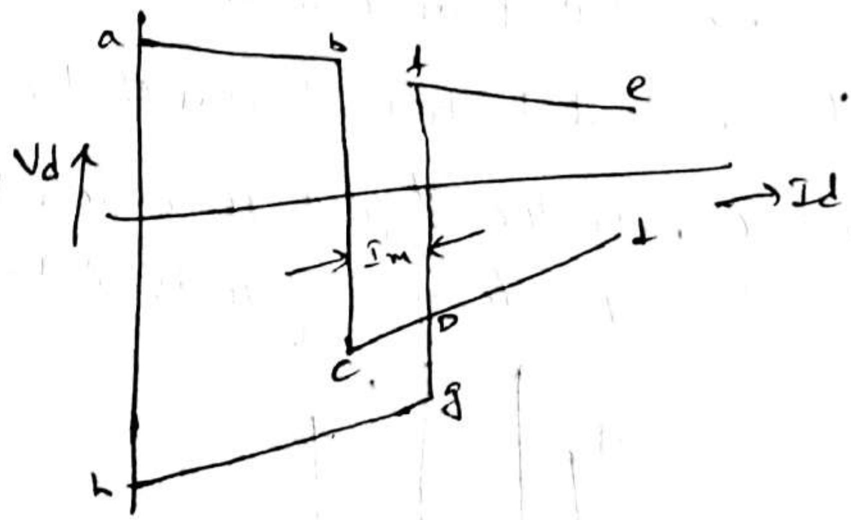
There are 3 modes of operation of the link depending on the voltage of the rectifier are defined below

(1) CC at rectifier and CEA at inverter (at A) is 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.

→ The characteristics ab has more -ve slope than fe b/z slope of ab due to the combined resistance Rcr+Rd while slope of fe is due to Rci, ~~to low~~ for low SCR at the inverter, the slope of fe could be more -ve than that of ab



from the above control characteristics til -ve current margin 'Im'. The operating point shifts to D which implies power reversal with station I operating with minimum CEA control while station II operating with CC.

The maintenance of proper current margin necessary to prevent power reversal in the link due to failure of telecommunication channels.

By fixing minimum limits on the delay angle of the inverter (100° to 110°) avoid Transmission.

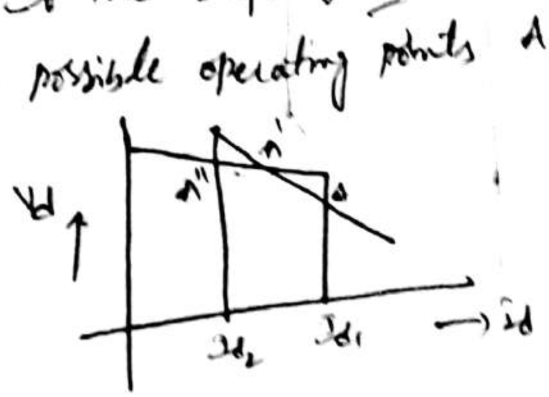
Modifications of the control characteristics

The need to restrict the control region to the first quadrant of the Vd-Id plane to avoid unwanted reversal of power.

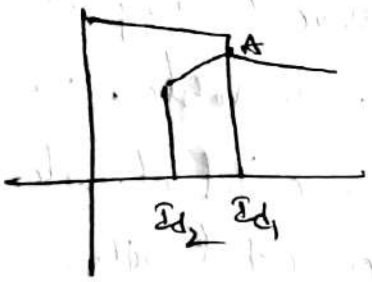
They are two other requirements which necessitate the modification of the control characteristics.

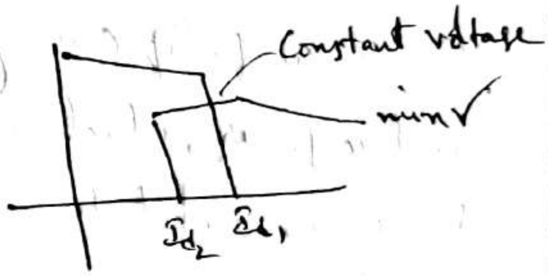
Mode stabilisation

The slop of ab and fe are nearly equal which can lead to poor definition of the intersection of point 'c'. If the slope of fe exceeds that of ab there will be possible operating points A, A' and A''



This implies instability of the control which will result in hunting between different modes of operation. To eliminate this problem the inverter characteristics are modified and given a positive slope when the current is between I_{d1} and I_{d2}. Alternate solution is to modify the inverter control to maintain a constant DC voltage with back up control of minimum CEA



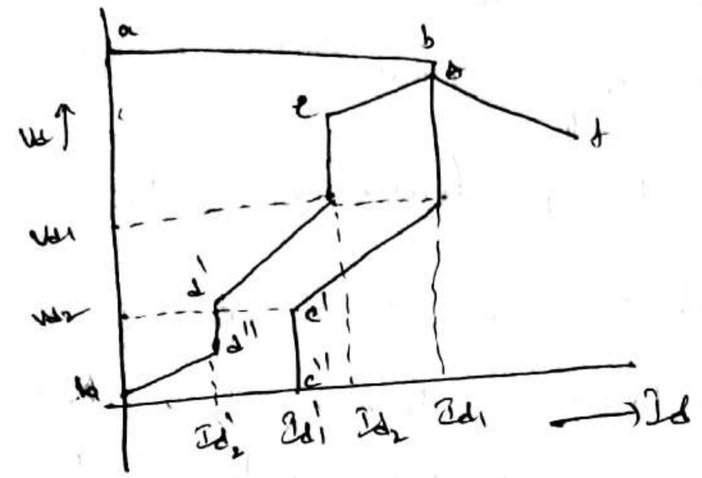


This requires the normal operating value of extinction angle to be greater than the minimum value

voltage dependent current limit.

The low DC voltage in the 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 commutation failure because of the increase of the overlap angle.

In such cases it is necessary to reduce the DC current in the line until the conditions that led to the reduced DC voltages are relieved. Also the reduction of current relieves valves in the inverter from overstressed due to continuous current flow



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 characteristic cc' and c'c'' shows the limitation of current due to the reduction in voltage. The DC current is reduced from I_{d1} to I_{d1}' linearly and maintained at I_{d1}' below the voltage V_{d2}. The inverter characteristic also follows the rectifier characteristic to maintain the current margin except for I_d'' which is due to the lower limit imposed on the delay angle of the inverter.

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

1) The firing instant for all the valves are determined at ground potential and firing signal send to individual thyristors by light signals through fibre optic cables.

2) while a single pulse is adequate to turn on a thyristor, the gate pulse generator must send a pulse whenever required.

There are two basic firing schemes

① Individual phase control (IPC)

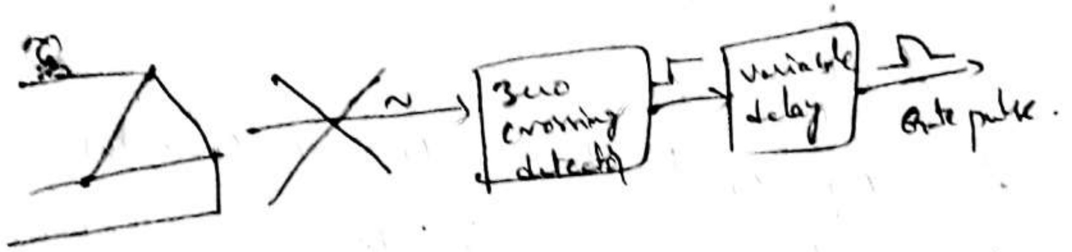
② Equidistance pulse Control (EPC)

IPC

The main feature of this scheme is that the firing pulse generation for each phase is independent of each other and the firing pulses are rigidly synchronised with the commutation voltages.

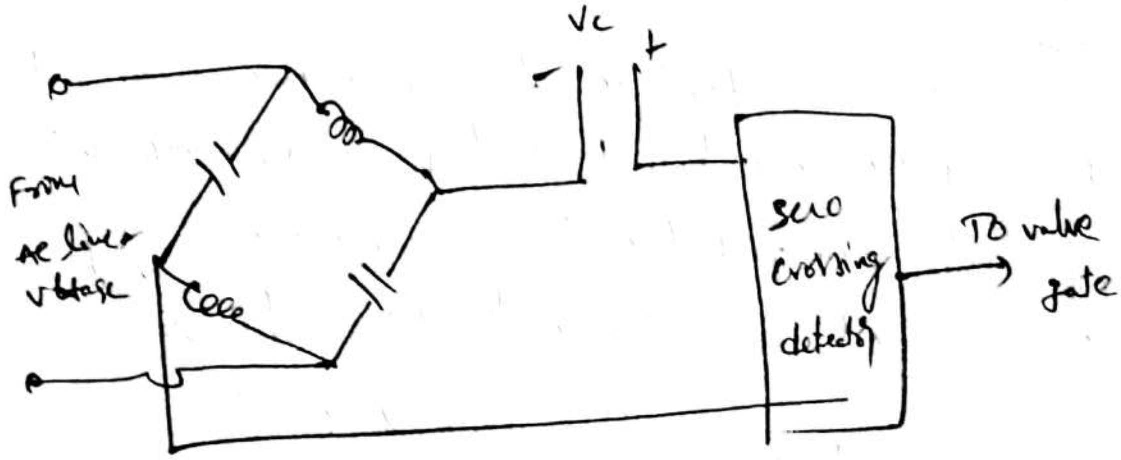
IPC < constant α control / inverse cosine control

Constant α Control



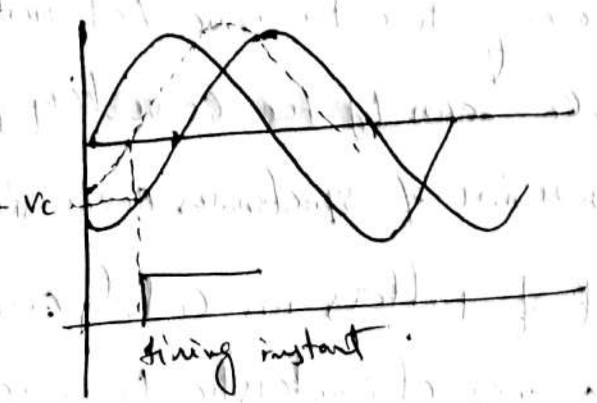
In this scheme six timing (Commutation) voltages are derived from the converter AC Bus via voltage Transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero crossings of a particular commutation voltage corresponds to α=0 for that value. The delays are produced by independent delay circuits and controlled by a common control voltage derived ~~to~~ from the current controllers.

Inverse Cosine Control



In this the six timing voltages are each phase shifted by 90^0 and added seperatly to a common control voltage.

The zero crossing of the sum of the two voltages initiates the firing pulse for the particular value considered



The delay angle α is proportional to the inverse cosine of the control voltage also depends on the AC system voltage amplitude & shape.

The main advantage of this control scheme is that the average DC voltage across the bridge varies linearly with the control voltage.

=) The main draw back of IPC is harmonic stability. Any distortion in the system voltage leads to disturbance in zero crossings which ~~effects~~ affect the instants of firing pulses in IPC. This implies even in fundamental frequency voltage components balanced, the firing pulses are not equidistant in s/s. This in turn leads to non characteristic harmonics which amplify the harmonic content

of the AC voltage at the converter bus.
The problem is aggravated at the frequencies for which the filter impedances and the system impedance are in parallel resonance.

=> The problem of harmonic instability can be overcome by the following measures:

1. Influencing the harmonic behaviour of AC N/W impedance seen by the converter (through the provision of synchronous condensors or filters)
2. Use of filters in control circuits to filter out non characteristic harmonics in the commutation voltages.
3. The use of firing angle control independent of the zero crossing of the AC voltages. This is the most attractive solution and leads to the equidistant pulse firing.

UNIT V

Need of Reactive power control

The converters used in HVDC are line commutated results in lagging PF operation of converters so for better voltage control reactive power sources are required.

The reactive power sources are required on both sides while Rectifier station appeal as load in the system, inverter station viewed as generator consuming Reactive power.

The characterstics of the inverter not desirable and require suitable modifications by providing var compensation.

The requirements of voltage control and cost dictates the choice of speed of response of the reactive power control under dynamic conditions.

The operation with weak AC systems can be problematic due to voltage instability and dynamic over voltages so better coordination of var sources is desired under such conditions.

Reactive power requirement under S.S can be explained by two ways ① conventional control strategies, ② alternate control strategies.

Conventional control stratagies

A DC link is operated with CC at Rectifier and minimum γ at inverter under normal conditions. This method of control leads to the minimum Reactive power requirement at both ends.

The eqn's for 'Q' as a function of 'P' are conveniently expressed in terms of per unit quantities

Base converter voltage - $V_{db} = \frac{3\sqrt{2}}{\pi} V_n$

where V_n = rated line voltage

Base dc current - $I_{db} = I_{dn}$ rated dc current

Base dc power - $P_{db} = n_b V_{db} I_{db}$

n_b = no of bridges connected in series

Base AC voltage (on valve side) = $V_b = V_n$

Base AC power = Base DC power

$= \frac{\sqrt{18}}{\pi} V_n I_{db} n_b$

The Average DC voltage across a converter bridge is given by

$$\bar{V_d} = \bar{v}\cos\alpha - \bar{R_c}\bar{I_d}$$

$$\bar{V_d} = \frac{V_d}{V_{db}}, \quad \bar{I_d} = \frac{I_d}{I_{db}}, \quad \bar{v} = \frac{V}{V_b}, \quad \bar{R_c} = \frac{\bar{X_c}}{2}$$

$\bar{X_c}$ = PU leakage reactance of the T/F on its own base.

The power is given by

$$\cos\phi \simeq \frac{\bar{V}_d}{V_{db}}$$

$$= \frac{\bar{V}_d}{\bar{V}} = \cos\alpha - \frac{\bar{R}_c \bar{I}_d}{\bar{V}}$$

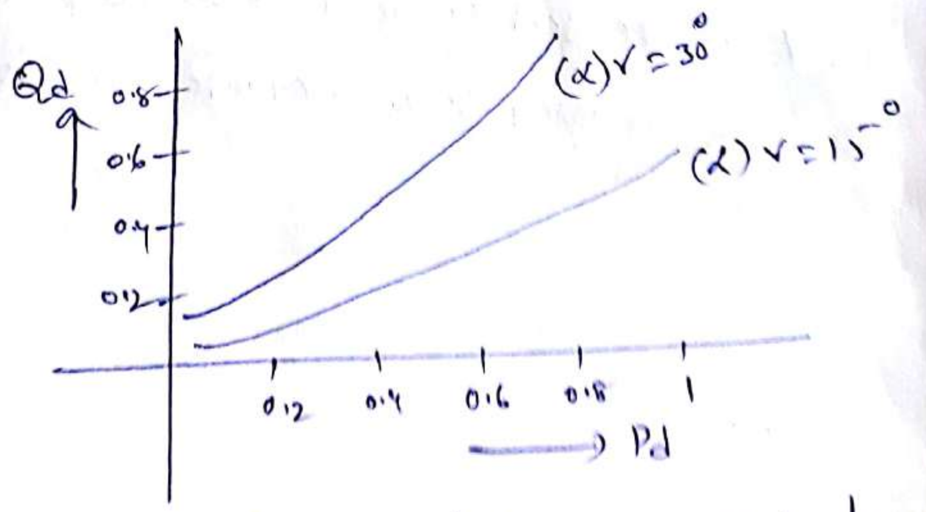
So power and reactive power in per unit are

$$\bar{P}_d = \bar{V} \bar{I}_d \cos\phi$$

$$\bar{Q}_d = \bar{V} \bar{I}_d \sin\phi$$

$$\bar{V}_d = \bar{V}\cos\alpha - \bar{R}_c \bar{I}_d \, , \quad \bar{V}_d = \bar{V}\cos\gamma - \bar{R}_c \bar{I}_d$$

The variation of Q_d, P_d for $\alpha = 15^0$, $X_c = 0.2$, $\bar{V} = 1$ is



It is to be noted that the rated DC power is less than 1pu as the rated voltage is less than the DC base voltage and the two are related by

$$\frac{V_{dn}}{V_{dbn}} = \bar{V}_{dn} = \cos\phi_n \quad \text{rated pf}$$

⟹ The Q requirement can be brought down by reducing $\bar{X}_C$

⟹ The increase in firing angle results sharp increase in Q_d this shows importance of maintaining low firing angle in S.S.

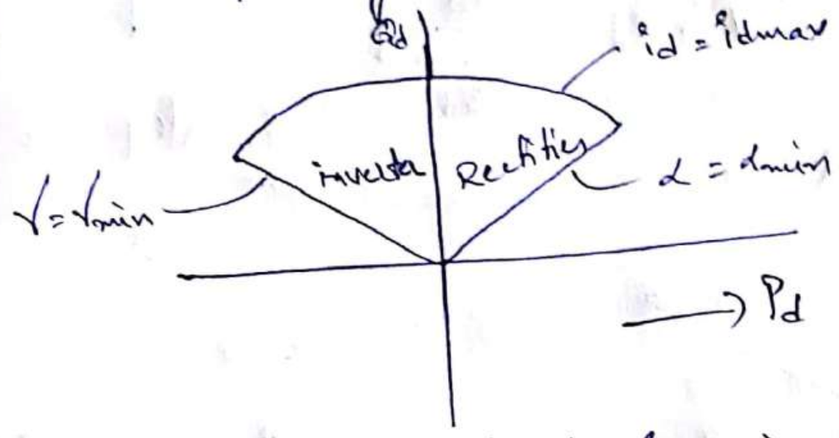
⟹ Too low value of "α" can result increased frequency of mode shifts, and too low values of $\underline{V}$ results in increased incidence of commutation failure.

⟹ The Q also affected by magnitude of AC voltage. The reduction in $\underline{V}$ leads to increase in $\underline{Q_d}$.
On load Tap changer can control V with in limits.

⟹ A 10% reduction in voltage (1 to 0.9 pu) require 15% increased current at rated power, which results in over 30% increase in losses.

Alternate Control strategies

⇒ The region of a Converter bridge is bounded by the limits on the DC current & firing angle by neglecting min current limit then the operating region of bridge is drawn for constant AC voltage.



This region is bounded by (i) Min α
(ii) Min γ
(iii) constant Rated DC current

In general locus of constant DC current is a part of circle in the Pd-Qd diagram.

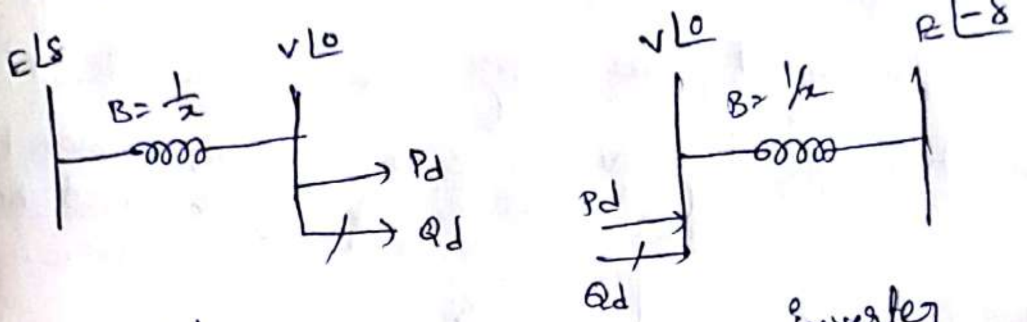
⇒ The constant DC voltage characterstic is a straight line passing through the origin.

⇒ The operation at constant DC voltage implies constant power characterstic at converter bus.

⇒ At Rectifier characterstic is that of a load with lagging PF at inverter viewed as a generator with leading PF.

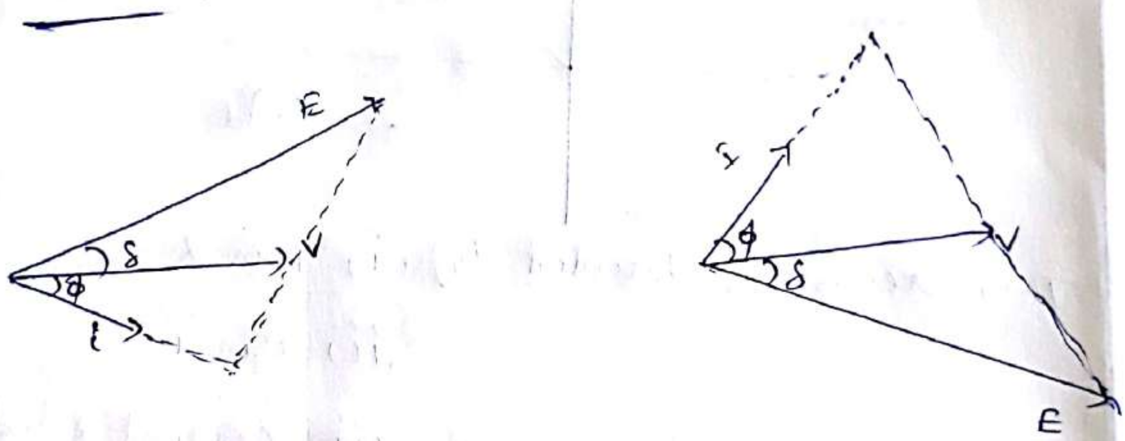
If there is no voltage support provided at converter bus the stability limit is reduced.

This is shown from the analysis.



Rectifier

Inverter



From the vector diagrams onwards

$$V\cdot\cos\phi = E\cos(\delta+\phi)$$

$$V = \frac{E\cos(\delta+\phi)}{\cos\phi}$$

~~P = VEB sin δ~~

$$P = \frac{VE}{X}\sin\delta$$

$$= VEB\sin\delta$$

$$= \frac{E^2 B\cos(\delta+\phi)\sin\delta}{\cos\phi}$$

It can be shown that max power T/F is obtained when $\delta = 45 - \phi/2$

at $\phi = 30^0$

$$P_{max} = 0.2887 E^2 B$$

This is much less than what we can be obtained

$\phi = 0 \quad P_{max} = 0.5 E^2 B$

$\phi = -30 \quad P_{max} = 0.866 E^2 B$

$V = E \quad P_{max} = E^2 B$

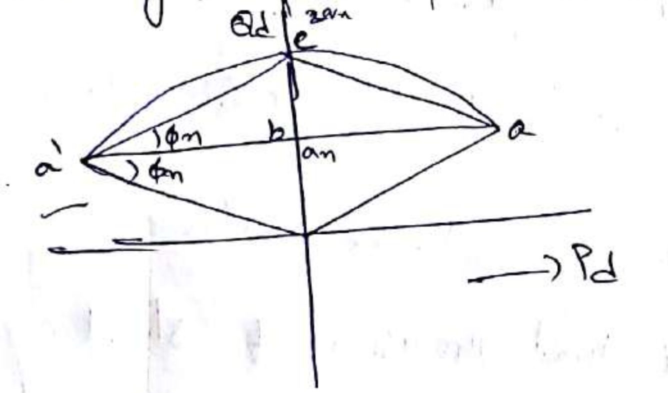
It is noted that provision of shunt capacitor (B_c) at converter bus results in the modification of the max power expression from eqn is

$$P_{max} = \frac{0.2877 E^2 B}{\left(1 - \frac{B_c}{B}\right)}$$

For $B = 3$ $B_c = 0.5 pu$ results increase of 20% of max power.

From the above there is a need to modify the R.power characterstic of the converter station either (i) choice of Q sources (ii) adjust converter control characteristics.

When the DC link operates for long distance with min of power in the line dictates operation of constant DC voltage and flexibility of converter not possible. However in Back-Back operation at constant voltage not critical so alternate control stratagie can be adapted these are constant Q characterstic (ab, a'b) constant leading power factor characterstic (ac, a'c)



⇒ It is to be noted that by providing a constant reactive power source of Q_n at the converter bus, the characterstic ab & a'b results in unity power factor operation of the converter. Similarly by providing a reactive source of $2Q_n$, the power factor angle is changed from ϕ to $-\phi$

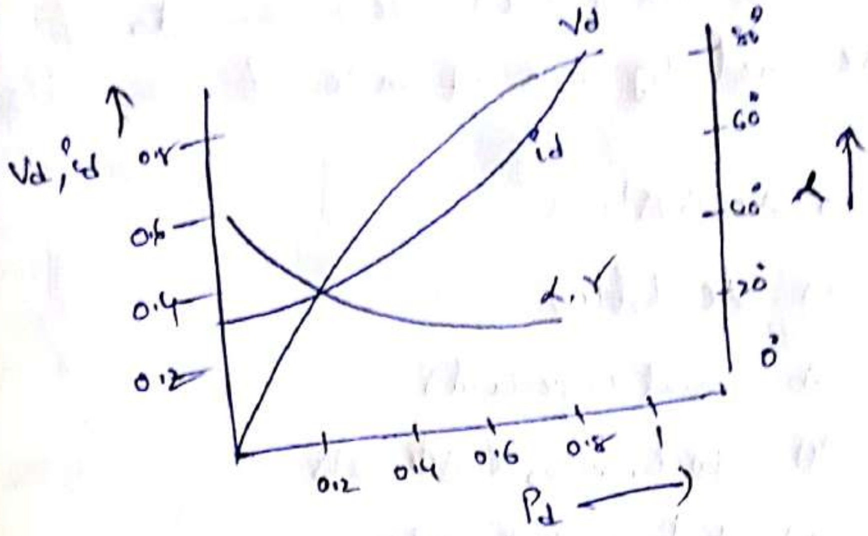
The expressions for the DC current and voltage for the two characterstics are given by

(i) $i_d = \left(\frac{P_{dn}}{V}\right)\left[\tan^2\phi_n + \left(\frac{P_d}{P_{dn}}\right)^2\right]^{1/2}$

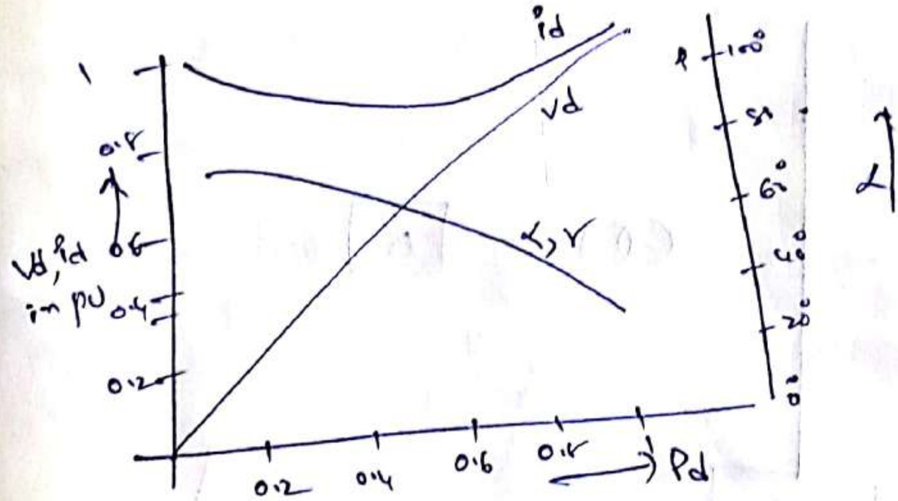
(ii) $i_d = (2Q_{dn}/V)\left[1-(P_d/P_{dn}) + (P_d/(2P_{dn}\sin\phi_n))^2\right]^{1/2}$

$$V_d = P_d/i_d$$

The variations of i_d, V_d and α with variation in P_d are shown below.



variation of i_d, V_d and α with P_d for constant reactive power.



variation of i_d, V_d and α with P_d for constant leading power factor

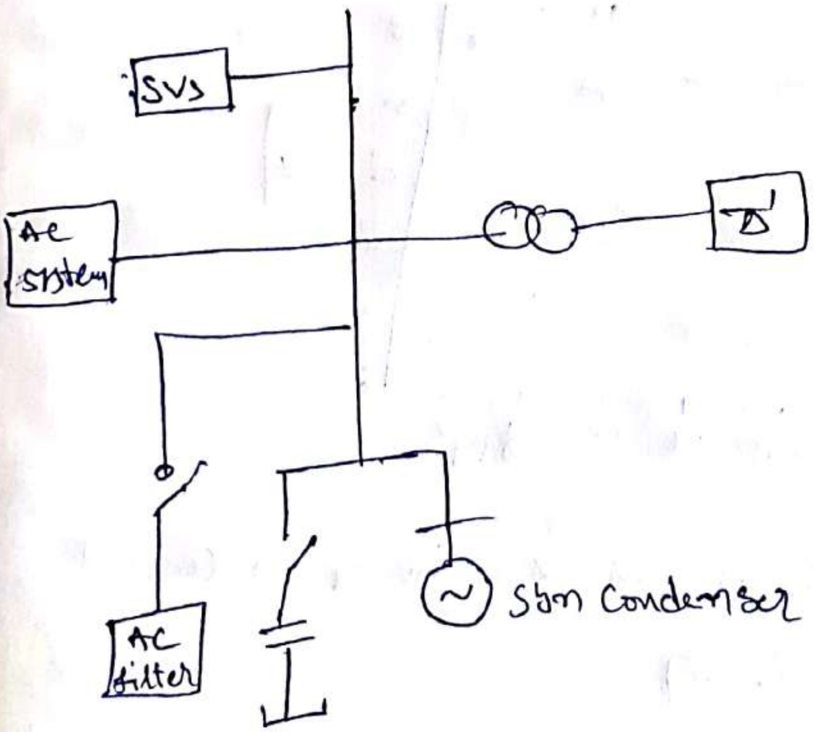
These are also applicable equally for the inverter operation except that α is replaced by γ.

The increase in α or γ above the minimum implies additional losses in the ~~st~~ snubber circuits.

Sources of Reactive Power

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

1) AC system
2) AC filter
3) Shunt capacitors
4) Synchronous condensors
5) Static var systems



The voltage regulation at the converter bus is desirable not only from the voltage control view point but also from the minimization of loss and stability considerations. This requires adjustable reactive power source which can provide variable reactive power as demanded.

for slow variations in the load, switched capacitors & filters can provide some control however it is descrete type of control and can result in voltage flicker unless the size of the unit, which is switched, is made sufficiently small.

In contrast the synchronous condensors and static var systems provide continuous control of the reactive power and can follow fast load changes.

The synchronous condensors are essentially synchronous motors operating at no load, with excitation control to maintain the terminal voltage. Their ~~action~~

advantages

1) The availability of voltage source for commutation at the inverter even if the connection to the AC system is temporarily interrupted. This also implies an increase in SCR as the fault level is increased. when the load supplied by the inverter is passive, the synchronous condenser is essential for providing voltage sources for the line commutations at the inverter.

2) Better voltage regulation during a transient due to the maintanance of flux linkages in the rotor windings. The effect of the armature reaction

is counteracted during a transient by induced currents in the feild and amortisseur circuits.

Dis advantages

(i) High maintenance and cost of ~~split~~ slip rings and brushes on the rotor.

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

The static var systems provide the fastest response and the configurations normally used are

(i) Fixed Capacitor, Thyristor controlled reactor (TCR)

(ii) Thyristor switched capacitor (TSC)-TCR combination.

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

Static var systems

The static var systems or compensators were used for load compensations where the objective is to dynamically control the reactive power demand of large fluctuating loads.

They are used for voltage control applications, possible to provide increased power transfer capability, control of dynamic overvoltages and damping of oscillations. By using auxiliary control signals, it is also possible to damp subsynchronous frequency oscillations.

There are basically three types of SVS schemes

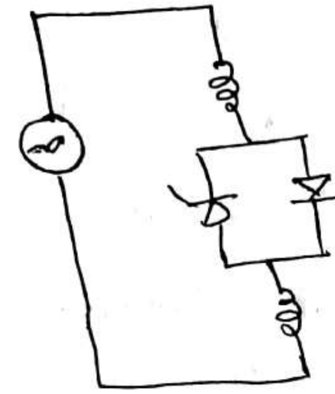
(i) variable impedance type ~~(SVS)~~ SVS

(ii) current source type SVS.

(iii) voltage source type SVS

The variable impedance type is used in power system applications.

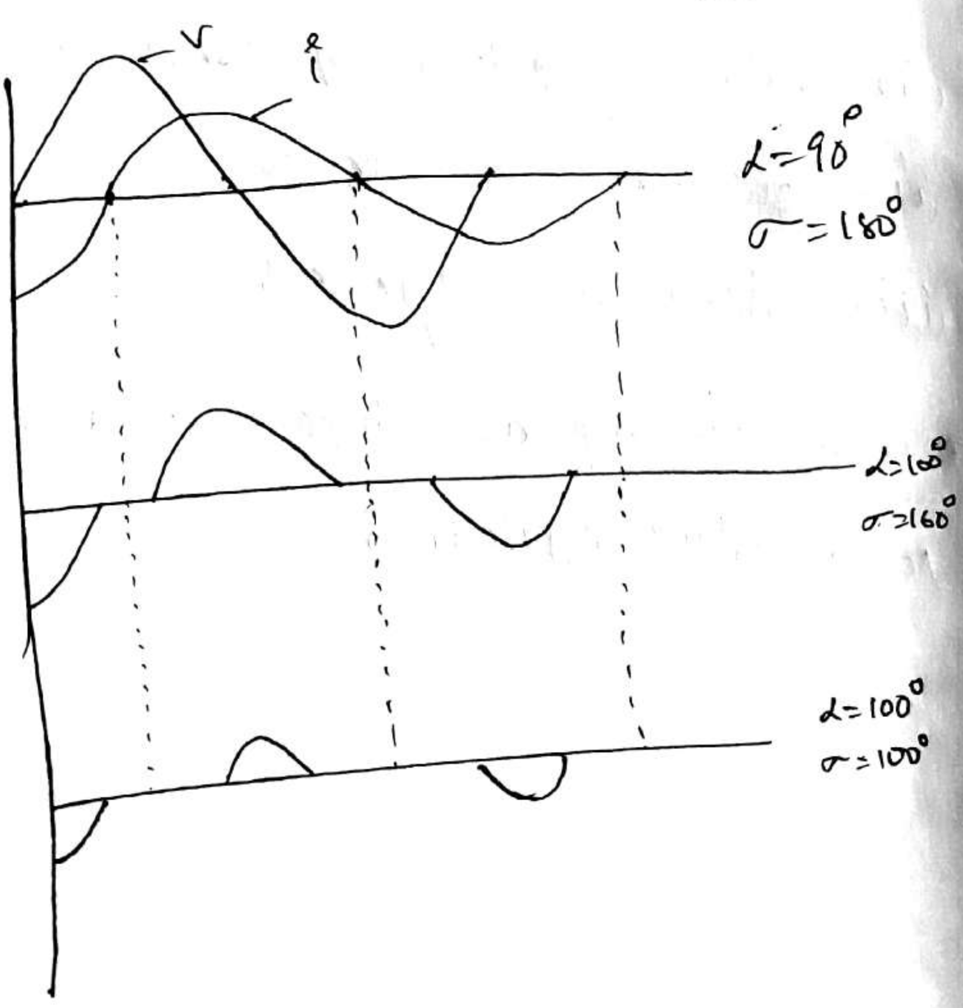
Thyristor controlled reactor TCR



The single phase thyristor controlled reactor is by controlling the firing angle of the back to back connected thyristors, the current in the reactor can be controlled. ~~when~~

For $\alpha = 90^\circ$ current is maximum

$\alpha = 180^\circ$ The current is zero



The fundamental component of the inductor current is given by

$$I_f = \frac{\sigma - \sin\sigma}{\pi X_L} \cdot V$$

where V rms voltage across the TCR.

X_L fundamental frequency reactance

σ conduction angle related to α

$$\sigma = 2(\pi - \alpha)$$

From the above equation I_f

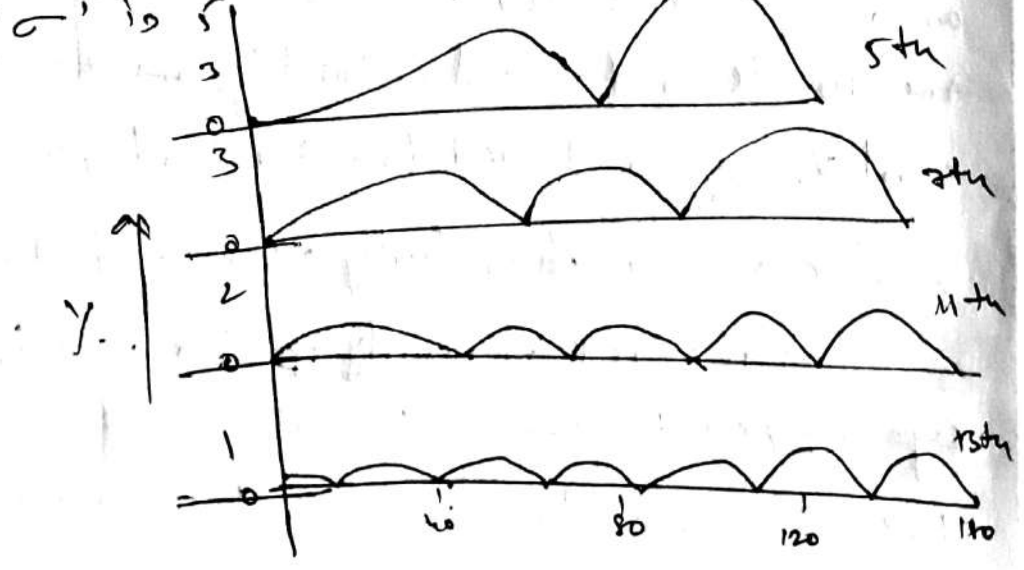
$$I_f = B(\sigma) V \qquad B(\sigma) = \frac{\sigma - \sin\sigma}{\pi X_L}$$

The harmonic component of the current corresponding to harmonic of order 'h' is given by

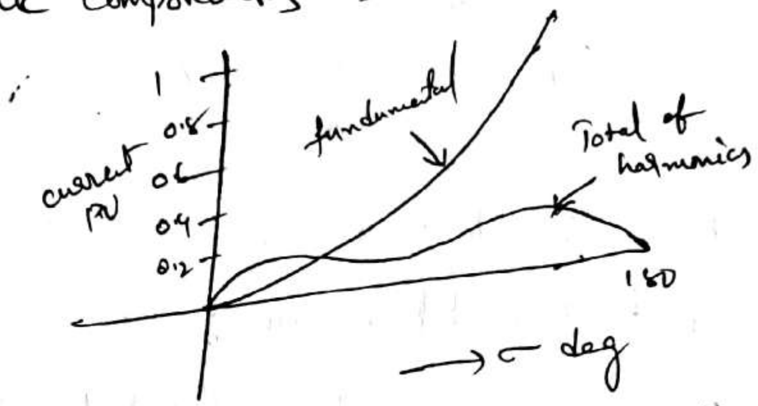
$$I_h = \left(\frac{4}{\pi}\right)\left(\frac{V}{X_L}\right) \frac{\sin[(h+1)\alpha]}{2(h+1)} + \frac{\sin[(h-1)\alpha]}{2(h-1)} - \frac{\cos\alpha \sin(h\alpha)}{h}$$

$h = 3, 5, 7 \ldots$

The variation of lower order harmonics with conduction angle 'σ' is

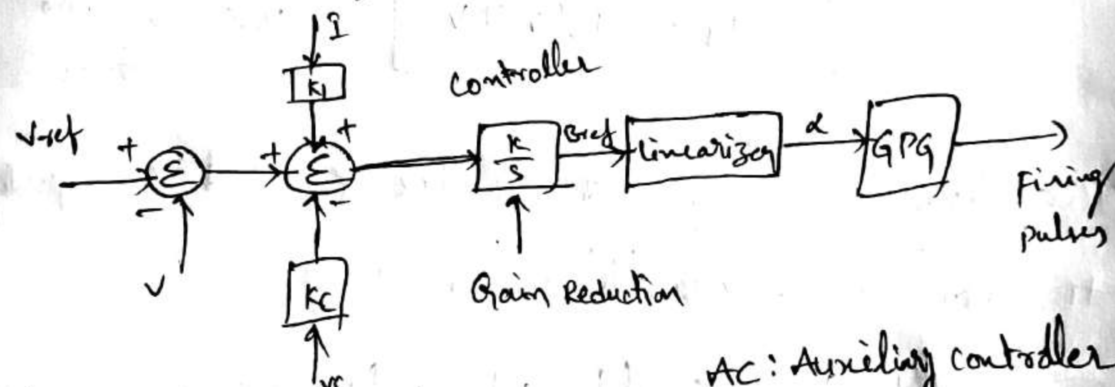


The variation of the fundamental and the total harmonic components is



The triplen harmonics in the lines are eliminated by the delta connection of the three single phase TCRs

The typical control system for a TCR is



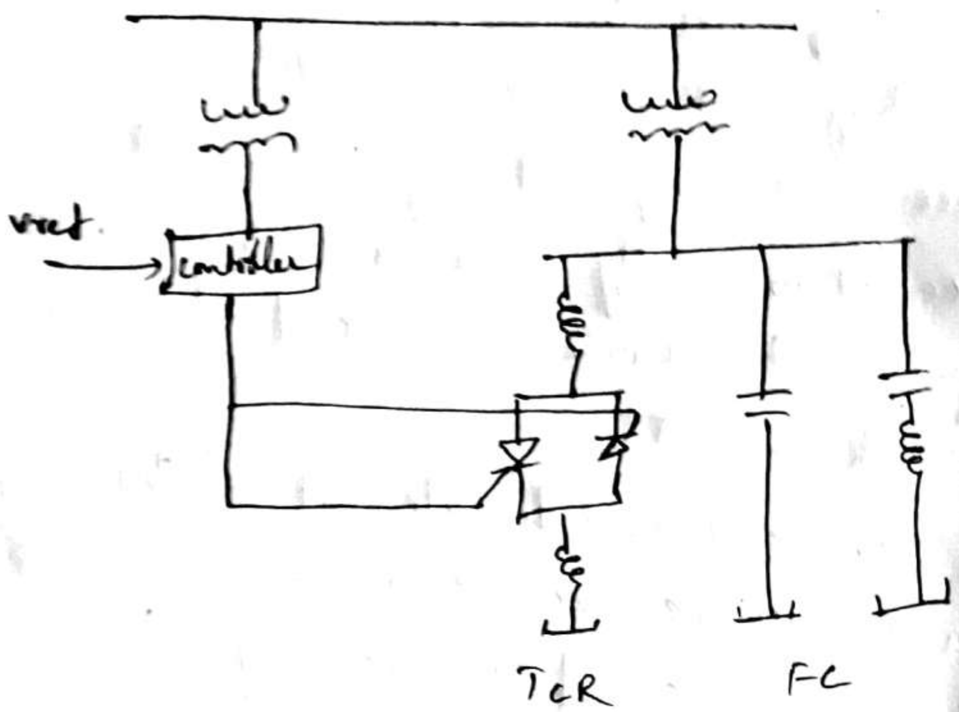
AC : Auxiliary controller

GPG = Gate pulse generator.

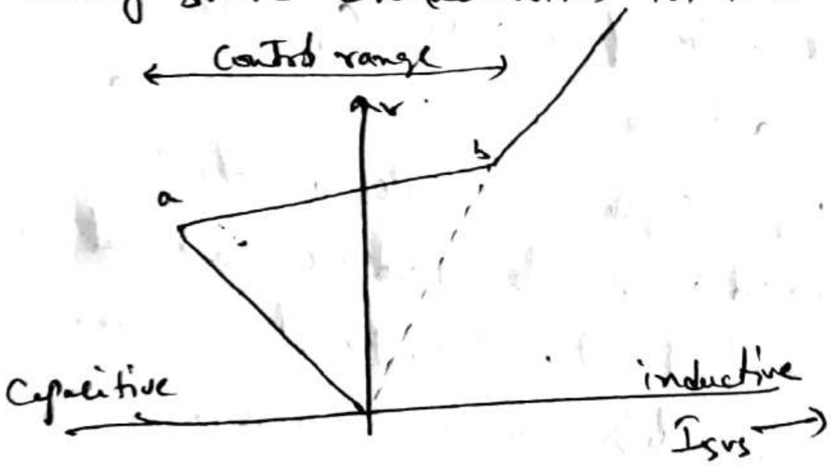
where the control signals are obtained from the voltage and the reactor current. The controller is usually an integral controller with variable gain to avoid the problems of control instability. The auxiliary signal Vs may be derived from the bus frequency, line reactive power or other locally measured quantities.

The TCR is usually operated with fixed capacitor (FC) to provide the variation of reactive power consumption from inductive to capacitive.

The schematic of FC-TCR is



The steady state characteristics in the V-I plane is

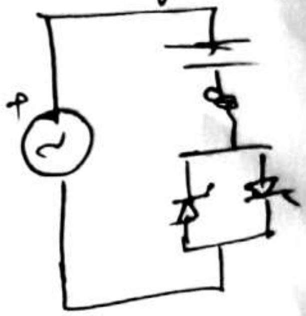


The control range 'ab' shows a +ve slope which can be adjusted from the gain in the current feedback path.

The harmonics injected by TCR into the system can be considerably reduced either with twelve pulse arrangement or with additional filters tuned to 5th and 7th harmonics.

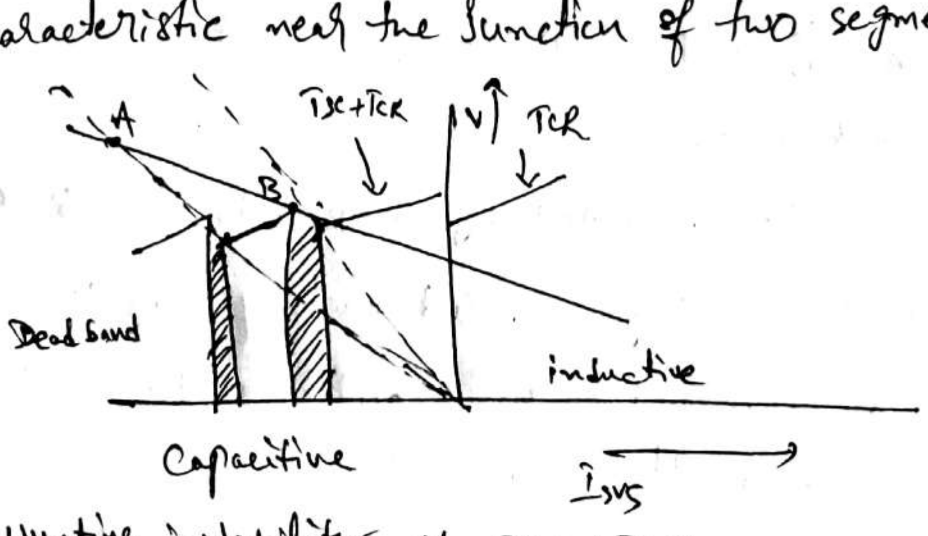
Thyristor switched capacitor

Thyristor switching is faster than mechanical switching and also it is possible to have transient free operation by controlling the instant of switching. A reactor is usually connected in series with the capacitor to reduce the rate of change of the inrush current



The TSC provides a discrete control over the reactive power generation.

For continuous control it is necessary to combine it with TCR of a rating slightly higher than the rating of individual capacitor bank. The SVS controller acts to switch in a capacitor as the voltage falls. By incorporating a hysterisis effect, the capacitor is switched in at a lower voltage than that at which it is switched out, it is possible to prevent a hunting instability which can ~~rise~~ arise if the system characteristic intersects the compensator characteristic near the junction of two segments.

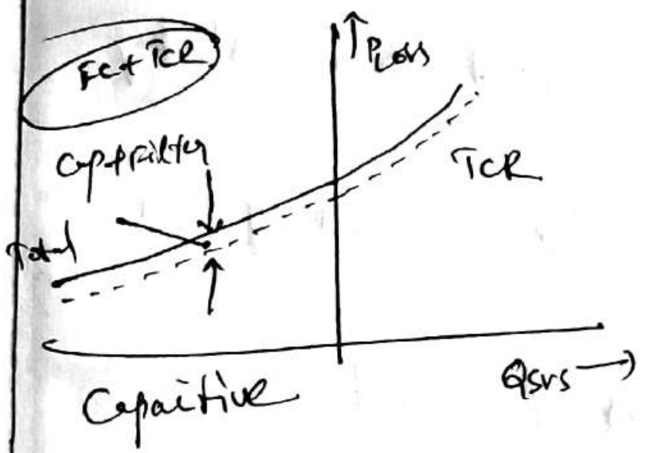


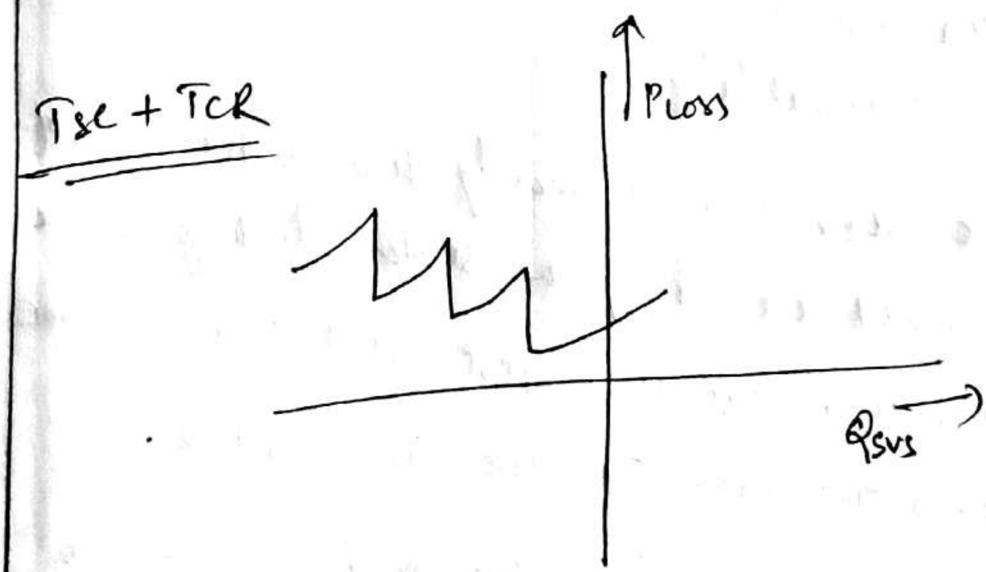
Hunting instability with TSC+TCR

The advantage of TSC instead of fixed capacitor is that (i). The rating of required TCR can be reduced

(ii) The power losses are reduced at the inductive operation.

The comparision of the losses between FC/TCR and TSC/TCR configurations is





Reactive power control during Transients

The control characteristics of the reactive power sources has a bearing on the system behavior during a transient. It is to be noted that the converter control characteristics can be modified to control the reactive power demand.

A suitable control of reactive power is required during a transient for the following reasons.

(1) control of dynamic over voltages caused by load rejection
(2) speedy recovery of power following a fault in the inverter system
(3) control of instability

The dynamic over voltages are mainly due to the excess of reactive power released by the sudden blocking of the converters. This requires a fast control of the reactive power generation from capacitive to inductive.

SVS can be ~~achieve~~ achieve the speed, however the initial control of over ~~ov~~ voltage may not be feasible unless the rating of the SVS is increased, which may be uneconomic.

The distortion of the voltage wave form produced during the recovery period. when the power is increased can cause commutation failures unless the rate of change of power is limited. This is crucial, particularly for low SCR. In this case the voltage support is also critical as increase in power can result in the reduction of voltage magnitude unless fast control of reactive power is implemented.

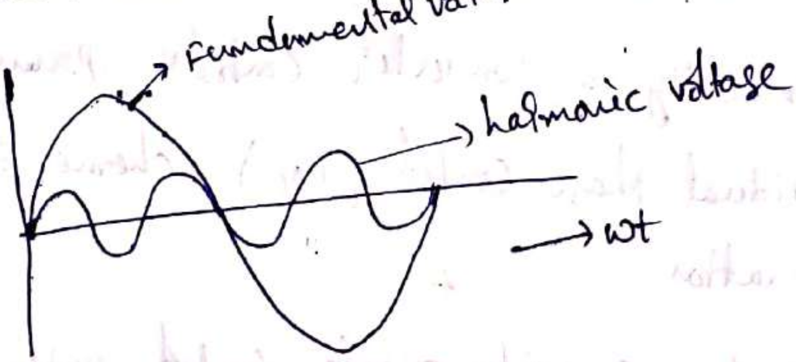
The voltage instability can also be a problem at low SCR and can be tackled by suitable converter control strategy or the provision of SVS at the converter bus.

Harmonics Unit V.7

Harmonics in HVDC Transmission.

~~For power quality control~~

Harmonics means the unwanted AC components in the system. These are generally multiples of fundamental frequency shown below



In power quality control harmonics plays a main role due to harmonics the power factor gets decreased and the reactive power increased so the efficiency of power quality will be lossed.

In HVDC Transmission there will be dc transmission and AC distribution so both AC & DC harmonics present in the system. In order to rectify AC harmonics use AC filters and to reduce dc harmonics use smoothing reactors and dc filters.

Disadvantages

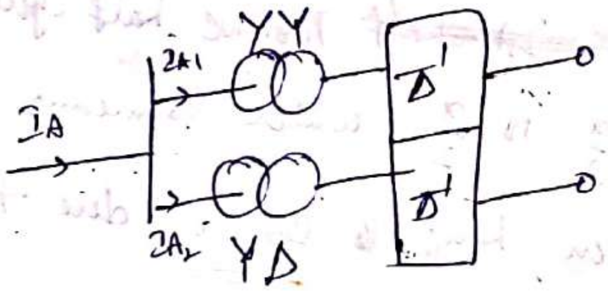
1) Telephonic interference
2) Extra power losses and consequent heating in machines and capacitors connected in the system.
(3) over voltages due to reasonable
(4) instability of converter controls, primarily with individual phase control (IPC) scheme of firing pulse generation
(5) Interference with ripple control systems used in load management.

Now these harmonics are divided into two groups in HVDC systems (i) characterstic harmonics
(ii) non characterstic harmonics.

Characterstic harmonic

Characterstic harmonics are harmonics of those order which are always present even under ideal operation (balanced AC voltages, symmetric 3ph N/W and equidistant pulses)

⇒ Consider a 12 pulse converter as shown below

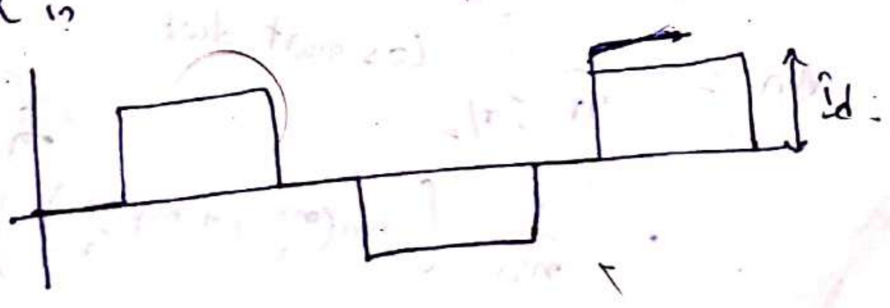


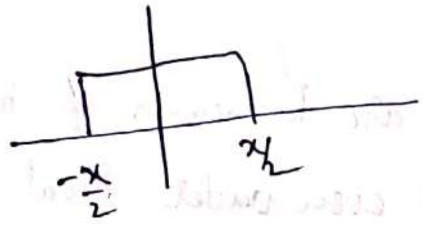
The harmonic currents can be evaluated by using fourier series analysis.

From above figure

$$I_A = I_{A1} + I_{A2} \quad \text{--- (1)}$$

For the 3ϕ supply one of the phase current of YY connected Transformer is





according to fourier series analysis

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n \cos n\omega t + \sum_{n=1}^{\infty} B_n \sin n\omega t$$

Let us take ~~1st half~~ positive half cycles with the limits of $\frac{-x}{2}$ to $\frac{x}{2}$ which means 120^0 conduction the function is even hence $B_n = 0$ due to half wave symmetry.

$$A_0 = \frac{1}{\pi}\int_{-x/2}^{x/2} d\omega t$$

$$\Rightarrow \frac{1}{\pi}\left[\frac{x}{2} + \frac{x}{2}\right] \Rightarrow \frac{x}{\pi}$$

$$\boxed{\frac{A_0}{2} = \frac{x}{2\pi}}$$

$$\Rightarrow A_n = \frac{1}{\pi}\int_{-x/2}^{x/2} \cos n\omega t \, d\omega t$$

$$= \frac{1}{n\pi}\left[\sin\left(\frac{nx}{2}\right) + \sin\left(\frac{nx}{2}\right)\right]$$

$$A_n = \frac{2}{n\pi} \sin\left(\frac{n\alpha}{2}\right)$$

For the '+ve' half cycles the function.

$$f_1(t) = \frac{\alpha}{2\pi} + \sum_{n=1}^{\infty} A_n \cos n\omega t + 0$$

$$= \frac{\alpha}{2\pi} + \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\left(\frac{n\alpha}{2}\right) \cos(n\omega t)$$

$$= \frac{\alpha}{2\pi} + \frac{2}{\pi} \sin\left(\frac{\alpha}{2}\right) \cos\omega t + \frac{2}{2\pi} \sin\alpha \cos 2\omega t + \frac{2}{3\pi} \sin\left(\frac{3\alpha}{2}\right) \cos 3\omega t - - - +$$

$$\Rightarrow \frac{2}{\pi}\left[\frac{\alpha}{4} + \sin\left(\frac{\alpha}{2}\right)\cos\omega t + \frac{1}{2}\sin\alpha \cos 2\omega t + \frac{1}{3}\sin\left(\frac{3\alpha}{2}\right)\cos(3\omega t) - - - - -\right]$$

Similarly for the '-ve' half cycles the function

$$f_2(t) = \frac{2}{\pi}\left[-\frac{\alpha}{4} + \sin\left(\frac{\alpha}{2}\right)\cos\omega t - \frac{1}{2}\sin\alpha \cos 2\omega t + \frac{1}{3}\sin\left(\frac{3\alpha}{2}\right)\cos(3\omega t) ..\right]$$

~~The current~~

For the +ve and -ve half cycles the function is

$$f(t) = f_1(t) + f_2(t)$$

$$f(t) = \frac{4}{\pi}\left[\sin\left(\frac{\alpha}{2}\right)\cos\omega t + \frac{1}{3}\sin\left(\frac{3\alpha}{2}\right)\cos 3\omega t + \frac{1}{5}\sin\left(\frac{5\alpha}{2}\right)\cos 5\omega t - - - ..\right]$$

where $\alpha = \frac{2\pi}{3} = 120^\circ$

then the expression becomes into

$$f(t) = \frac{4}{\pi}\left[\frac{\sqrt{3}}{2}\cos\omega t + 0 - \frac{1}{5}\times\frac{\sqrt{3}}{2}\cos 5\omega t + \frac{1}{7}\times\frac{\sqrt{3}}{2}\cos 7\omega t - - - -\right]$$

$$\Rightarrow \frac{2\sqrt{3}}{\pi}\left[\cos\omega t - \frac{1}{5}\cos(5\omega t) + \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t - - -\right]$$

The function in terms of currents

$$I_{A_1} = \frac{2\sqrt{3}}{\pi} I_d\left[\cos\omega t - \frac{1}{5}\cos(5\omega t) + \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t - - - -\right]$$

similarly

The current which is flowing on the YΔ winding

which is 30° phase shift with the YY winding is

$$I_{A_2} = \frac{2\sqrt{3}}{\pi}\angle 120^\circ I_d\left[\cos\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t - - -\right]$$

The flow of current in the 12 pulse converter

$$I_A = I_{A_1} + I_{A_2}$$

$$I_A = \frac{4\sqrt{3}}{\pi} I_d\left[\cos\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t - - - - -\right]$$

From the above expression

Rms value of fundamental component when $\mu = 0$ is

$$I_{10} = \frac{\frac{4\sqrt{3}}{\pi} I_d \cos\omega t}{\sqrt{2}}$$

$$\boxed{I_{10} = \frac{2\sqrt{6}}{\pi} I_d \cos\omega t}$$

The harmonic current $I_{h0} = \frac{I_{10}}{h}$

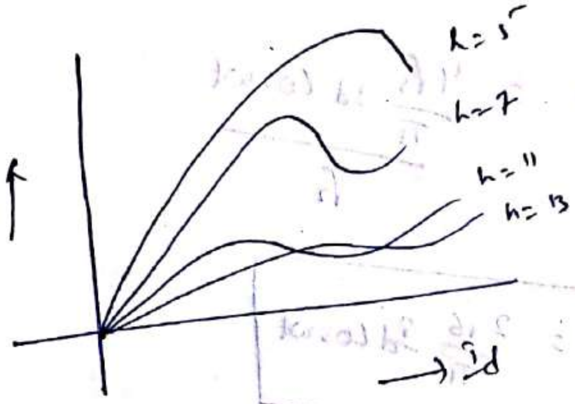
when over lap angle is non zero

$$i_h = \frac{I_{h0}\left[A^2+B^2-2AB\cos(2\alpha+\mu)\right]^{1/2}}{\cos\alpha - \cos(\alpha+\mu)}$$

where $A = \frac{\sin(h+1)\frac{\mu}{2}}{(h+1)}$ $B = \frac{\sin(h-1)\mu/2}{(h-1)}$

The effect of overlap angle is to prevent step changes in the AC currents this implies I_h is small than 'I_{h0}'

The magnitudes of the characteristic harmonics are function of load currents is shown below is



DC voltage harmonics

From the fourier analysis of DC voltage wave form

$$V_h = \frac{V_{do}\left[C^2+D^2-2CD\cos(2\alpha+\mu)\right]^{1/2}}{\sqrt{2}}$$

where $C = \frac{\cos(h+1)\frac{\mu}{2}}{(h+1)}$ $\quad D = \frac{\cos(h-1)\mu/2}{(h-1)}$

The order of harmonics in AC currents is

$$h = np \pm 1$$

The order of harmonics in DC voltages is

$$h = np$$

Non characterstic harmonics

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

These are due to

(i) imbalance in operation of bridge forming 12 pulse converter.

(ii) un equal T/F leakage impedences

(iii) Firing angle errors.

(iv) un balance & distortion in AC voltages.

These harmonics are mainly due to the difference in firing angle in two bridges which lead to unequal cancellation of harmonics of order 5, 7, 17, 19 etc

The unequal leakage impedence of the two converter T/Fs feeding the two bridges also leads to residual harmonics.

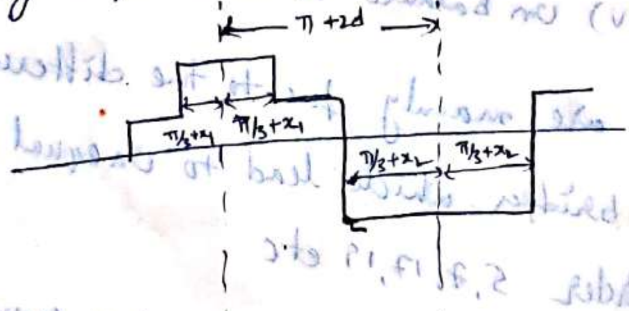
Affect of unbalanced voltages

The zero crossing of the commutation voltage gets shifted due to the presence of -ve sequence voltages. The zero crossing along with individual phase control system (IPC) introduce dissymetry in firing angles which leads to generation of non characterstics harmonics. By using (EPC) equidistant pulse control scheme the firing angle dissymetry can be avoided.

Effect of firing angle errors

The errors in the firing angles can be due to the nature of the control system [due to ripple in current feed back signal, not more than ± 0.2 %.]

The current wave form in the primary winding of YY T/F with firing angle errors is



This is for one phase and deviation of current waveform from the ideal case described by 3 parameters x_1, x_2, d

but for 3ph 9 parameters are obtained from the following relationship

$$x_{1A} + x_{1B} + x_{1C} = x_{2A} + x_{2B} + x_{2C} = 0$$

$$d_A - d_C = x_{1B} - x_{2B}$$

$$d_C - d_B = x_{1A} - x_{2A}$$

From the fourier analysis the non characteristic wave form

$$\frac{I_h}{I_P} = \frac{2}{h\sqrt{3}}\left[F_1^2(x_1,x_2) + (-1)^h \sin^2(hd)\, f_2(x_1,x_2)\right]^{1/2}$$

where $F_1(x_1,x_2) = \left|\sin\left(m\frac{\pi}{3}+hx\right)\cos(h\Delta x)\right|$ $h = \text{odd}$

$= \left|\cos\left(m\frac{\pi}{3}+hx\right)\cdot\sin(h\Delta x)\right|$ $h = \text{even}$

$$F_2(x_1,x_2) = \frac{1}{2}\left[\cos(2h\Delta x) - \cos 2\left(m\frac{\pi}{3}+hx\right)\right]$$

$h = 6n+m$

$x = \frac{x_1+x_2}{2}$ $\Delta x = \frac{x_1-x_2}{2}$

① If $d \neq 0$ then an even harmonics are present

② The magnitude of the characterstic harmonics are also effected

③ For heigher values of 'h' there is non characterstic harmonics dominate the characterstic harmonics.

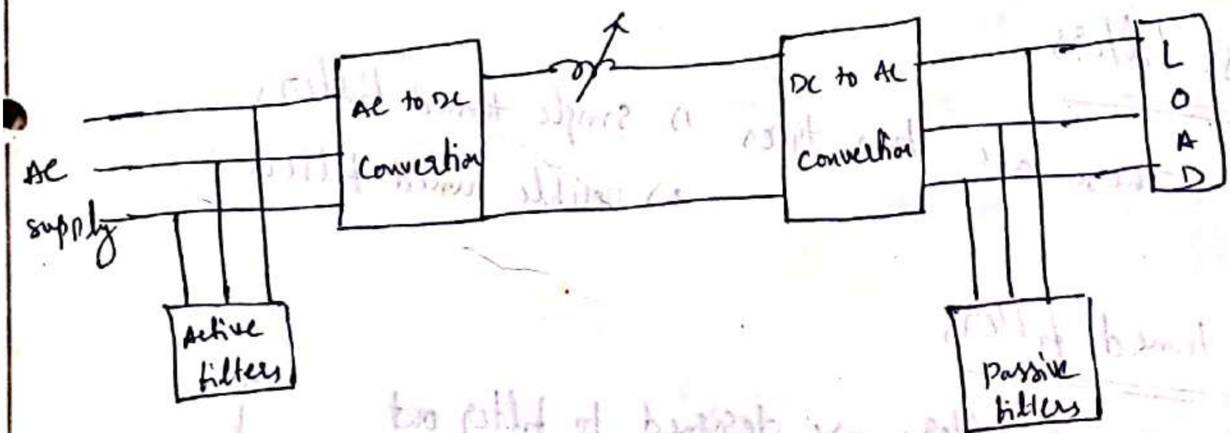
Filter

Filter is a device which consis of L, LC elements and it offers a low impedence to bypass the harmonic voltages.

Filters are used to reduce the harmonics as well as to increase the reactive power by increasing power factor.

There are 3 different Techniques to filter the harmonics in HVDC Transmission.

(i) using 12 pulse converter
(ii) Using un grounded Transformer
(iii) Using filters.



There are mainly two types of filters are used in HVDC system

AC filters
DC filters.

Ac filters which are used to reducing the Ac harmonics.

These filters are classified into 2 types

(1) Active filters

(2) passive filters.

The filters which we are connected ~~towards~~ at source end are called active filters, The filters which connected at load end are passive filters.

The passive filters are further classified into 2 types

(1) Band pass filters (low pass filters)

(2) High pass filters

Band pass filters are used to reduce lower order harmonics where are high pass filters are to reduce higher order harmonics

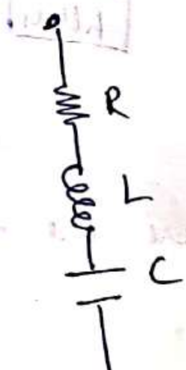
Band pass filters

These are two types 1) single tuned filters

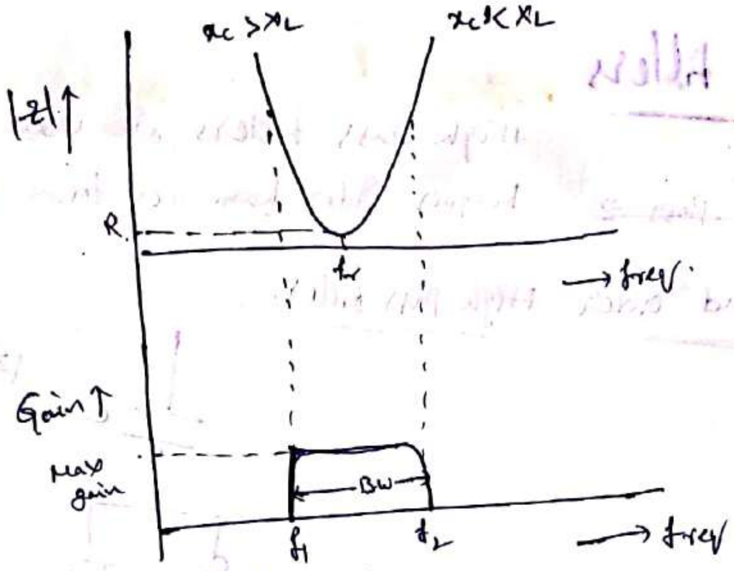
2) Double tuned filters

single tuned filters

single tuned filters are designed to filter out characteristic harmonics of single frequency like 5, 7, 11, 13



The impedence characteristic of single tuned filter is shown below.



From the impedence curve $x_C > x_L$ at below resonant freq 'fr'

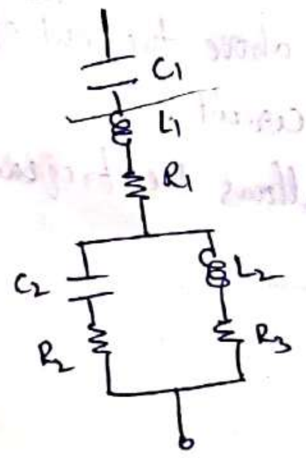
$x_C < x_L$ at above resonant freq 'fr'

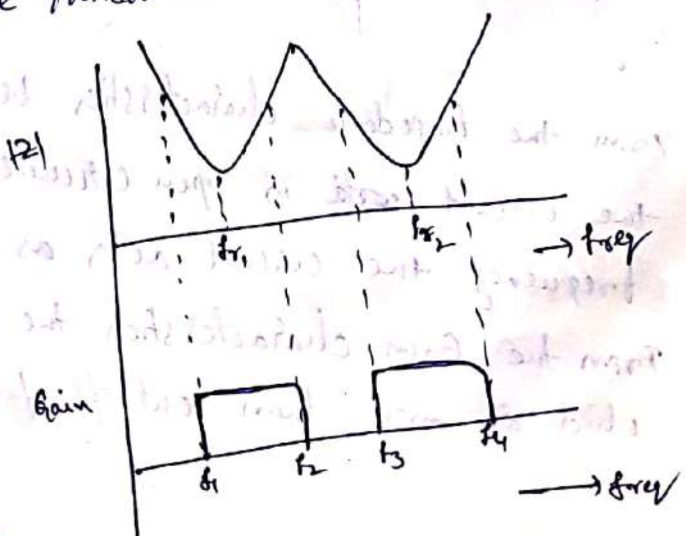
From the Gain characterstics the filter allows only frequencies in between f_1 & f_2

Double Tuned filters

The double tuned filters are used to filter out two discrete frequencies instead of using two single tuned filters

Advantage power loss at the fundamental freq is reduced.



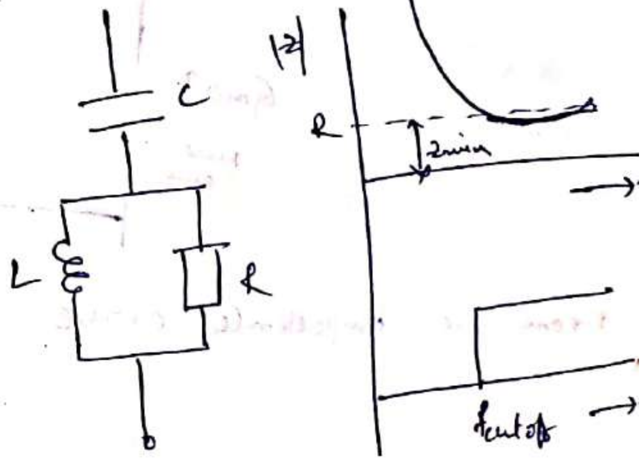


High Pass filters

High pass filters are used to eliminate heigher order harmonics from 21, 23, 25, 43, 45 - - .

(1) ~~High Pass~~

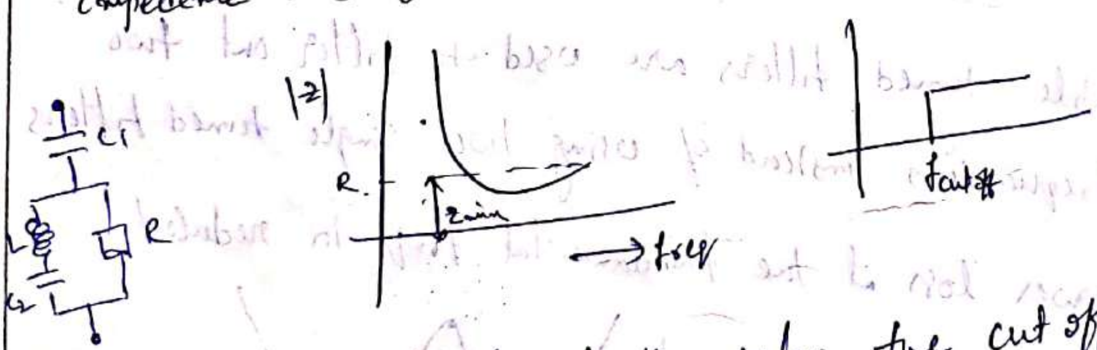
(1) second order High pass filters



(2) C type filter

By using C type power loss at fundamental frequency Reduced

Empedence and gain characterstics are



From the Empedence characterstics below the cut off frequency the circuit ~~acts~~ is open circuited and above the cut off frequency the circuit acts as a short circuit.

From the Gain characterstics the filter allows the frequency which are more than cut off frequency

Design criteria of filters

The major design objective of the filter is to reduce the telephone interference and this can be measured by any of the following performance indices.

(1) Harmonic distortion.

This is measured in 2 ways

The harmonic distortion is defined as

$$D = \left(\frac{\sum_{n=2}^{m} I_h Z_h}{E_1} \right) \times 100$$

where I_h is the harmonic current

Z_h is the harmonic impedance of the system

E_1 is the fundamental component of line to neutral voltage

m = heighest harmonic order.

2nd definition

$$D_{RSS} = \frac{\left[\sum_{h=2}^{m} (I_h Z_h)^2 \right]^{1/2}}{E_1} \times 100$$

This is in the range of 2-5

In some cases the harmonic distortion can be defined individually for a single harmonic as

$$D_h = \left(\frac{I_h Z_h}{E} \right) \times 100$$

(2) Telephone influence factor. (TIF)

$$TIF = \frac{\left[\sum_{h=2}^{m} (I_h Z_h F_h)^2\right]^{1/2}}{E_1}$$

where $F_h = 5 h f_1 P_h$

P_h = C-Message weighting

This weighing reflects the frequency and has a max value at the frequency of 1000 Hz.

This is in the range of 25-50%.

~~Used in USA~~.

This indices uses in ~~USA~~ 'USA'

Telephone harmonic form factor (THFF)

Telephone harmonic form factor is same like that of TIF

$$THFF = \frac{\left[\sum_{h=2}^{m} (I_h Z_h F_h)^2\right]^{1/2}}{E_1}$$

where $F_h = \left(\frac{h f_1}{800}\right) W_h$

W_h = Psophometric weight at the harmonic order 'h'

It is popular in Europe.

IT Product.

BTS - EEI system has defined another index known as IT Product and is given by

$$IT = \left[\sum_{h=2}^{m} (I_h F_h)^2 \right]^{1/2}$$

Another product

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

(BTS = Bell telephone systems

EEI = Edison electric institute.)

=) uses in USA.

Design of single tuned filter.

Filter impedance Z_f is

$$Z_f = R + j(X_L - X_C)$$

$$Z_f = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

At resonant frequency $|Z_f| = R$.

$$\omega L = \frac{1}{\omega C}$$

$\therefore \quad \omega = \omega_m = \frac{1}{\sqrt{LC}}$ = Tuned angular frequency in rad/sec

where $\omega_m = 2\pi f_m$

$$X_0 = \omega_m L = \frac{1}{\omega_m C} = \sqrt{\frac{L}{C}}$$

Quality factor : $Q = \frac{X_0}{R}$

Deviation of resonant frequency for any frequency 'ω' other than the tuned frequency ω_m is

$$\delta = \frac{\omega - \omega_m}{\omega_m}$$

$$\omega = \omega_m (1+\delta)$$

As we know $X_0 = \omega_m L = \frac{1}{\omega_m C} = RQ$

$$\therefore \quad C = \frac{1}{\omega_m X_0} = \frac{1}{\omega_m R Q}$$

$$L = \frac{X_0}{\omega_m} = \frac{RQ}{\omega_m}$$

$$Z_f = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

$$Z_f = R + j\left[\omega_m(1+\delta)\frac{RQ}{\omega_m} - \frac{1}{\omega_m(1+\delta)\frac{1}{\omega_m RQ}}\right]$$

$$= R + j\left((1+\delta)RQ - \frac{RQ}{1+\delta}\right)$$

$$= R\left[1 + jQ\left(1+\delta - \frac{1}{1+\delta}\right)\right]$$

$$= R\left[1 + jQ\left(\frac{\delta^2+2\delta}{1+\delta}\right)\right]$$

For $\delta << 1$

$$Z_f = R(1+j2\delta Q) \Rightarrow |Z_f| = R\sqrt{1+4\delta^2 Q^2}$$

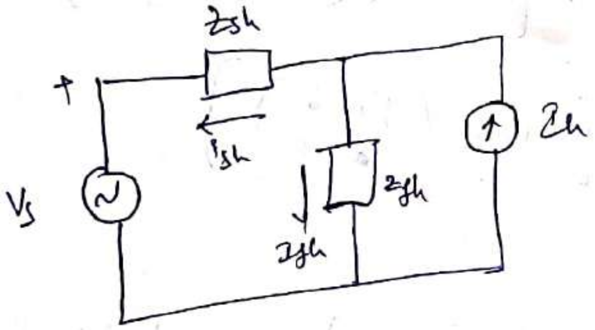
$$= \frac{X_0}{Q}(1+j2\delta Q)$$

$$= X_0\left(\frac{1}{Q}+j2\delta\right)$$

$$|Z_f| = X_0\sqrt{\frac{1}{Q^2}+4\delta^2}$$

Illy $$|Y_f| = \frac{1}{R\sqrt{1+4\delta^2 Q^2}} = \frac{Q}{X_0\sqrt{1+4\delta^2 Q^2}}$$

The ~~equivalent~~ single tuned filter can be seen its equivalent circuit by its harmonic current 'I_h' generated by the converter can be represented as shown in fig below, Z_{fh} and Z_{sh} parameters to be considered as filter and system impedances at its harmonic frequency as (Hf)



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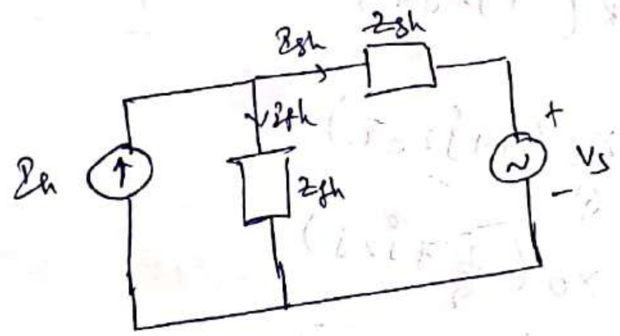


From equivalent circuit $I_{fh} = \frac{I_h |Z_{sh}|}{|Z_{sh} + Z_{fh}|}$

harmonic voltage in filter.

$$V_{fh} = I_{fh} |Z_{fh}|$$

$$= \frac{I_h |Z_{sh}| |Z_{fh}|}{|Z_{sh} + Z_{fh}|}$$

$$= \frac{I_h}{|Y_{fh} + Y_{sh}|}$$

The main consideration in designing the filter is to select the filter admitance Y_{fh} in order to minimize V_{fh}. The consideration of designing filter is difficulty by the uncertainity about its network admitance 'Y_{sh}'

The main possible considerations of the system impedence in its complex plane are

(a) Impedence angle (θ) is limited as shown below

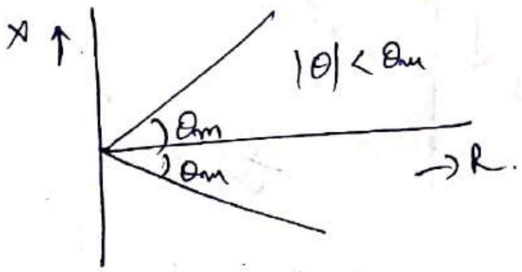


fig a)

(b) Impedence is limited both in angle and magnitude as shown in below and its economic design considerations of filters and also have assesment of its harmonic distortion the converter bus voltage

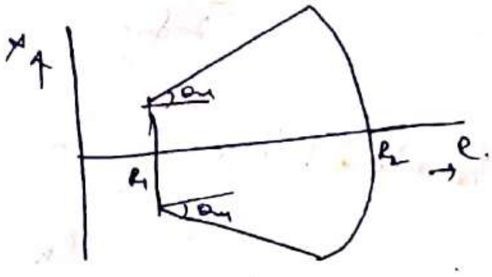


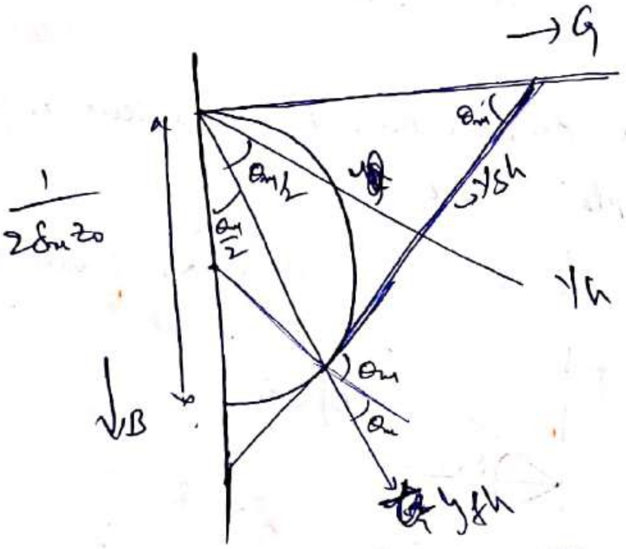
Fig b

Fig a is simplistic it allows a simple choice of Q

~~The locus of ti~~

The locus of filter admittance with variation in Q is shown below

$$Y = G + jB$$



where $X_0 = QZ_0 = RQ = \sqrt{\frac{L}{C}}$

$$\therefore \quad Q_{opt} = \frac{\cot\left(\frac{\theta_m}{2}\right)}{2\delta_m} = \frac{1+\cos\theta_m}{2\delta_m \sin\theta_m}$$

$$Y_h = Y_{fh} \cos\theta_m/2$$

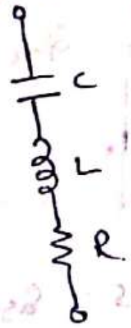
$$|Y_{fh}| = \frac{\cos\theta_m/2}{2\delta_m X_0}$$

Its harmonic voltage 'V_{fh}' is

$$V_{fh} = \frac{I_h}{|Y_{fh} + Y_{sh}|}$$

$$V_{fh} = \frac{4\delta_m Z_0 I_h}{1+\cos\theta_m}$$

Design of minimum cost tuned filter



The MVAR Rating of the Capacitor in tuned 'h' order branch is the sum of the fundamental component MVAR and the 'h' th order harmonic component MVAR.

The Total rating 'Q' of tuned AC filter capacitor is given by the sum of MVAR rating due to fundamental 'Q_1', constant voltage source V_1 and MVAR rating due to harmonic current of h^{th} order through the filter.

⇒ The reactive power rating of capacitor

$$Q_{rc} = Q_1 + Q_h$$

$$= I_1^2 X_c + I_{hf}^2 X_c$$

$$= \frac{V_1^2}{X_c} + \frac{I_{hf}^2}{h\omega_1 C}$$

$$= V_1^2\omega_1 C + \frac{I_{hf}^2}{h\omega_1 C} \qquad V_1^2\omega_1 C = S$$

$$= S + \frac{I_{hf}^2}{h\omega_1 C}\cdot\frac{V_1^2\omega_1 C}{V_1^2\omega_1 C}.$$

= ~~S + I_{hf}^2~~

$$\Rightarrow \boxed{Q_{rc} = S + \frac{I_{hf}^2 V_1^2}{Sh}}$$

where S = Size of Capacitor

w_1 = Fundamental frequency

V_1 = Fundamental voltage of AC N/W phase to ground

I_{hf} = harmonic current of h^{th} order through the tuned filter branch

Similarly The rating of reactor

$$\boxed{Q_{rL} = \frac{S}{h^2} + \frac{V_1^2 I_{hf}}{Sh}}$$

Assuming the unit costs of capacitors and reactors to be directly proportional to their respective MVAR ratings.

cost of capacitor = $K_C\, Q_{rc}$, K_C = PU value of Q_{rc} Rs/MVAR

cost of reactor = $K_L\, Q_{rL}$ K_L = PU value of Q_{rL} Rs/MVAR.

cost of resistance is constant

where K_C & K_L are in Rs/MVAR

∴ Total cost K = cost of capacitor + cost of reactor + cost of Resistance

Scanned with CamSc

$$K = K_c Q_{rc} + K_L Q_{rL} + K_r$$

Subtitute Q_{rc} and Q_{rL} in above expression

$$K = K_c\left(S + \frac{V_1^2 I_{hf}^2}{Sh}\right) + K_L\left(\frac{S}{h^2} + \frac{V_1^2 I_{hf}^2}{Sh}\right) + K_r$$

$$\Rightarrow \quad K = S\left[K_c + \frac{K_L}{h^2}\right] + \frac{1}{S}\left[\frac{V_1^2 I_{hf}^2}{h}K_c + \frac{V_1^2 I_{hf}^2}{h}K_L\right] + K_r$$

$$K = AS + \frac{B}{S} + K_r$$

where $A = K_c + \frac{K_L}{h^2}$ $\quad B = \frac{V_1^2 I_{hf}^2 (K_c + K_L)}{h}$

Also the minimum cost of filter occurs at

$$\frac{dK}{ds} = 0$$

$$A - \frac{B}{S_{min}^2} = 0$$

$$S_{min} = \sqrt{\frac{B}{A}}$$

corresponding S_{min} the cost of filter is the minimum

cost of filter

$$K_{min} = A S_{min} + \frac{B}{S_{min}} + K_r$$

$$= A\sqrt{B/A} + \frac{B}{\sqrt{B/A}} + K_r$$

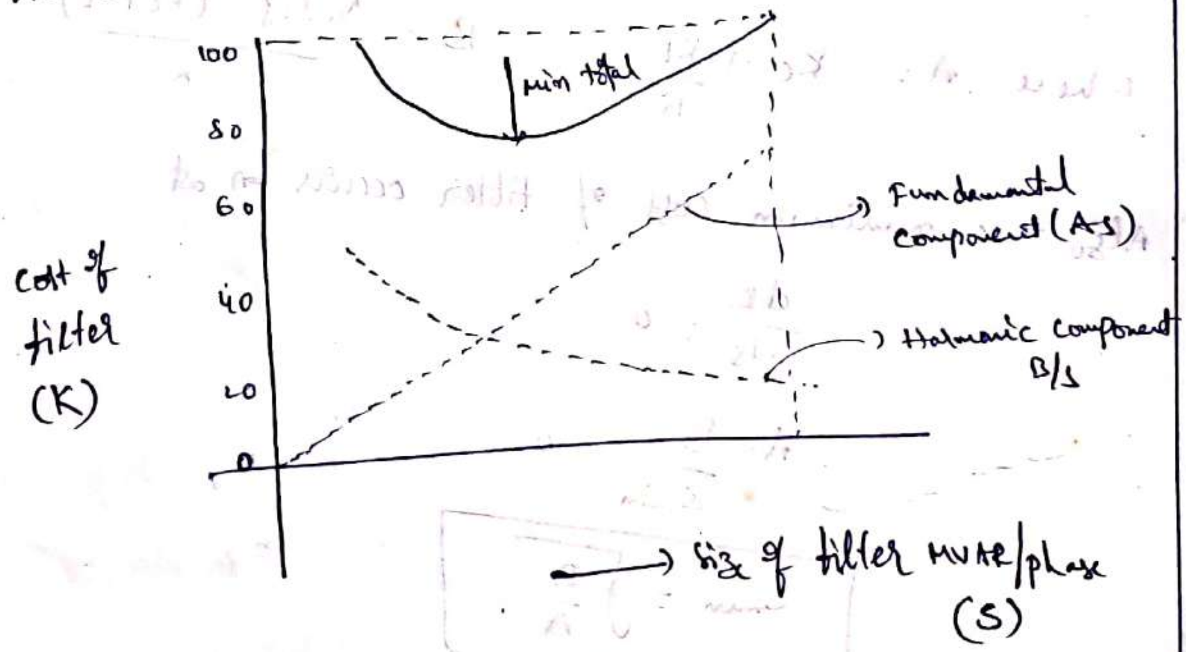
$$= \sqrt{AB} + \sqrt{AB} + K_r$$

$$= 2\sqrt{AB} + K_r$$

where K_r cost of resistance is constant

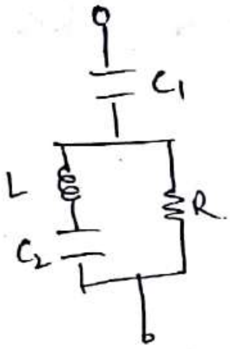
$$K_{min} = 2\sqrt{AB}$$

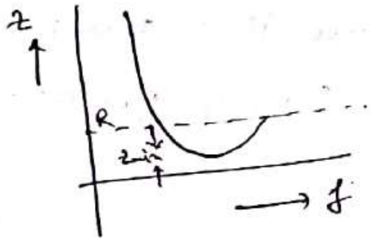
Filter design based on minimum cost is called "minimum cost filter"



Design of high pass filter

The design of high pass filter is to filter out the harmonics of higher order above 17. Its circuit and characteristics are





The filter impedence Z_f

$$Z_f = \frac{Z_0\left[\sigma + j\left(\frac{h_0}{h}\right)\left(\sigma^2 - 1 - \left(\frac{\sigma h_0}{h}\right)^2\right)\right]}{1+\left(\frac{\sigma h_0}{h}\right)^2}$$

and reactive power supplied by filter is

$$Q_f = \frac{h_0}{(h_0^2 - 1)}\left(\frac{V_1^2}{Z_0}\right)$$

where $\sigma = R/Z_0$. $\quad Z_0 = \sqrt{L/C}$

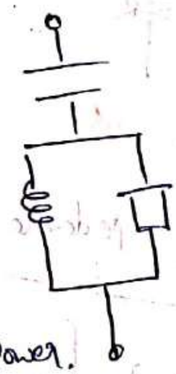
$0.5 < \sigma < 2$

$h_0 \leq \sqrt{2}\, h_{min}$

h_{min} is the smallest value of 'h' at this value filter impedence has decreased to approximatly to 'R'

The filtering is improved if Q_f is increased and higher value of 'h_o' hence it is advantage to design high pass filter to exclude six pulse operation.

Dc filters



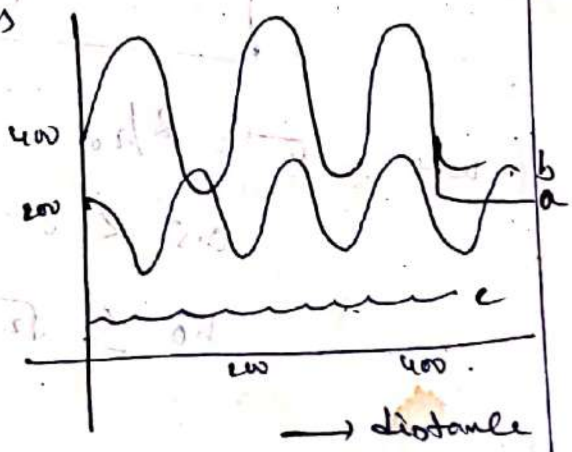
The design of Dc filters similar to that of Ac filters except the value of the capacitor, ~~in filter~~ the The filter is choosen from considerations other than that of reactive power.

The harmonics in the DC voltage across the converter contains both characterstic and non characterstic harmonics

These harmonics results current harmonics in Dc lines and cause noise in Telephone circuits.

The effectiveness of Dc filter is judged by

1. Max voltage TIF on dc high voltage bus
2. Max induced noise voltage (INV)
3. Max permissible noise to ground



where a = earth return
b = Metallic return
c = Bipolar.