HVDC UNIT-I and FACTS

Introduction :- The Electrical Energy is normally generated at the power stations far away from the consumers & is delivered to the load consumers through a network called Transmission & distribution.

In power systems, voltage is supposed to be constant which is obviously not. So we have to control it in such a way that it remains constant.

→ Why does the voltage need to be constant at all?

- Because most of the devices, apparatus, consumer appliances etc, are all designed to work at a specified voltage.
- Too wide variations of voltage due to the continuous variations in the load may cause mis-operation (or) even malfunctioning of the consumers appliances.
- such voltage variations are undesirable & the supplier is required to maintain the voltage within the prescribed limits such that the consumers appliances may operate satisfactorily.

→ The major advantage of Electrical Form of Energy is that it can be transported & controlled with high degree of efficiency & Reliability.

A properly designed & operated Power system should therefore, meet the following fundamental Requirements.

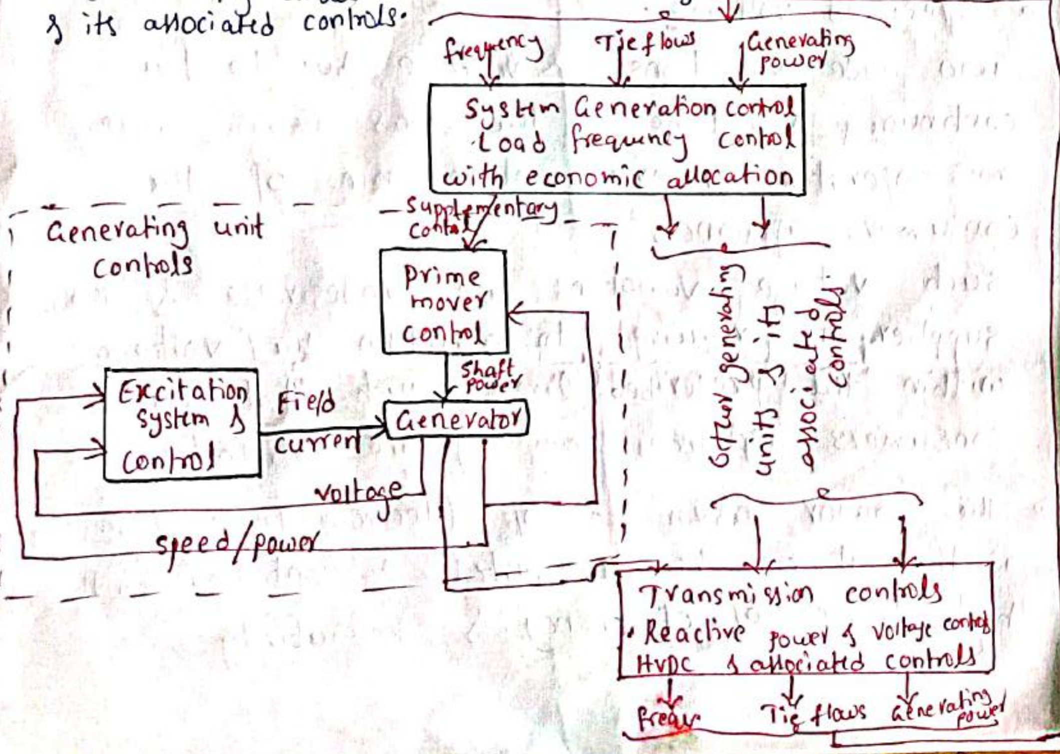
(i) The system must able to meet the continuously changing load demand for Active & Reactive power.

(ii) The system should supply energy at minimum cost & with minimum ecological impact.

(iii) The quality of power supply must meet the following considerations.

(a) constancy of frequency
(b) " " voltage.

Several levels of controls involving a complex array of devices are used to meet the above requirements. The below fig. shows the various subsystems of power systems & its associated controls.



The above figure shows that the controllers operating directly an individual system Elements.

→ In a generating unit there consists of prime mover control & Excitation controls.

The prime mover control are concerned with speed Regulation. The function of Excitation control is to regulate the generator voltage & Reactive power output.

→ The desired Active power output of the individual units are determined by the system Generation control.

→ The Transmission controls include power & voltage control devices such as static VAR compensators, synchronous condensors, switched capacitors, Tap changing transformers, phase shifting transformers etc.

Conventional control Mechanisms :– As we have discussed earlier that if a power system is said to be a properly designed system, it should meet the basic requirements that must meet the continuously changing load demand for Active & Reactive power, must maintain(or) try to maintain the voltage & Frequency constant.

To meet the above we have basic control methods.

→ For generation control ⇒ (a) Excitation control
(b) System Generation control.

→ For Transmission control ⇒ (a) Tap changing Transformer
(b) Phase Shifting Transformer.

(a) Excitation control :- (For Generator control).

Due to the continuous changes in the load on the supply system, the terminal voltage of the Alternator also changes. So as to maintain the constant voltage, the use of Excitation is made.

→ Induced EMF (E) of an alternator depends on the excitation current (field current). The terminal voltage of an alternator can be given as $V = E - IZ$. As the load current, & hence the armature current also increases, voltage drop in the armature also increases (i.e, IZ).

So the field current must be increased to compensate this voltage drop, such that the terminal voltage (V) is at the target value.

For this purpose, Alternators are provided with excitation control or automatic voltage regulator systems.

→ The control which is used for providing the necessary field current to the Rotor winding of the synchronous machine. Such control system is known as Excitation control.

→ In other words, Excitation control is defined as the system which is used for the production of flux by passing the current in the field winding.

→ An Automatic Voltage regulator (AVR) detects the terminal voltage & compares it with the reference voltage. The difference b/n the detected voltage & given reference voltage is called as the error voltage.

→ The Regulator then controls the excitation voltage of the alternator to cancel out the error voltage. Thus ~~the~~ an automatic voltage regulator controls the voltage by controlling the excitation.

The main requirement of an Excitation is Reliability under all conditions of service, a simplicity of control, ease of maintainance, stability & Fast transient response.

☆ Due to high inductance of an alternator either a variation of field current Resistance or change in the excitation voltage will not be able to give quick Response. To achieve the quick response, which is required due to voilent fluctuations in the industrial load, quick acting Regulators or Power system stabilizers (PSS) are used.

[AVR is used for maintainance of the terminal voltage of the synchronous M/c (alternator) according to the reference.

PSS are used for mitigation of the Electromechanical oscillations (voltage fluctuations) of the Synchronous M/c of various disturbances].

In General Excitation control System ~~con~~ is mainly clasified into 3 types.

They are ⓐ DC Excitation system
(b) AC " "
(i) Rotor Excitation system
(ii) Brushless " "
(c) Static Excitation system..

(b) Automatic Generation control :- In an Electrical power system, Automatic Generation control is a system for adjusting the output power of Multiple generators at different power plants, in response to changes in the load. since a power grid requires that generation & load closely balance moment by moment, frequent adjustments to the output of generators are necessary.

→ The balance can be judged by measuring the "system frequency". If it is increasing more power is being generated than used which causes all the machine in the system to accelerate.

If the system frequency is decreased more load is on the system than the instantaneous generation can provide, which causes all the generators to Deaccelerate.

As the system load is continuously changing, it is necessary to change the output of generators automatically.

→ The primary objective of AGC is to regulate frequency to the specified value & to maintain the interchange power b/n control areas at the scheduled values by adjusting the output of selected generators.

This function is commonly referred to as Load frequency control (LFC).

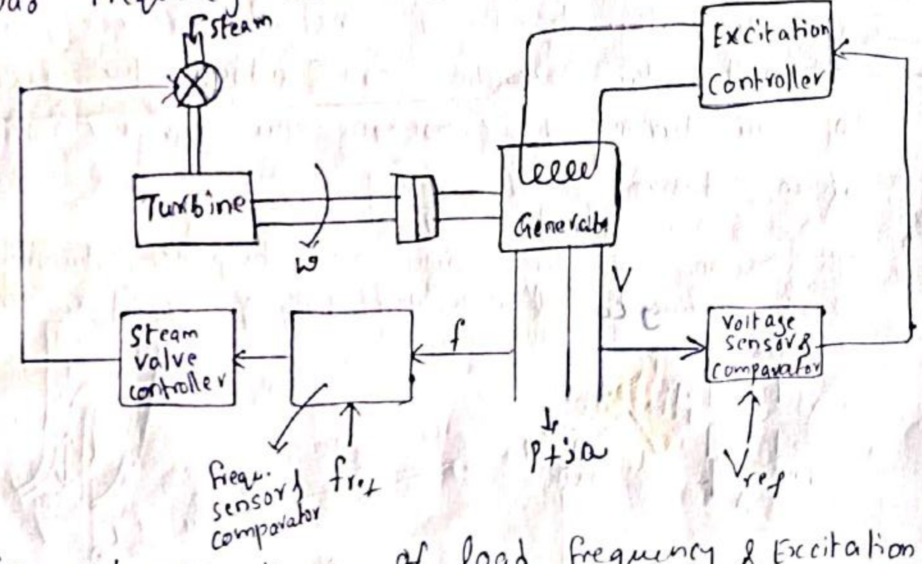


Fig:- Schematic diagram of load frequency & Excitation voltage Regulator.

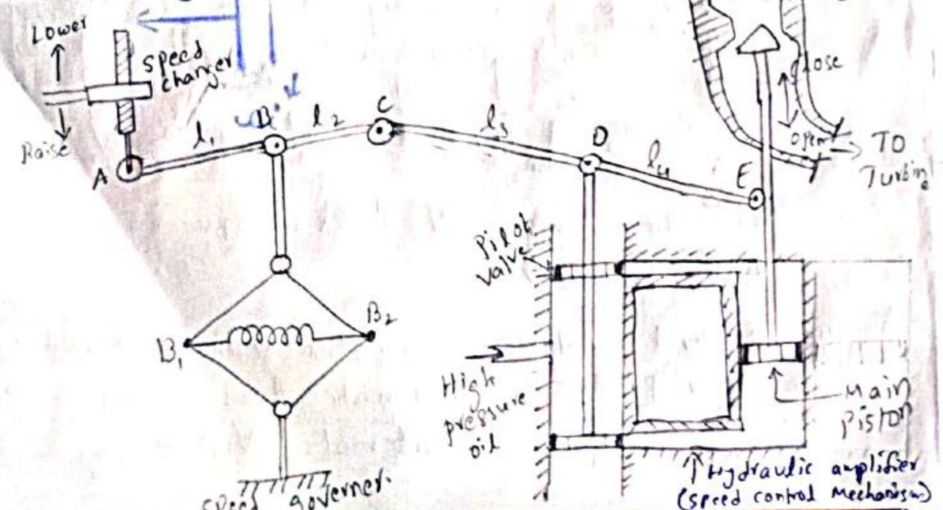
* In General Automatic Generation control clasified into two major parts. (i) Automatic load frequency control
(ii) Automatic Voltage Regulator control.

Now when the load on the power system changes continuously, ~~atted~~ automatically the speed of the Generators will changes, this shows the direct impact on Frequency.

→ If the system consists of a single Machine connected to a group of loads, the speed & frequency changes in accordance with the load variations.

→ Normally, frequency would vary about 5% b/n light load & full load conditions. On the other hand if constant frequency is required, the operator can adjust the speed of the turbine by changing the governor characteristics when desired. $\left[N = \frac{120f}{P}\right]$.

This can be done with the help of Automatic load frequency control with the help of speed Governing system.



The above figure shows the diagram of speed governing system which control the Real power flow in the System. The speed governing system consists of the following parts.

(1) Speed governor :- This is a fly ball type of speed governor & constitutes the heart of the system as it senses the change in speed or frequency. With the increase in speed the fly ball moves outwards & the point B on linkage mechanism moves downwards & viceversa.

[If the speed governor senses that there is an increase in speed then fly ball moves outwards i.e., B moves downwards → A moves upwards

If A moves upwards means lower speed changer that means we have to reduce the turbine speeds means control the steam inflow.

B ↓ A ↑ C ↑ D ↓ E ↑ pivot moves upwards means Main piston valve closes that means control the steam inflow.

ll ly Speed governor senses that there is a decrease in speed (load increases) then the fly ball moves inwards i.e., B moves upwards → A moves downwards.

A moves downwards means raise in speed changer. That means we have to increase the turbine speed by increasing the steam sent to the turbine to rotate.

B ↑ A ↓ C ↓ . D ↑ E ↓ → means open the Main piston valve to increase the steam flows.]

(ii) **Linkage Mechanism**:- ABC & CDE are the rigid links pivoted at B & D respectively. The mechanism provides a movement to the control valve in proportion to the change in speed. Link 4 (l_4) provides a feed back from the steam valve movement.

(iii) **Hydraulic Amplifier**:- This consists of the main piston & pilot valve. Low pressure pilot valve movement is converted into high pressure pilot valve movement which is necessary to open or close the steam valve against the high pressure steam.

(iv) **Speed changer**:- The speed changer provides a steady state power o/p setting for the turbine. The downward movement of the speed changer opens the upper pilot valve so that more steam is admitted to the turbine under steady state condition. ||ly The ~~dow~~ upward movement of speed changer closes the upper pilot valve & opens the lower pilot valve so that less steam flows to the turbine.

For Transmission Control:- To control the voltage & power in the transmission side we generally prefers the conventional devices.

(1) **Tap Changing Transformers**:- Excitation control is particularly used for the generator side to keep the alternator voltage constant. Eventhough, excitation control is satisfactory only for Relatively short lines. However it is not suitable for long lines as the voltage at the alternator terminals will have to be varied too much in order that the voltage at the far end of the line may be constant.

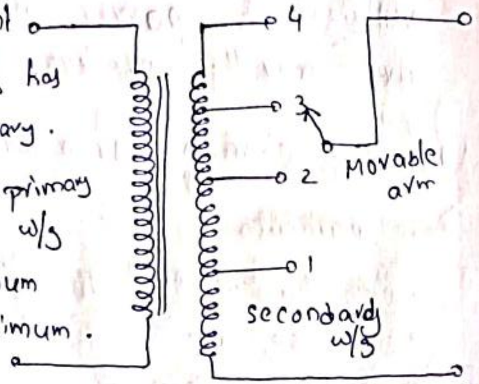
Under such situations, the problem of voltage control can be solved by employing other methods. One important method is to use Tap-changing Transformer.

(i) off-load Tap changing T/F's
(ii) ON-load " "

In Tr. & distribution systems there can be voltage fluctuations when the load varies in the system. To maintain the voltage constant Tap changing T/F's are used.

(i) OFF-load Tap changing Transformer:-

Figure shows the arrangement where a number of tappings has been provided on the secondary. when the movable arm makes contact with stud-1, the secondary voltage is minimum & with stud-5, it is maximum.



→ During light load conditions, the movable arm is placed at stud-1 & with increase in load the movable arm is taken to the stud-2, 3, 4 so that the voltage drop in the Tr. line is compensated & the o/p secondary voltage is maintained.

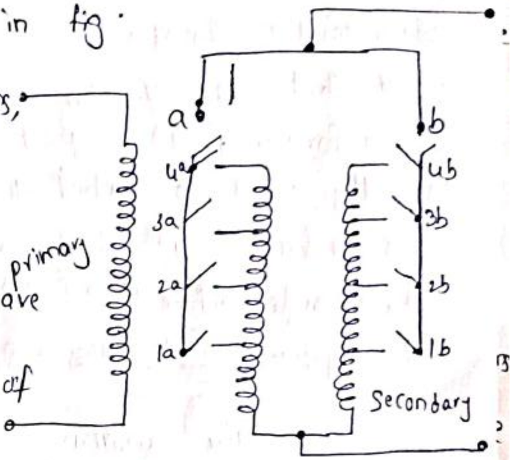
→ The disadvantage of this scheme is whenever the tapping is to be made the load must be disconnected first, from the T/F & thus it is referred to as off-load tap-changing Transformer.

→ This type of tap-changing cannot be used where continuity of supply to the load is the main priority. This drawback can be overcomed by ON-load tap-changing transformer.

(ii) ON-load tap changing transformer:-

Here the coils of the winding in which tapping are to be done are divided into two parallel ~~divid~~ sections of the coil. This forms the two w/s's 'a' & 'b' as shown in fig.

In normal working conditions, switches 'a' & 'b' & with the identical tapping (1a & 1b (or) 2a & 2b - - -) are in closed condition. Each secondary w/s carries half of the total current.



Suppose the T/F is working with tap position of 2a & 2b & it is desired to alter its position to 3a & 3b. For this purpose one of the switches say 'a' is opened. This takes the secondary w/s 'a' out of the circuit.

Now the secondary w/s controlled by switch b has to carry the total current. Then the tapping on the disconnected side is changed to 3a & switch 'a' is closed. After this, switch b is opened to disconnect its winding, tapping position on this w/s is changed to 3b & then switch b is closed.

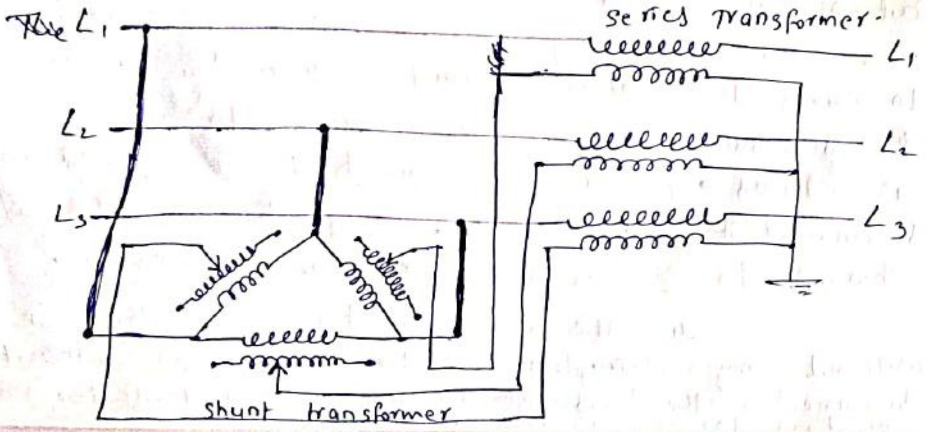
In this way the tapping position is changed without any interruption in the supply (or) without disconnecting the load from the supply. And thus the name ON-load tap-changing Transformer.

(2) **Phase shifting Transformer**:- As we know that, Day to day the load on the power system gradually increases & it is very important to improve the transfer capability of complex power generation through transmission lines.

For that, one of the best choice is phase shifting Transformer (PST). PST is a special type of T/F typically used to control the flow of Active power in 3-ø tr. line. It does so by regulating the voltage phase angle difference (δ) b/n any two buses of the system. $[\because \delta = \delta_1 - \delta_2]$.

The working principle of phase shifting Transformer is mainly depends on an injection of the phase shifted voltage source into the line using a series connected Transformer. This can be fed through a shunt transformer. Thes two transformer's configuration mainly includes the phase shift.

⇒ ~~The~~



The construction of PST mainly includes two sets of transformer. The first one is the shunt unit that is connected in parallel through the line where as the second is series unit connected in series through the Tr-line.

→ The shunt unit is used to shift the power angle (δ) by 90° to apply this power toward the series unit. The series unit includes the phase shifted power toward the transmission line.

→ The modification of phase angle can be done by the blend of connection as well as the position of the tap change.

→ These kinds of Transformers are also called phase angle Regulator (PAR), phase shifter other wise quadrature booster.

Types of phase shifting Transformers

(a) Direct PST
(b) Indirect PST
(c) Symmetrical PST
(d) Asymmetrical PST

Advances in power Electronic switching devices :-

→ The Mercury Arc Rectifier (MAR) developed in 1900's is reported to be the first power electronic device have been developed.

→ The power Electronics Industry, however did not take off really untill the Thyristors or SCR came in to play.
The SCR's were proposed by Bell laboratories in early 1950's. However the inability of the SCR to be turned off directly from its gates proved to be quite a hurdle.

→ Thus slowing down its adoption in other applications.

To overcome the above disadvantage in SCR, The advanced device Transistor has been discovered in 1947.

→ In April, 1950 with very thin germanium crystal as the base, first NPN transistor was created.
Later using Diffusion Technique, first Germanium NPN transistor working at 500 MHz & Then Silicon NPN transistor working at 120 MHZ was developed.

→ Silicon was prefered for Transistors Than Germanium due to its property of having large band gap at low temperatures & the structure of Germanium crystals will be destroyed at high temperatures.

→ By doping a silicon semiconductor material with impurities of Arsenic n-type silicon & by adding gallium (or) Boron, p-type silicon were created. Hence the Bipolar Junction transistor came into picture.

→ The first integrated chip (IC) was prepared using the two BJT's on a single chip in 1958∴ since implementing complicated circuits were easy with BJT's.

→ Later due to advantage of metal oxide semiconductor Field Effect transistor (MOSFET) technology including simpler IC processing & packing more devices on the single chip, IC's ~~are~~ were produced using MOSFET's since the 1970's.

→ Advantages of MOSFET over BJT made them preferred technology for computer applications which include few processing steps with less cost.

→ Although MOSFET received more adoption, it had a few limitations, because it is a minority carrier devices thus leading to non-viability of MOSFET's for high voltage applications.

On the other hand, there was a continuous research in SCR to improve its turn-off capability which gave birth to Gate turn off Thyristor (GTO).

→ However GTO requires a high turn off control current through the gate which is related to higher cost & so limited its (GTO) applications to only inverters.

→ To ~~over this~~ overcome this, Insulated Gate Bipolar Transistor (IGBT) was developed which is the combination of MOSFET & BJT.

In the thyristor family after GTO, another interesting power electronic device was Triode AC switch also known as TRIAC & also one more which is Diode AC Switch nothing but DIAC etc.

Comparision of the power Electronic switching devices across their controllability & Bidirectional capability are shown below.

	Uncontrollable	Semi controllable	Fully controllable
(1) Unidirectional →	Diode	Thyristor/SCR	BJT, MOSFET, GTO, IGBT etc
(2) Bidirectional →	DIAC	TRIAC	—

From the above table, it is clear that there is still for continuous improvements & advancements in power Electronic Switches as their applications can be continuously improved as the switches got better by the years. In the above table there is an empty cell which represents the most ideal switch, a switch that supports the bidirectional flow of current & is fully controllable in both directions.

Principles & Applications of Semiconductor Switches:

The Silicon is most widely used material in semiconductor devices. Its usefull temperature range makes it currently the best compromise among the various materials.

These semiconductor switches or devices are mainly classified whether they are two terminal devices or 3 terminal devices & some times 4 terminal devices.

2 - terminal devices → diode, zener diode, LED Photo cell, Solar cell etc.

3 - terminal devices → IGBT, BJT, SCR, FET, TRIAC etc

4 - terminal devices → photo coupler, Hall effect sensor.

→ It is literally impossible to list all the applications of semiconductors devices today, it has penetrated almost all the fields where the Electrical Energy is in picture. some of them are mentioned below.

ⓐ They are used in the designing of logic gates & Digital circuits.

(b) They are used in microprocessors.

(c) They are also used in Analog circuits such as Amplifiers & oscillators.

(d) They are widely used in High voltage applications.

Limitations of AC Transmission systems :-

The AC Transmission is commonly used to transfer the power from the generating units through transmission lines to the load customers. Due to continuous fluctuations in load, the Voltage fluctuates in the AC system typically at a rate of 50 Hz or 60 Hz.

→ The skin effect caused only in AC system where it causes losses.

→ In AC transmission, the interference with other communication lines is more.

→ there are problems in maintaining the system stability & synchronization.

→ The losses due to CORONA effect increases in AC system

→ string efficiency is less than 100%

→ Ground return is not possible.

→ Power flow cannot be easily controlled.

→ In case of EHVAC, the intermediate substations are required at every 250 km to improve the performance of transmission line.

→ Asynchronous tie is not possible.

→ stability of EHVAC is very low due to presence of inductance & capacitance effects.

→ There is a limitation on power transfer due to the presence of inductance & capacit of transmission line & power angle.

→ To improve the performance of AC transmission, additional equipments such as series/shunt reactors, capacitors are required which increases the cost of substation.

→ If the voltage increased, the higher level of insulation is required in the conductor.

→ The charging current will flow through the conductor due to the presence of capacitance effect. Because of this charging currents the voltage at the Receiving end increased than the sending end voltage. This effect is known as Ferranti effect.

Emerging Transmission Networks :- The Day to Day demand for large amount of power today, necessitates transmission at increasingly high voltages, Until 1960, the electrical power was transmitted through AC 3-ϕ system only. Voltage transformation from one level to another level is quite easy with a suitable transformer. Also the power generation by large size generator is feasible with AC only.

However the bulk power transmission over long distances (above 500 km) gives rise to number of problems like variation of voltage levels, decrease in power transfer capability & generation of Reactive power & also other issues associated with which already discussed in previous section.

∴ Power transfer using alternate means is thought of so DC Transmission is considered.

over the years, the DC transmission has been developed for

(i) Power transfer over long distances from point to point.

(ii) Interconnection of two AC systems with two different frequencies

(iii) Better power system stability as a parallel link with existing AC system.

→ In General application of Electricity originally started with the use of Direct current.

The first Electric station was installed by Edison in newyork 1882 with DC generators & steam Engine.

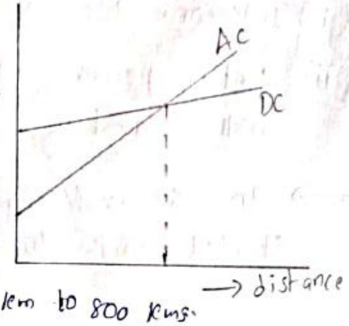
→ The invention of Transformer & Induction motor & the concept of 3-ϕ AC around 1890 initiated the use of AC. The advantages of 3-ϕ AC almost eliminated the use of DC systems.

→ Today DC Transmission has entered as a comeback in the form of HVDC to overcome the limitations & disadvantages of HVAC Transmission systems.

→ With the development of Mercury valves in early 1950's the HVDC transmission becomes more economical in some situations. It is attractive for transmission of large power over long distances. ~~the~~ ~~eo~~

→ The other factors that influence the line costs are the costs of compensation & the terminal equipment. DC lines donot require compensation but the terminal equipment costs are increased due to the presence of converters & ~~inverters~~ filters.

In the fig. shows, ~~the~~ ~~xxx~~ for distance less than "break even" distance, AC tends to be economical than DC & costlier for longer distance.



The distance can vary from 500 km to 800 kms.

→ In 1970 Thyristor valves are replaced the mercury arc technique. With the ~~HVDC~~ advent of Thyristor value converters HVDC transmission become more attractive.

→ HVDC is an effective means to improve the system performance.

In India first HVDC 810 km long distance ON line is Rihand- Delhi.

→ Now IGBT's have been developed & are being used extensively in bridge converters of HVDC systems.

Some of the HVDC schemes in India shown below

Name	converter station-I	Converter station-II	line length	Year
Sileru - Barsoor	Sileru	Barsoor	196 km	1989 (experiment)
Rihand - Delhi	Rihand	Dadri (Delhi)	814 km	1990
Chandrapur - Padghe	Chandrapur (M-H)	Padghe (M-H)	752 km	1999
Talcher - Kolar	Talcher - odisha	Kolar (K-A)	1450 km	2003
Ballia - Bhiwadi	Ballia (U.P)	Bhiwadi (Raj)	800 km	2010
Mundra - Haryana	Mundra	Mohindergarh	960 km	2012
Champa - Kurukshetra	Champa	Kurukshetra	1365 km	2016
North- East	Agra (U.P)	Biswanath (Assam)	1728 km	2016
Raigarh- Pugalur	Raigarh	Pugalur	1830 km	2019

(Flexible AC Transmission systems)

Back to Back converter station :

It has no transmission line & connects two Ac grids at different frequencies.

some of the Back-to-Back converter stations in India.

Name	converter Station	Year.
vindhyachal	vindhyachal	1989
chandrapur	chandrapur	1988
Vizag - I	Gajuwaka	1999
Sasaram	Sasaram	2003
Vizag - II	vishakapatnam	2005.

In general HVDC transmission is very efficient when there is a need to transfer over 500 kms. For less than 500 kms the Ac transmission is very economical than HVDC.

∴ While dealing with Ac Transmission systems to improve the power handling capability, to increase the voltage levels up to desired value at each bus in system, to reduce the voltage drops & power loss etc., we have an alternate devices to maintain all the parameters in the power system knows as FACTS devices.

(Flexible Ac Transmission system)

2/15/23

Facts devices are static power electronic devices installed in AC transmission networks to increase power transfer capability, stability, & controllability of the networks through series & and/or shunt compensation.

~~These are~~ In general FACTS devices are classified into four categories.

(i) shunt controllers (ii) series controllers
(iii) combined series - series controllers
(iv) " series - shunt "

Some of the benefits of FACTS controllers have given below.

(i) control of power flow as ordered
(ii) Increases the loading capacities of lines to their thermal capabilities.
(iii) Increases the system security through raising the Transient stability limit, limiting short circuit currents & overloads, & damping the oscillations of power circuit systems.
(iv) provides greater flexibility in siting new generation
(v) Upgrade of lines.
(vi) Reduce reactive power flows, thus allows the line to carry more amount of Real power.
(vii) Increase the utilization of lowest cost generation
(viii) Reduces loop current flows.

UNIT - II

HVDC - I

Comporision of AC & DC Transmission :-

The Relative merits of two modes of ~~op~~ transmission (AC & DC) should be compared with the following aspects.

(i) Economics of transmission
(ii) Technical performance
(iii) Reliability.

(i) Economics of power Transmission :-

The cost of the transmission line includes the

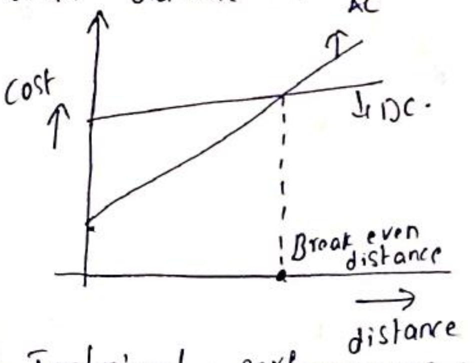
(i) Investment cost
↓
includes the
(a) cost of the transmission towers
(b) conductors
(c) Insulators
(d) terminal equipment.

(ii) operational cost includes mainly the cost of losses.

The characteristics of insulators vary with the type of the applied voltage ie, AC or DC. For simplicity, if it is assumed that the insulators characteristics are similar for AC & DC & depend upon the peak value of voltage applied, then it can be shown that for lines designed with same insulation level, a DC line can carry as much power with two conductors as an AC line with 3 conductors of same size.

→ The absence of Skin effect with DC is also beneficial in reducing power losses marginally. The corona effects on DC conductors tends to be less significant than of AC & This is also leads to the choice of economic size of conductors with the DC transmission.

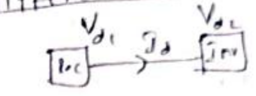
For long distances of power transmission ranges over 500 km, the saving in cost is substantial, & the variation in costs of transmission with distance for AC & DC are shown below.



For distances less than the "Break even" distance AC is more economical than DC. For long distances over 500 km to 800 km DC transmission is more economical.

(ii) Technical performance :- The DC transmission has +ve features which are lacking in AC, mainly the fast controllability of power in DC lines through converter control.

The power ~~control~~ transfer capability of a DC system is limited only by thermal conditions & current carrying capacity of conductor which is a function of difference of voltages b/n the two ends of line.

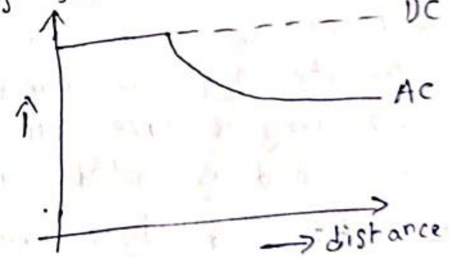


$I_d = \frac{V_{d1} - V_{d2}}{R}$

However, in AC system, the power transfer capability depends on sending end voltage (V_s), recieving end voltage (V_R), line Reactance (X), phase angle (δ) difference b/n V_s & V_r ie., $P = \frac{V_s V_r}{X} \sin\delta$ is reduced with increase in line length due to increase in line Reactance (X).

⟶ To compensate this, shunt reactors, series capacitors are to be used.

The characteristics b/n distance & power transfer capability as shown below.



$Z = \overset{\text{negligible}}{R} + jX$, so

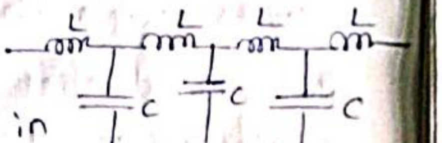
$Z = X$

if length of line ↑ X also ↑

$\downarrow P = \frac{V_s V_r}{X \uparrow} \sin\delta$

Voltage profile :- The voltage profile along the Ac line is complicated by line capacitance charging & inductive voltage drops. when the lagging Volt - Amperes is equal to the leading volt--Amperes for a particular load, such a load is called Surge Impedance loading (or) Natural loading on the line.

[Capacitance & reactance are the main parameters of the transmission line. It is distributed uniformly along the line. These parameters are also called distributed parameters : when the voltage drops occur in transmission line due to inductance, it is compensated by the capacitance of the Tr. line.



The transmission line generates capacitive reactive volt - amperes in its shunt capacitance & absorbing reactive voltamperes in its series inductance. The load at which the inductive & capacitive reactive volt-amperes are equal & opposite, such load is called surge Impedance load.

It is also called Natural load of the tr.line because power is not dissipated in transmission. In surge Impedance loading, the voltage & current are in the same phase at all the point of the line.

→ when the surge Impedance of the line has terminated the power delivered by it is called surge Impedance loading]

Surge Impedance loading is also defined as the power load in which the total reactive power of the lines becomes zero. The reactive power generated by the shunt capacitance is consumed by the series inductance of the line.

under these conditions,

$$V^2 WC = I^2 WL$$

$$\frac{V^2}{I^2} = \frac{L}{C} \Rightarrow \frac{V}{I} = \sqrt{\frac{L}{C}}$$

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

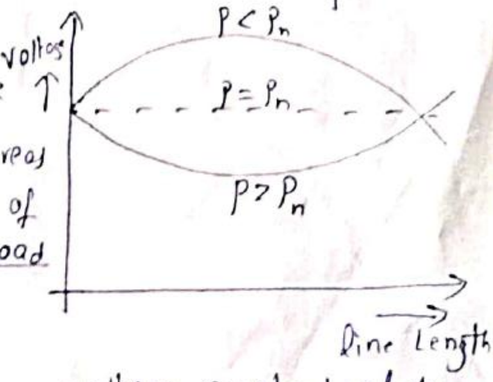
Surge Impedance loading $P_n = \frac{V^2}{Z_n}$

$\because P = VI$

$= \frac{V.V}{Z_n}$

$P_n = \frac{V^2}{Z_n}$

when the load is equal to the SIL, the voltage profile in an Ac line is relatively flat $\underline{P = P_n}$.



Now the voltage in the middle of line raises when the load is less than the SIL $(P < P_n)$, whereas the voltage profile at the middle of the line decreases when the load is more than SIL $(P > P_n)$ as shown in above fig.

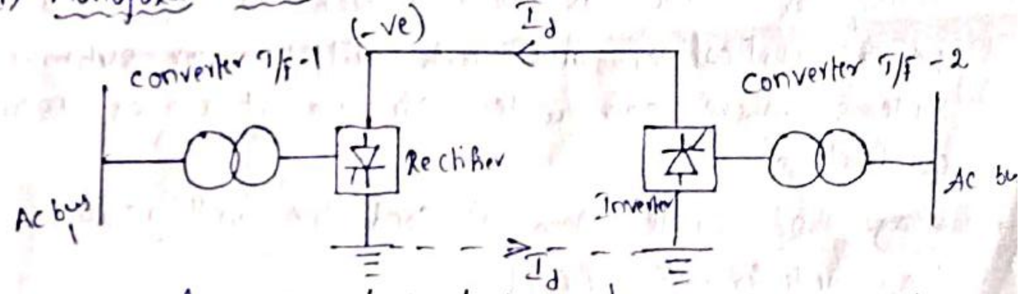
Now to maintain the voltage constant at the two ends reactive power compensation is required. In case of DC converter stations requires reactive power depends on the line loadings, & the line it self does not require reactive power.

(iii) Reliability :- The Reliability of power supply is more in DC line compared to AC. If a single line to Ground fault occurs at on DC line, enables it to supply at least 50% power But in 3-ϕ AC system morethan 50% capacity is lost.

Types of HVDC Links :- Sources & Generation of power is usually in AC mode. An essential requirement of DC system is conversion of AC to D at one end & inversion back to AC at the othe end. In b/n these two there should be an mediu to transfer power from one end to another end which is usually known as Link, simply DC Link.

There are mainly 4 types of HVDC links that are in use
(i) Monopolar link
(ii) Bi-polar link
(iii) Homo polar link &
(iv) Back to Back HVDC link.

(i) Monopolar link :-



A monopolar DC link has only one conductor may be of -ve or +ve polarity & Earth to be taken as Return conductor.
Generally -ve polarity conductor will be choosen than the +ve polarity. Corona effects are substantially less when compared with positive polarity conductor.

→ water can also be used as returnpath in case of underwater transmission or submarine transmission some times the Metallic return is also used which is burried in earth.

→ The major drawback in this system is power flow is interrupted due to either converter failure or DC link.

so, practically this link is not much in use Now a days.

→ Monopolar link is more economical than a Bipolar link because the ground return solves the cost of one metallic conductor.

→ Monopolar link is very much suited to low power applications and also suitable for submarine systems where sea water can be taken as Return conductor.

→ Usage of single (Negative) conductor will reduces the interference effect.

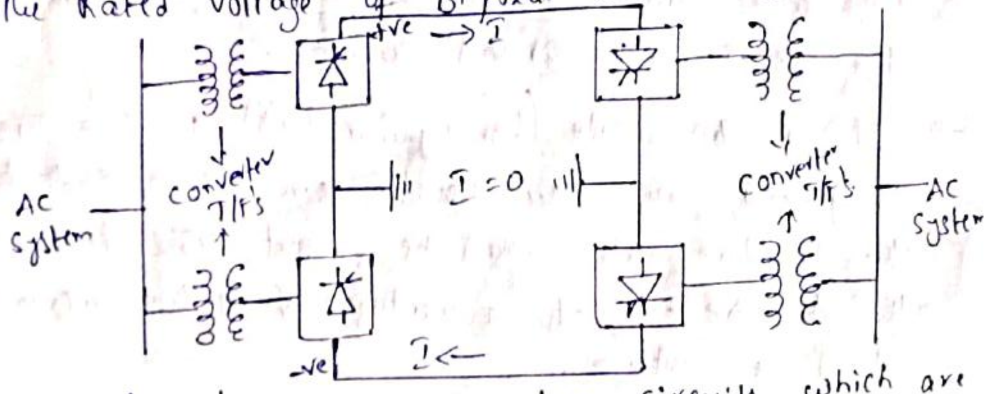
(ii) Bi-polar link :- A Bi-polar link has two conductors, one positive & the other Negative potential of the same polarity.

→ At each terminal, two converters of equal rated voltages are connected in series on the DC side.

→ The Neutral points are grounded at one or both ends. Normally both poles or conductors operate at equal currents & hence there is zero ground current flowing under these conditions.

→ If one conductor is isolated due to fault, the other conductor can operate with ground return & carry half of the rated load.

The Rated voltage of Bi polar link is given as I 650



A bi-polar transmission has two circuits which are almost independent of each other. A bipolar link in case can be operated as a monopolar line of any emergency.

→ Bi polar link is widely used in long distance HVDC transmission.

(iii) Homo polar link :- Homopolar link has two or more conductors have same polarity usually negative & they always operate with ground return.

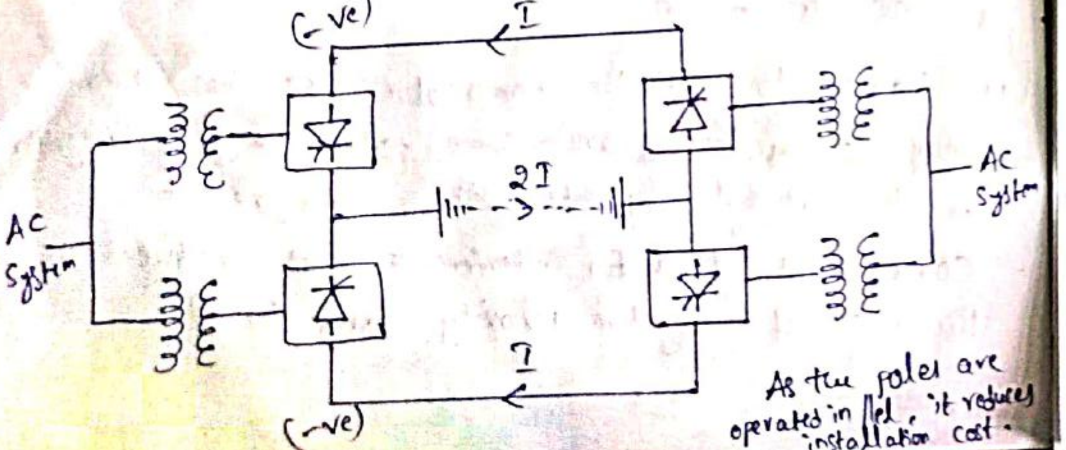
→ Corona loss & Ratio interference gets reduced with the use of Negative polarity conductors.

If one of the conductors gets affected with fault, the converter equipment can be reconnected. so that the healthy conductor with some overload capacity can supply more than 50% of the Rated power.

→ Homopolar link has limited applications due to the presence of ground currents.

→ If a two pole (homo polar link) DC line is compared with the Double circuited 3-ø Ac line, the DC line costs would be about 45% less than the AC line. Cost advantage of DC line increases at higher voltages.

A two conductor DC line is more reliable than 3- conductor AC, because in the event of fault in one conductor, the other conductor continue to operate with ground return during the fault period. The same is not possible in case of AC.



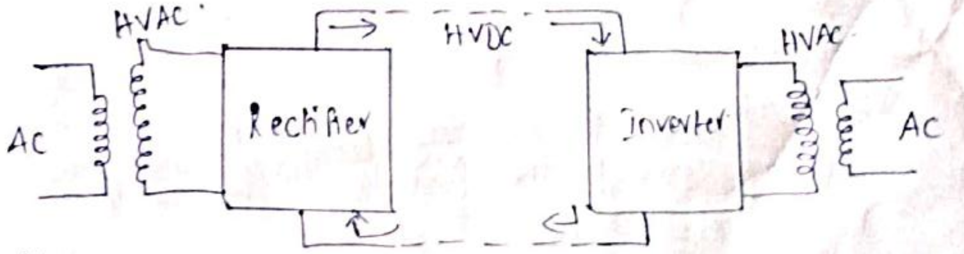
As the poles are operated in ||el, it reduces installation cost.

Back to Back DC link:- The HVDC link which doesn't have any transmission line & connects two AC grids at different frequencies is known as Back to Back DC link.

→ In this the Rectifier & the Inverter are in the same converter station. Generally HVDC links are used to enhance weak AC lines by transmitting large amount of active power & facilitating fast controllability of the power flow.

Process involved in this system is simple theoritically. But in practice it is very much complex as it involves high voltage semi- conductor devices.

→ Power from two or more systems is first converted to DC with the help of Rectifier system & they are summed up. After summing, the resultant power is again converted in to AC with the help of inverter station & supplied to different grids.



Adv

(i) Power can be upgraded to desired frequency.
(ii) Two Asynchronous Systems can be joined successfully without loss of stability.

(iii) More Active power can be added where the AC system is already at the limit of its short circuit capability.

Advantages & Disadvantages of HVDC Tr-line.

Analysis of Greatz circuit :- A typical HVDC transmission system consists of one Rectifier station at the sending end & one inverter station at the receiving end.
The two stations are interconnected by a DC transmission line. The Rectifier station converts AC to DC while the Inverter station from DC to AC

The Basic principle of HVDC system is by varying the firing angle of the thyristor in the converter, the DC output voltage magnitude is controlled.

→ In Rectifier the firing angle is $0^\circ < \alpha < 90^\circ$ & in the inverter the firing angle is $90^\circ < \alpha < 180^\circ$
As the DC output voltage is a function of firing angle & hence the converter voltage becomes negative when $\alpha > 90^\circ$.
This makes the converter to operate as an Inverter.

→ In practical HVDC system 3-ϕ 6-pulse bridge Converters are used both in Rectifier & Inverter side. By controlling the firing angle Reversible operation of converters as well as bidirectional power flow is possible in HVDC links.

In general, two types of converters are to be used generally in practical HVDC systems are,

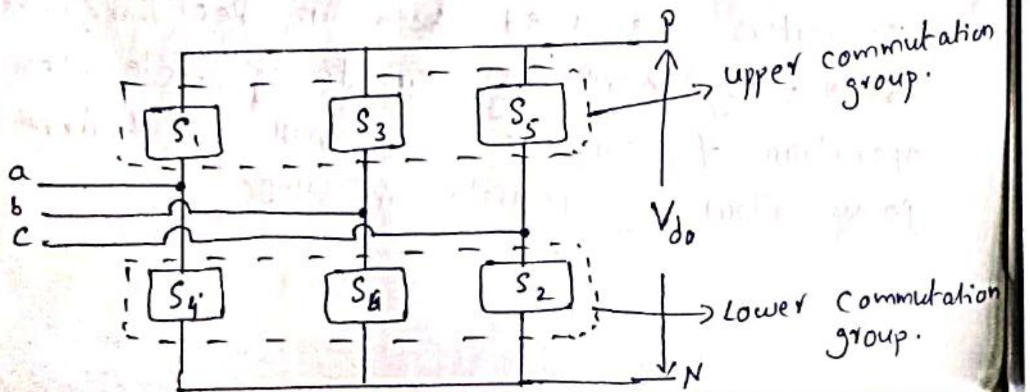
(i) Voltage source converters
(ii) current source converters. } Both are designed with IGBT's with capacity of self commutation.

→ current source converters in which Direct current always has one polarity & the power Reversal takes place through the Reversal of DC voltage polarity.

→ voltage source converters in which DC voltage has one polarity & the power Reversal takes place through the reversal of DC current polarity.

For reasons of economics & performance voltage source converters are often prefered than CSC.

All Modern HVDC converter station systems use either 6-pulse or 12 pulse converters.
Now the basic configuration for 3-Ø 6-pulse bridge converter (both VSC & CSC) as shown below.
And this basic circuit is known as "GREATZ" ckt.



This greatz ~~ckt~~ utilizes
The "Greatz" circuit is having best configuration values when compared with other converter configurations. so it is selected as the best choice for HVDC systems.

The Best configuration of Bridge converters are based on valve utilization factor (VUF) & Transforme utilization factor (TUF).

For a given pulse number select the configuration such a way that both the valve & Transformer utilization are minimized.

TUF :- Defined as the Ratio of DC o/p power available at the load resistor to the AC Rating of T/F

$$\boxed{T.U.F = \frac{P_{dc}}{VA \text{ rating of } T/F}}$$

where P_{dc} = DC o/p voltage

VA rating = average VA ratings of both primary & secondary of a T/F.

V.U.F :- It is defined as peak Inverse voltage (PIV) across the converter to the Avg DC o/p voltage across the converter.

$$\boxed{V.U.F = \frac{PIV}{V_{do}}}$$

The above "Greatz" ckt is of 6-pulse configuration. 12-pulse configuration also available but consists of 2- 6-pulse converters in series. The numbering provided the order ~~in~~ which they are turned ON.

→ The upper ~~commutation~~ port of the bridge is known as upper commutation group in which S_1, S_3, S_5 are connected to a, b, c phases respectively & Lower commutation group in which S_4, S_6, S_2 are to the phase a, b, c respectively.

Briefly about "Greatz" ckt :-

→ 6 pulse Bridge Converter.

→ utilizes circuit transformer & converter unit to atmost level & maintains low voltages at the valve when it is not in conduction.

→ 3-ϕ converter (Both VSC & CSC) is a bridge converter fed from T/F winding connecting in star or Delta.

→ The converter T/F feeding a greatz ckt serves

(i) Galvanic seperation b/n AC & DC sides.

(ii) Voltage transformation b/n AC & DC Networks.

(iii) Adjustment of the applied AC voltage by OLTC.

OLTC → on Load Tap changer.

→ It is having 6 switches, in order to turn on.

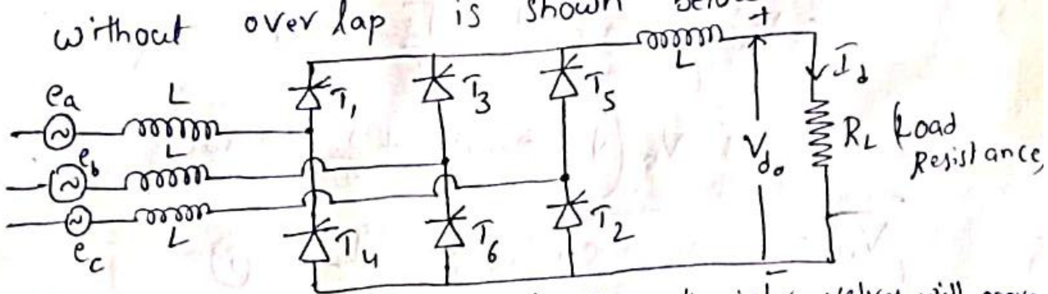
↳ LCC → Switches ~~valves~~ made up of thyristor valves

VSC → Switches are made up of IGBT valves.

→ each ~~of~~ switches are connected in series to provide voltage rating required.

Analysis of GREATZ Circuit without overlap :-

The Basic Greatz circuit for the analysis without over lap is shown below.



At any instant of time only two thyristor valves will opera one from upper commutation & 2nd from lower commutation. The valves ~~will~~ be fired according to the number given in the circuit at an interval of 60° (π/3

As we know that the 3-phases will be displaced at 120° & the phase voltages are given as

$$V_a = V_m \sin\omega t$$

$$V_b = V_m \sin(\omega t - 120°)$$

$$V_c = V_m \sin(\omega t - 240°)$$

Now the voltage across a & b phases will be V_{ab}.

$$\therefore V_{ab} = V_a - V_b$$

$$= V_m \sin\omega t - V_m \sin(\omega t - 120^\circ)$$

$$= V_m \left[\sin\omega t - \sin(\omega t - 120^\circ)\right]$$

$$V_{ab} = V_m \left[\sin\omega t - (\sin\omega t \cos 120^\circ - \cos\omega t \sin 120^\circ)\right]$$

$$= V_m \left[\sin\omega t - \left(\sin\omega t\left(-\tfrac{1}{2}\right) - \cos\omega t\left(\tfrac{\sqrt{3}}{2}\right)\right)\right]$$

$$= V_m \left[\sin\omega t + \frac{1}{2}\sin\omega t + \frac{\sqrt{3}}{2}\cos\omega t\right]$$

$$= V_m \left[\frac{3}{2}\sin\omega t + \frac{\sqrt{3}}{2}\cos\omega t\right]$$

$$= \sqrt{3}\, V_m \left(\frac{\sqrt{3}}{2}\sin\omega t + \frac{1}{2}\cos\omega t\right)$$

$$\boxed{V_{ab} = \sqrt{3}\, V_m \sin(\omega t + 30^\circ)} \longrightarrow ①$$

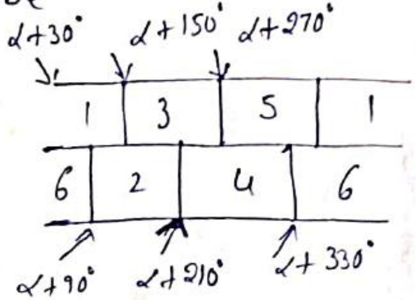
Now this voltage is to be converted from AC to DC.

Let us assume that 5, 6 are in conduction initially. After the completion of 60°, the valve 5 have to be turned off & the valve 1 should get ON. But due to the presence of source inductance of T/F, the valve 5 will not stop conduction upto ~~the~~ certain interval.

The condition where <u>two valves of same commutation group</u> are <u>in conduction</u> is known as <u>overlap condition</u>.

But our analysis is without overlap, so neglecting the source inductances of T/F.

Now considering T_1 & T_6 are conduction. Then the o/p DC voltage will be



$$V_{do} = \frac{1}{\pi/3}\int_{\alpha+30^\circ}^{\alpha+90^\circ} V_{ab}\, d\omega t$$

[∵ V_{ab} appears when 1, 6 are in conduction ie, from $\alpha + 30^\circ$ to $\alpha + 90^\circ$]

$$V_{do} = \frac{3}{\pi}\int_{\alpha+30^\circ}^{\alpha+90^\circ} \sqrt{3}\, V_m \sin(\omega t + 30^\circ)\, d\omega t$$

$$= \frac{3\sqrt{3}}{\pi} V_m \int_{\alpha+30^\circ}^{\alpha+90^\circ} \sin(\omega t + 30^\circ)\, d\omega t.$$

$$V_{do} = \frac{3\sqrt{3}V_m}{\pi}\left[-\cos(\omega t + 30^\circ)\right]_{\alpha+30^\circ}^{\alpha+90^\circ}$$

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

$$= \frac{3\sqrt{3}V_m}{\pi}\left[-\cos\left(180^\circ + (\alpha - 60^\circ)\right) + \cos(\alpha + 60^\circ)\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\cos(\alpha - 60^\circ) + \cos(\alpha + 60^\circ)\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\, 2\cos\alpha \cos 60^\circ \qquad \because \cos(A-B) + \cos(A+B) = 2\cos A \cos B.$$

$$= \frac{3\sqrt{3}V_m}{\pi}\, \cancel{2}\cos\alpha \times \frac{1}{\cancel{2}}$$

$$\boxed{\therefore V_{do} = \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha} \rightarrow ②$$

[V_m - Peak value of phase voltage with reference to Neutral.]

similarly for V_{bc} & V_{ca}.

wave forms

We have assumed that source inductances are neglected which eliminates the overlap condition. With zero source inductance, the transfer of current b/n the valves on the same side of the bridge takesplace instantaneously.

The switching sequence & the Rectified o/p voltage wave forms are shown in above figure. Performance of 3-ϕ Greatz circuit under balanced condition is considered with following assumptions.

(i) The DC current is constant & ripple free.
(ii) Valves can be modelled as ideal switches.
[ie, valves offer zero impedance in ON state & infinite impedance in OFF state].
(iii) Valves are turned ON at equal intervals of 60
(iv) The AC voltages at the converter bus are Sinusoidal & remains constant.

Inverter operation :- As we know from equ ② when α varies b/n 0° to 90° the converter acts as Rectifier & when α varies from $90° < \alpha < 180°$ it acts as Inverter.

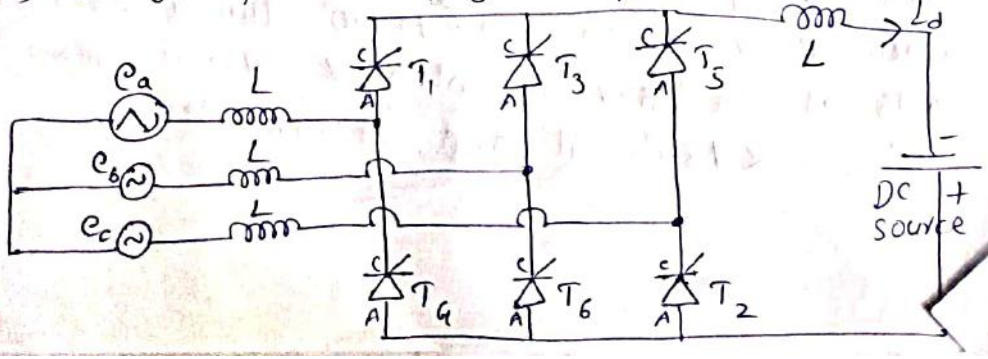
The Bridge operation can only be maintained in the presence of DC power supply in the place of DC load. The supply must be connected such that the <u>polarity (+ve)</u> to <u>common Anodes</u> & the <u>negative polarity</u> to <u>common cathodes</u>, so that it <u>overcomes</u> <u>negative voltages</u> & forces the <u>current</u> to conduct in the same direction in <u>opposition</u> to the induced emf in the converter <u>transformer</u>. This suggests that power is being supplied from DC to the AC system. Thus operating as an <u>Inverter</u>.

Three conditions required for power flow from the DC side to AC source during Inversion are:-

(i) An active AC voltage source which provides commutating voltage wave forms.

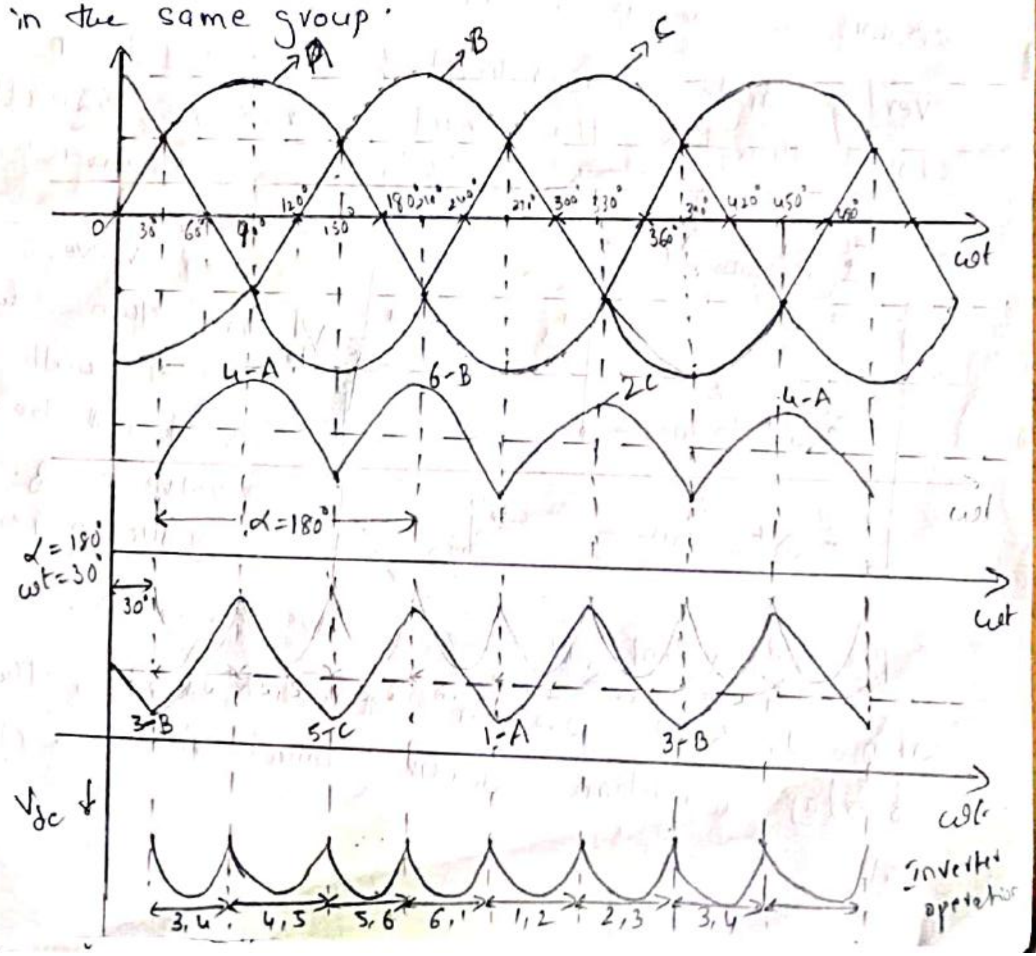
(ii) Provision of firing angle control must provide to delay commutations beyond $\alpha = 90°$ ie, $\alpha > 90°$.

(iii) A DC power supply in place of the DC load.



In Rectifier operation valves 1, 3, 5 will conduct when their cathodes are driven more positive & 4, 6, 2 will conduct when their anodes are driven with more -ve polarity.

However in Inverter operation, the valves 1, 3, 5 will conduct when their cathodes are driven with more -ve polarity & valves 4, 6, 2 will conduct when their Anodes are driven with more +ve polarity w.r.to the others in the same group.

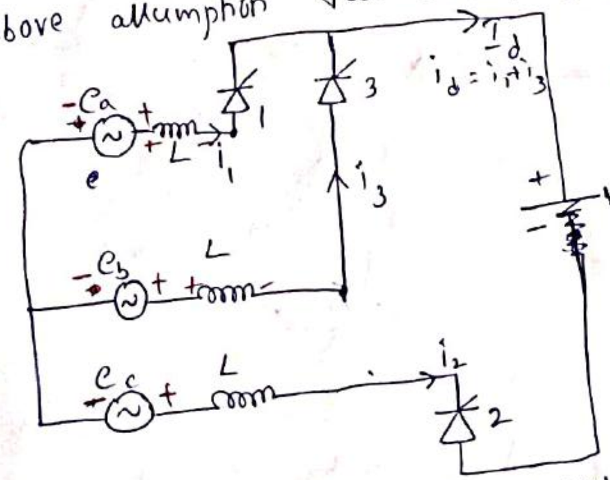


Due to the presence of leakdge inductance of the converter T/F's & the impedance in the supply network, the current in a valve cann't change this commutation from one valve to next cann't be instantaneous. - Here

Analysis of Bridge with overlap

initially assuming 1, 2 are conducting. After 60° the valve 1 should get turn OFF & valve 3 should get turn ON. But due to the presence of source inductances the valve-1 will continue to conduct upto certain interval. This condition of two valves (1, 3) of same commutation group is ON condition upto certain time interval is known as overlap condition.

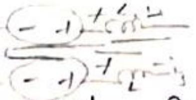
overlap angle is represented by μ. Based on above assumption the circuit diagram of Bridge ckt is given below.

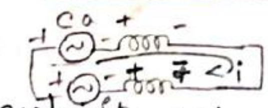


when valve 3 is fired then 3 will overlap with 1 & it will be three valve (1, 2 & 3) conduction periods.

fig:- Equivalent ckt for 3 valve conduction.

when T_1 & T_3 are in conduction mode, the overlap condition occurs which forms a closed path.





From the above ckt, By applying KVL

$-e_a + L\,di_1/dt + e_b - L\frac{di_3}{dt} = 0$ $\quad -e_a - L\frac{di}{dt} - L\frac{di}{dt} + e_b = 0$

~~$e_a + L\frac{di_1}{dt} = L\frac{di_3}{dt} + e_b = 0$~~

$\therefore$ from fig

$e_b - e_a = L\frac{di}{dt} + L\frac{di}{dt}$

$i_1 + i_3 = I_d$

$$e_b - e_a = -L\frac{di_1}{dt} + L\frac{di_3}{dt}$$

$e_b - e_a = L\frac{di_1}{dt} - L\,di_3/dt$

$\frac{dI_d}{dt} = \frac{di_1}{dt} + \frac{di_3}{dt}$

I_d is dc current

$\frac{dI_d}{dt} = 0$

$$e_{ba} = +L\frac{di_3}{dt} + L\frac{di_3}{dt}$$

$$e_{ba} = +2L\frac{di_3}{dt}$$

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

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

$$\frac{di_3}{dt} = \frac{e_{ba}}{2L} \longrightarrow Ⓐ$$

$$i_3 = \int_{i_3}^{i_1} \frac{e_{ba}}{2L}$$

$\therefore$ from equ ①

$e_{ab} = \sqrt{3}\,V_m \sin(\omega t + 30°)$

$e_{ba} = -\sqrt{3}\,V_m \sin(\omega t + 30°)$

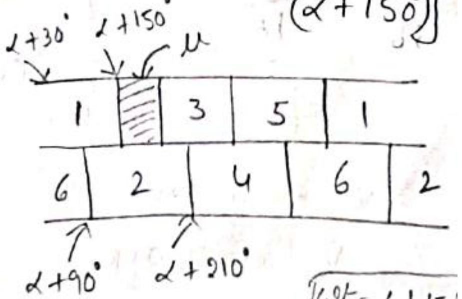
$$i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\int -\sin(\omega t + 30°)\,dt$$

$$i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\cos(\omega t + 30°) + K \rightarrow ③$$

$$\therefore i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\cos(\alpha + 180°) + K \rightarrow ④$$

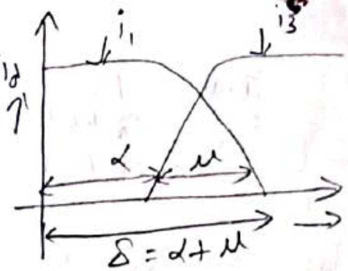
[$\because$ 1, 2 will conduct upto $(\alpha + 150°)$]

From the circuit diagram (or) from the current waveform $i_3 = 0$ at initial condition & $i_3 = i_d$ at final condition.



$\boxed{\omega t = \alpha + 150}$

At initial condition, $i_3 = 0$



$$i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\cos(\alpha + 180^\circ) + K$$

$$K = -\frac{\sqrt{3}\,V_m}{2\omega L}\cos(\alpha + 180^\circ)$$

$$= -\frac{\sqrt{3}\,V_m}{2\omega L}(-\cos\alpha) \quad \because \cos(180^\circ + \alpha) = -\cos\alpha$$

$$\boxed{K = \frac{\sqrt{3}\,V_m}{2\omega L}\cos\alpha} \rightarrow ⑤$$

Now substitute equ ⑤ in equ ③

$$i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\cos(\omega t + 30^\circ) + \frac{\sqrt{3}\,V_m}{2\omega L}\cos\alpha$$

$$= \frac{\sqrt{3}\,V_m}{2\omega L}\left[\cos(\omega t + 30^\circ) + \cos\alpha\right] \rightarrow ⑥$$

Now considering the overlap condition, $\Rightarrow \omega t = \alpha + 150^\circ + \mu$

$$\omega t = \delta + 150^\circ \rightarrow ⑦$$

⑦ in equ ⑥

$$\therefore i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}\left[\cos(\delta + 180^\circ) + \cos\alpha\right]$$

$$\boxed{i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}(\cos\alpha - \cos\delta)} \rightarrow ⑧.$$

Now after the overlap condition the DC voltage appears across the terminals will be

$$V_{d_0} = V_b - V_c - L\frac{di_3}{dt} \qquad \because \frac{di_3}{dt} = \frac{e_{ba}}{2L}$$

$$V_d = V_{bc} - L\frac{e_{ba}}{2L} \qquad V_{ba} = -\sqrt{3}\,V_m\sin(\omega t + 30^\circ)$$

$$V_d = V_{bc} - L\frac{V_{ba}}{2L} \qquad \therefore V_{ab} = +\sqrt{3}\,V_m\sin(\omega t + 30^\circ)$$

$$V_d = V_{bc} - \frac{V_{ba}}{2} \rightarrow ⑨ \qquad \text{llr}^{ly}\ V_{bc} = \sqrt{3}\,V_m\sin(\omega t - 90^\circ)$$

Integrating the above equation we get, the overall output DC voltage across the DC terminals,

$$V_d = \frac{1}{\pi/3}\int_{\alpha+150^\circ}^{\alpha+210^\circ}\sqrt{3}\,V_m\sin(\omega t - 90^\circ) - \frac{1}{\pi/3}\int_{\alpha+150^\circ}^{\alpha+150^\circ+\mu}\frac{\sqrt{3}\,V_m}{2}\left[-\sin(\omega t + 30^\circ)\right]$$

$\alpha + \mu = \delta$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left\{\underbrace{\int_{\alpha+150^\circ}^{\alpha+210^\circ}\sin(\omega t - 90^\circ)}_{\text{Actual o/p voltage}} + \underbrace{\int_{\alpha+150^\circ}^{\alpha+150^\circ+\mu}\frac{\sin(\omega t + 30^\circ)}{2}}_{\text{overlap occurs } e_{ba} \text{ in b/n these limits.}}\right\}$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left\{-\cos(\omega t - 90^\circ)\Big|_{\alpha+150^\circ}^{\alpha+210^\circ} + \left(\frac{-\cos(\omega t + 30^\circ)}{2}\right)\Big|_{\alpha+150^\circ}^{\delta+150^\circ}\right\}$$

$$V_d = \frac{3\sqrt{3}\,V_m}{\pi}\left\{-\left[\cos(\alpha + 120^\circ) - \cos(\alpha + 60^\circ)\right] - \left[\frac{\cos(\delta + 180^\circ) - \cos(\alpha + 150^\circ)}{2}\right]\right\}$$

$$V_d = \frac{3\sqrt{3}\,V_m}{\pi}\left\{\left[-\cos(\alpha + 120^\circ) + \cos(\alpha + 60^\circ)\right] - \left[-\frac{\cos\delta}{2} + \frac{\cos\alpha}{2}\right]\right\}$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left[-\cos(180^\circ + (\alpha - 60^\circ)) + \cos(\alpha + 60^\circ) + \frac{\cos\delta}{2} - \frac{\cos\alpha}{2}\right]$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left\{\cos(\alpha - 60^\circ) + \cos(\alpha + 60^\circ) + \frac{\cos\delta}{2} - \frac{\cos\alpha}{2}\right\}$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left[2\cos\alpha\cos 60^\circ + \frac{\cos\delta}{2} - \frac{\cos\alpha}{2}\right]$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\left[\cancel{2}\cos\alpha \times \frac{1}{\cancel{2}} + \frac{\cos\delta}{2} - \frac{\cos\alpha}{2}\right]$$

$$\boxed{V_d = \frac{3\sqrt{3}\,V_m}{\pi}\left[\frac{\cos\alpha + \cos\delta}{2}\right]} \rightarrow ⑩$$

Waveforms

Fig: 6 pulse bridge converter (GREATZ) with overlap

Equivalent circuit of Rectifier operation with overlap < 60° :-

The o/p voltage from equ ⑩ $\Rightarrow V_d = \frac{3\sqrt{3}V_m}{\pi}\left(\frac{\cos\alpha + \cos\delta}{2}\right)$

$$V_d = \frac{3\sqrt{3}\,V_m}{\pi}\left[\cos\alpha - \left(\frac{\cos\alpha - \cos\delta}{2}\right)\right] \rightarrow Ⓑ$$

from equ ⑧ $i_3 = \frac{\sqrt{3}\,V_m}{2\omega L}(\cos\alpha - \cos\delta)$

$$\Rightarrow \cos\alpha - \cos\delta = i_3 \times \frac{2\omega L}{\sqrt{3}\,V_m} \rightarrow ⑪$$

Now substitute ⑪ in Ⓑ $\left[\because i_3 = I_d \text{ at final condition}\right]$

$$\therefore \Rightarrow V_d = \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha - \frac{3\cancel{\sqrt{3}}\,\cancel{V_m}}{\pi} \times \frac{I_d}{\cancel{2}} \times \frac{\cancel{2}\omega L}{\cancel{\sqrt{3}}\,\cancel{V_m}}$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha - \frac{3 \times 2\cancel{\pi} f L}{\cancel{\pi}} \times I_d$$

$$V_d = \frac{3\sqrt{3}\,V_m}{\pi}\cos\alpha - \underset{R_{cr}}{\underbrace{\boxed{6fL}}}\, I_d$$

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

Let $V_{do} = \frac{3\sqrt{3}\,V_m}{\pi}$

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

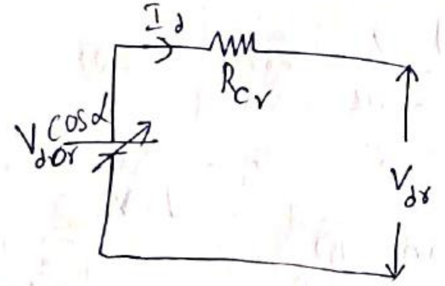
$$\boxed{V_d = V_{dr} - R_{cr} I_d}$$

where $R_{cr} = \frac{3\omega L}{\pi}$ (or) $6fL$

Equivalent resistance of the rectifier with overlap.

The Rectifier can be represented by a Dc equivalent circuit as shown below.

$$\boxed{\begin{aligned} V_d &= V_{dr} - R_{cr} I_d \\ V_{dr} &= V_{dor}\cos\alpha - R_{cr} I_d \end{aligned}}$$



Equivalent circuit of Rectifier operation

Inverter operation with overlap :-

The conditions for Inverter operation has been discussed in previous section under Ideal condition (without overlap). In Practice, full Inversion ($\alpha = 180°$) is not possible & the delay angle must be < 180°.

In the Rectifier operation, the delay angle 'α' can be choosen accuratly to satisfy the particular control constraint, but the same is not possible w.r.to γ (extinction angle), because of the uncertainity of the overlap angle (μ).

The waveform analysis for Inverter operation under the overlap condition is very similar to Rectifier operation, but only the polarity changes (+ve polarity to -ve polarity).

Analysis of Inverter operation is not different from that of Rectification. But when α is more than 90°, it is more convinient to define the angle of advance 'β' such that

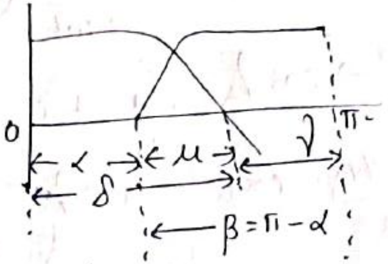
$\beta = \pi - \alpha$ ← To get the expression for equivalent ckt of Inverter.

$\Rightarrow \alpha = \pi - \beta$ & $\boxed{\alpha + \mu = \delta}$

also the extinction angle γ for inverter operation can be

$\gamma = \pi - \delta$

$\delta = \pi - \gamma$



For the inverter operation with overlap $\mu < 60°$, the o/p voltage is negative & is given by

$$V_d = -\frac{3\sqrt{3}V_m}{\pi}\left[\frac{\cos\alpha + \cos\delta}{2}\right]$$

$$V_{di} = -\frac{V_{doi}}{2}(\cos\alpha + \cos\delta) \longrightarrow ⑫$$

from the equ ⑧ $\Rightarrow i_3 = i_d = \frac{\sqrt{3}V_m}{2\omega L}(\cos\alpha - \cos\delta) \rightarrow ⑬$

⑫ $\Rightarrow V_{di} = -\frac{V_{doi}}{2}\left[\cos(\pi-\beta) + \cos(\pi-\delta)\right]$

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

$$\boxed{V_{di} = \frac{V_{doi}}{2}(\cos\beta + \cos\gamma)} \longrightarrow ⑭$$

//ry DC current

$$I_d = \frac{\sqrt{3}V_m}{2\omega L}(\cos\alpha - \cos\delta)$$

$$I_d = \frac{\sqrt{3}V_m}{2\omega L}\left[\cos(\pi-\beta) - \cos(\pi-\gamma)\right]$$

$$= \frac{\sqrt{3}V_m}{2\omega L}\left[-(\cos\beta \mp \cos\gamma)\right]$$

$$I_d = \frac{\sqrt{3}V_m}{2\omega L}(\cos\gamma \mp \cos\beta)$$

$$\Rightarrow \cos\gamma = \frac{I_d}{I_i} + \cos\beta \qquad \text{Let } I_i = \frac{\sqrt{3}V_m}{2\omega L}$$

//ry $\cos\beta = \cos\gamma - \frac{I_d}{I_i}$

Now the o/p voltage in terms of β is given as

$$V_{di} = \frac{V_{doi}}{2}\left[\cos\beta + \cos\gamma\right] \quad \because \text{from equ } ⑭.$$

$$= \frac{V_{doi}}{2}\left[\cos\beta + \cos\beta + \frac{I_d}{I_i}\right]$$

$$= \frac{V_{doi}}{2}\left(2\cos\beta + \frac{I_d}{I_i}\right)$$

$$= \frac{V_{doi}}{\cancel{2}}\cancel{2}\cos\beta + \frac{V_{doi}}{2} \times \frac{I_d}{I_i}$$

$$= V_{doi}\cos\beta + \frac{V_{doi}}{2} \times \frac{I_d}{\frac{\sqrt{3}V_m}{2\omega L}} \qquad \because V_{doi} = \frac{3\sqrt{3}V_m}{\pi}$$

$$I_i = \frac{\sqrt{3}V_m}{2\omega L}$$

$$= V_{doi}\cos\beta + \frac{\cancel{3}\sqrt{3}V_m}{\cancel{2}\pi} \times \frac{\cancel{2}\omega L\, I_d}{\cancel{\sqrt{3}V_m}}$$

$$V_{di} = V_{doi}\cos\beta + \frac{3\omega L}{\pi} I_d$$

$$= V_{doi}\cos\beta + \frac{3 \times 2\pi f L}{\pi} \times I_d$$

$$= V_{doi}\cos\beta + (6fL) I_d$$

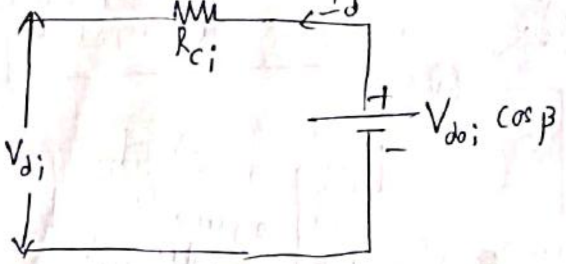
$$\boxed{V_{di} = V_{doi}\cos\beta + R_{ci} I_d} \rightarrow ⑮$$

→ Interms of cos β.

//ry Interms of cos γ

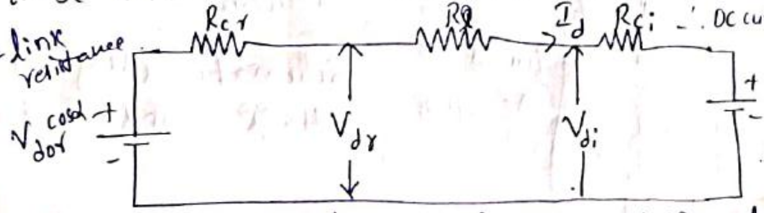
$$\boxed{V_{di} = V_{doi}\cos\gamma - R_{ci} I_d} \rightarrow ⑯$$

The equivalent circuit for Inverter operation will be,



Complete Equivalent circuit of HVDC link :-

Now combining the Equivalent circuits of Rectifier & Inverter, the total (complete) equivalent ckt of HVDC link will be obtained which is shown below.



$\therefore$ DC current $I_d = \frac{V_{dr} - V_{di}}{R_{cr} + R_l + R_{ci}}$

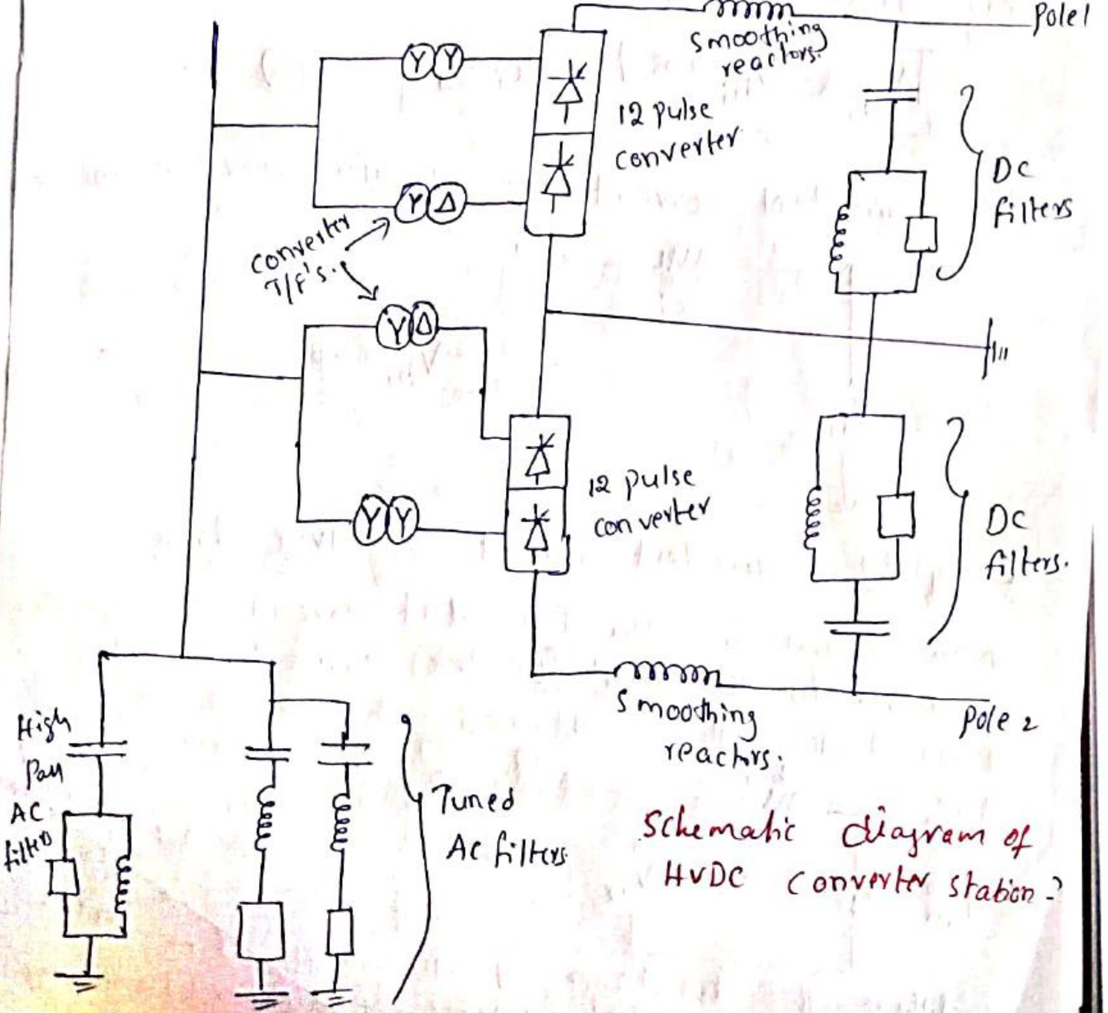
$\therefore I_d = \frac{V_{dor}\cos\alpha - V_{doi}\cos\beta}{R_{cr} + R + R_{ci}}$

where R = Resistance of the HVDC link

R_{cr} & R_{ci} = Equivalent resistance of Rectifier & Inverter respectively

HVDC converter station:- The major components of HVDC Transmission system are converter stations where the conversions from AC to DC & from DC to AC are permformed. A point to point transmission requires two converter stations.

A typical converter station with one 12-pulse converter unit per pole is shown below. The various components of a converter station are given below.



Schematic diagram of HVDC converter station:-

Converter unit:- This usually consists of two 3-ϕ converter bridges connected in series to form a 12-pulse converter unit. The total no. of valves in such a unit are twelve. The valves can be packed as a single valve, double valve or quadrivalve arrangements. Each valve is used to switch in a segment of an AC voltage waveform. The converter is fed by converter T/F's connected in Y-Y & Y-Δ arrangements. The valves can be cooled by air, oil, water or freo

These valves are protected by snubber ckts, protectiv firing angle & gaplen surge arrestors.

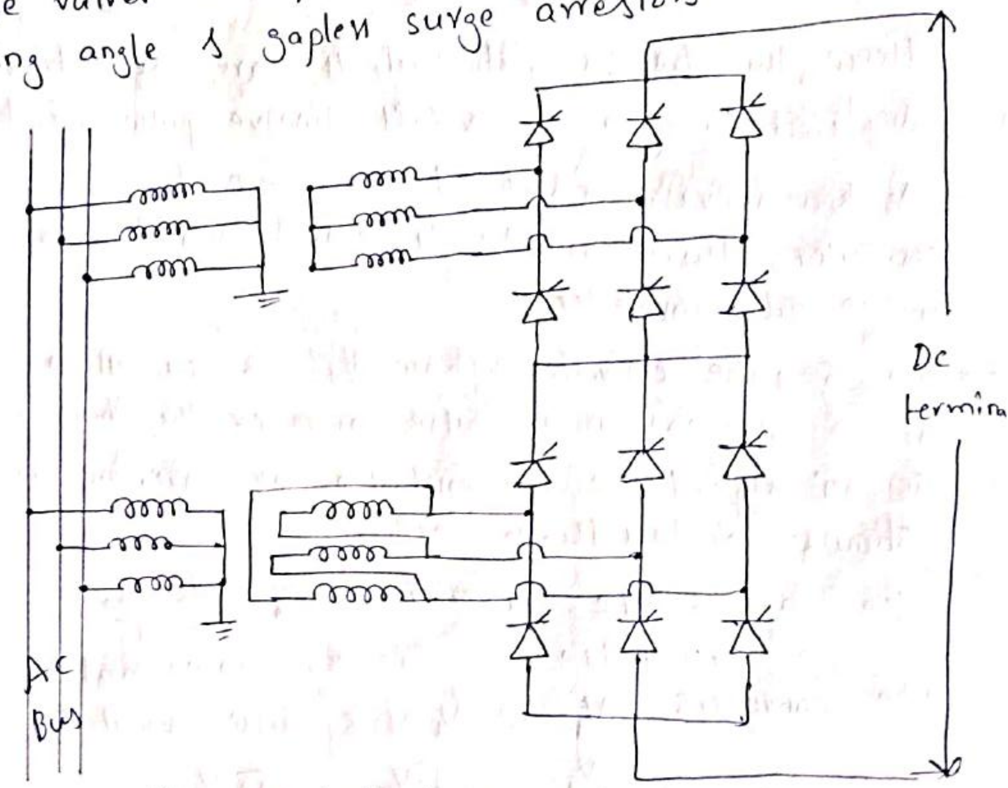


Fig:- A typical 12-pulse converter unit.

In HVDC transmission applications, it is important to reduce the voltage ripple produced on the dc side of the converter & current harmonics generated on HV AC side.

This is done by using high pulse number converter.

→ 12 pulse converter is obtained by connecting two 6-pulse bridge converters in series.
The AC supply is from transformers having star connected & delta connected secondaries.

→ The 3-ϕ voltages supplying the two bridges are displaced by a phase angle $\frac{2\pi}{12} = \frac{360}{12} = 30°$.
Hence the two six pulse outputs are symmetrically displaced to give an overall twelve pulse output.

→ As two valves conduct at the same time in 6-pulse converter, there will be 4 valves conducting at a time in 12-pulse converter.

→ In 6-pulse converter, phase d/f b/n successive SCR's is 60° whereas in 12-pulse converter, the phase difference is 30° only. Hence commutation or overlay angle should be less than 30°.

In a 6-pulse converter, $V_d = \frac{3\sqrt{3}V_m}{\pi}$

12 pulse " is the combination of two 6 pulse converters, $V_d = 2$ (V_d of 6-pulse converter)

$$V_d = 2\left(\frac{3\sqrt{3}V_m}{\pi}\right) = \frac{6\sqrt{3}V_m}{\pi}.$$

Converter Transformer :- The valve side windings are connected in star & Delta with neutral point ungrounded. on the Ac side, the transforme are connected in parallel with neutral grounded. The leakage reactance of the transformer is chosen to limit the short ckt currents through any valve.

These are designed to withstand Dc voltage stresses and increased eddy current losses due to harmonic currents.

one problem that can arise is caused by the DC magnetization of the core due to unsymmetrical firing of valves.

Filters :- There are 3-types of filters are used.

(i) Ac filters:- These are passive ~~filters~~ circuits used to provide low impedance, shunt paths for Ac harmonic currents. Both tuned & damped filter arrangements are used.

(ii) Dc filters:- These are similar to Ac filters & are used for the filtering of Dc harmonics.

(iii) High frequency filters:- These are connected b/n the converter transformer & the Ac bus to suppress any high frequency currents.

Reactive power source: Converter stations require reactive power supply that is dependent on the active power loading. This part of Reactive power requirement is provided by AC filters. In addition, shunt capacitors, synchronous condensors & static var systems are used depending on the speed of ~~the~~ control desired.

Smoothing Reactor: - A sufficient large series Reactor is used on DC side to smooth DC current & also for protection.

DC switchgear: - This is usually a modified AC equipment used to interrupt small DC currents. DC Breakers or Mettalic return transfer breakers are used, if required for interruption of rated load currents.

Complete characteristics of converter as Rectifier/Inverter: $(6 < \mu < 60^\circ)$

The characteristics b/n V_d & I_d

The complete characteristics of converter as Rectifier / Inverter can be obtained by modifying the equations derived earlier.

For a Rectifier,

$$I_d = i_s = \overbrace{\frac{\sqrt{3} V_m}{2\omega L}}^{I_S} (\cos\alpha - \cos\delta) \qquad \because \text{from equ } ⑧$$

$$\because \delta = \alpha + \mu$$

$$\Rightarrow \frac{I_d}{I_S} = [\cos\alpha - \cos(\alpha + \mu)]$$

$$\overline{I_d} = \frac{I_d}{I_S} = [\cos\alpha - \cos(\alpha + \mu)] \rightarrow ①$$

$$||^{ly} \quad V_d = \frac{3\sqrt{3} V_m}{\pi} \left[\frac{\cos\alpha + \cos\delta}{2}\right] \qquad \boxed{\because \text{from equ } ⑩}$$

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

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

W.K.T $\alpha + \mu = \pi - \gamma$

Now by expressing $\overline{I_d}$ & $\overline{V_d}$ interms of extinction angle.

$$① \Rightarrow \overline{I_d} = [\cos\alpha - \cos(\pi - \gamma)] \qquad \because \cos(\pi - \theta) = -\cos\theta$$

$$\overline{I_d} = \cos\alpha + \cos\gamma \longrightarrow$$

$$② \Rightarrow \overline{V_d} = \frac{\cos\alpha - \cos\gamma}{2} \Rightarrow 2\overline{V_d} = \cos\alpha - \cos\gamma \rightarrow \Big\} \rightarrow Ⓐ$$

Eliminating cos γ in the above equations, we get

$$\overline{I}_d + 2\overline{V}_d = 2\cos\alpha \Rightarrow \overline{V}_d = \cos\alpha - \frac{1}{2}\overline{I}_d \rightarrow (B_1)$$

$$\& \quad 2\overline{V}_d - \overline{I}_d = -2\cos\gamma \Rightarrow \overline{V}_d = -\cos\gamma + \frac{1}{2}\overline{I}_d \rightarrow (B_2)$$

$\rightarrow$ (B)

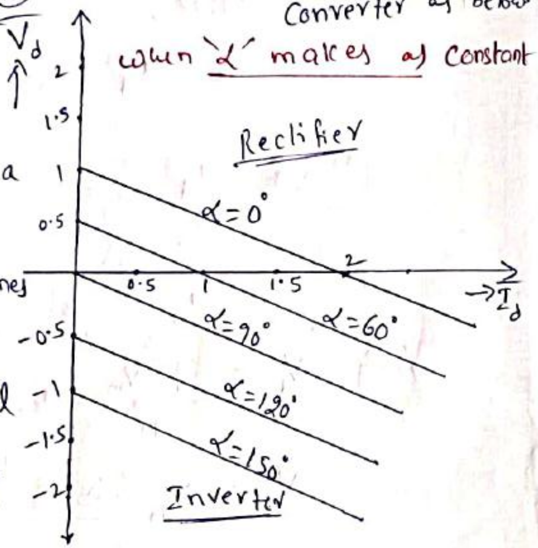
From the above eqn (B) the characteristics of Converter as below

when 'α' makes as constant

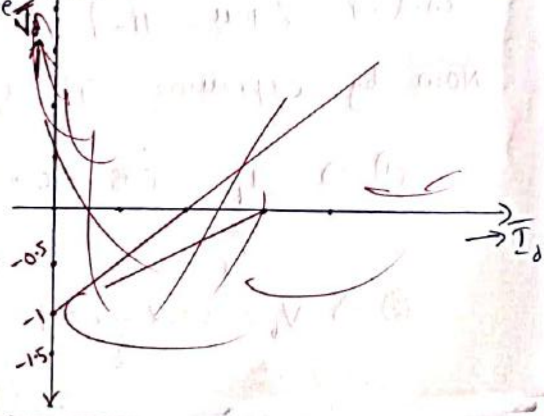
If $\overline{V}_d$ & $\overline{I}_d$ are plotted on the x-y plane, the expression of (B_1) represents a straight line

The slope of the above lines is $-\frac{1}{2}$.

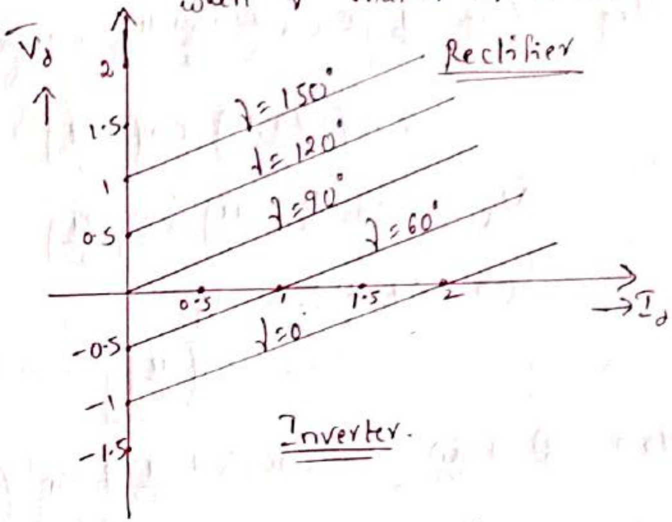
These are family of parallel lines for different values of "α" ranging from 0-180°



lly If we plotted the $\overline{V}_d$ & $\overline{I}_d$ characteristics on the x-y plane for the eqn (B_2), it is also represents a st-line with a +ve slope of ½. These are family of ||el lines for different values of γ ranging from 0-180°.



when γ makes as constant.



If we considered the overlap angle for the converter to be operated μ < 60° then

① $\Rightarrow \overline{I}_d = [\cos\alpha - \cos(\alpha+\mu)]$

② $\Rightarrow \overline{V}_d = \frac{1}{2}[\cos\alpha + \cos(\alpha+\mu)]$

$\because \cos x + \cos y = 2\cos\left(\frac{x+y}{2}\right)\cos\left(\frac{x-y}{2}\right)$

$\cos x - \cos y = -2\sin\left(\frac{x+y}{2}\right)\sin\left(\frac{x-y}{2}\right)$

$$\therefore \overline{I}_d = -2\sin\left(\frac{\alpha+\alpha+\mu}{2}\right)\sin\left(\frac{\alpha-\alpha-\mu}{2}\right)$$

$$= -2\sin\left(\frac{2\alpha+\mu}{2}\right)\sin\left(-\frac{\mu}{2}\right)$$

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

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

$$\boxed{\sin\left(\alpha+\frac{\mu}{2}\right) = \frac{\overline{I}_d}{2\sin\left(\frac{\mu}{2}\right)}} \rightarrow ③$$

$$\text{llly } \overline{V_d} = \frac{1}{\cancel{2}}\left[\cancel{2}\cos\left(\frac{\alpha+\alpha+\mu}{2}\right)\cos\left(\frac{\alpha-\alpha-\mu}{2}\right)\right]$$

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

$$\overline{V_d} = \cos\left(\alpha+\frac{\mu}{2}\right)\cos\left(\frac{\mu}{2}\right) \qquad \because \cos(-x) = \cos x$$

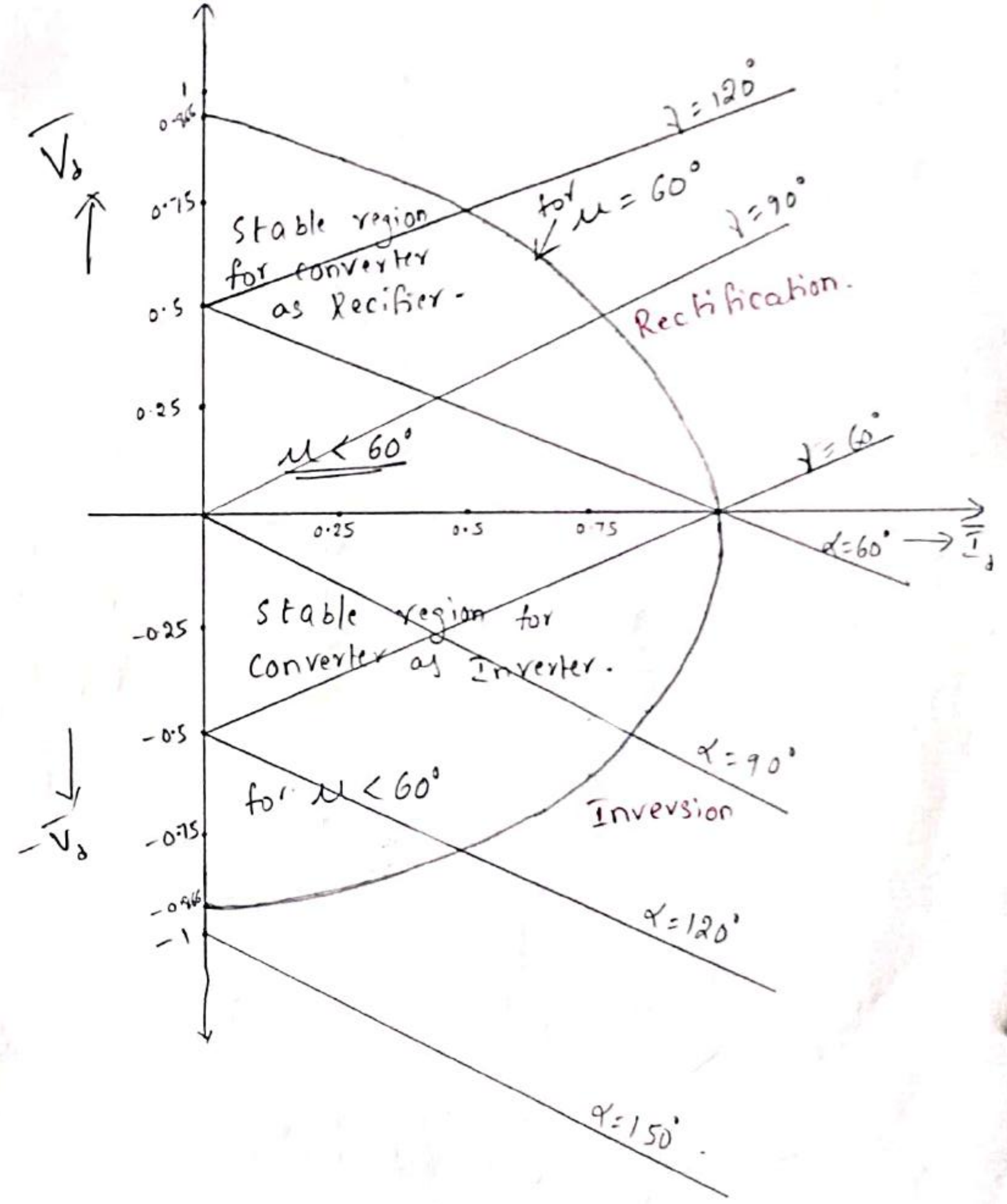
$$\boxed{\cos\left(\alpha+\frac{\mu}{2}\right) = \frac{\overline{V_d}}{\cos\left(\frac{\mu}{2}\right)}} \longrightarrow ④$$

Now $③^2 + ④^2 \Rightarrow \cos^2\left(\alpha+\frac{\mu}{2}\right) + \sin^2\left(\alpha+\frac{\mu}{2}\right)$

$$= \left[\frac{\overline{V_d}}{\cos\left(\frac{\mu}{2}\right)}\right]^2 + \left[\frac{\overline{I_d}}{\sin\left(\frac{\mu}{2}\right)}\right]^2$$

$$\Rightarrow \boxed{\left[\frac{\overline{V_d}}{\cos\left(\frac{\mu}{2}\right)}\right]^2 + \left[\frac{\overline{I_d}}{2\sin\left(\frac{\mu}{2}\right)}\right]^2 = 1} \longrightarrow Ⓒ.$$

The above equation represents an equation of Ellipse.



Unit - III

HVDC Transmission - II

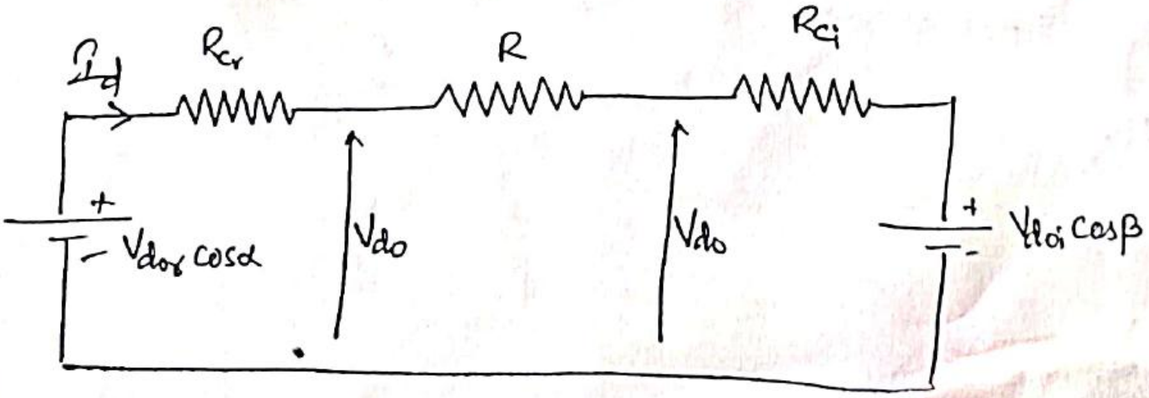
* Introduction :-

One of the major Advantage of a HVDC link is the rapid Controllability of transmitted power through the control of firing angles of the Converters. Modern Converter Controls are not only fast, but also very Reliable and they are used for the protection against line and Converter faults

The Control of DC power in a DC link can be achieved through the Control of Current (or) Voltage. From the minimization of loss Considerations, it is important to maintain "Constant Voltage" in the link and adjust the Current to meet the required power. This strategy also helpful for Voltage regulation in the system. It is to be noted that the Voltage drop in DC System is small Compared to AC System, mainly because of the absence of Reactive Voltage drop in DC Syste

* principles of Control :-

The Typical HVDC System can be Conviniently Represented by an Equivalent circuit as shown in fig.



When we are analyzing from the Rectifier station, with the help of above Equivalent circuit,

$$\boxed{I_d = \frac{V_{dor}\cos\alpha - V_{doi}\cos(\beta (or) \gamma)}{R_{cr} + R \pm R_{ci}}} \quad ①$$

The above equation expressed on the assumption that both (Rectifier & Inverter) stations are to operate at the Constant delay angles α and β (or) γ Respectively.

Now, from the above, the power transfer in HVDC link Can be achieved by changing the DC Current and that Can be achieved by altering any one of the four Variables.

i, Control angle of Rectifier "α"
ii, Control angle of Inverter "β (or) γ", mostly "γ".
iii Rectifier transformer secondary winding voltage by the tap changer (V_{dor}).
(iv) Inverter transformer secondary winding voltage by the tap changer (V_{doi}).

The Cases iii, & (iv) Can be achieved by Employing the Tap-changers to change the AC Voltage.

* Desired Control features:-

The Control Scheme Should have following features,

i, Control System should not be sensitive to Normal Variation in Voltage and frequency of the AC System.

ii, Control Should be fast, Reliable and Easy (simple) to implement.

iii, There should have Continuous operating range from full Rectification to full Inversion.

(iv) Control Scheme should be such that it should Require less Reactive power.

(v) Under Steady state Condition, the Valves must be fired Symmetrically.

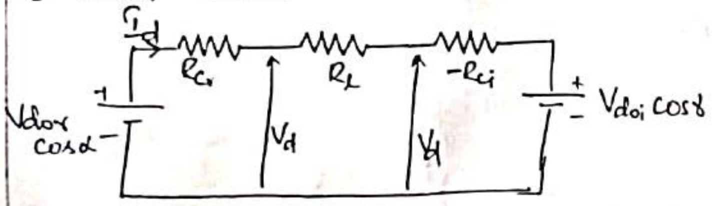
Vi, Control Should be Such that it must Control the maximum Current in the link, and limit the fluctuation of Current

Vii, Power Should be Controlled independently and Smoothly which Can be done by Controlling the Current / Voltage simultaneously in the link

Viii, Control Should be Such that it Can be Used for protection of line and Converter faults.

* Converter Control Characteristics :-

Already we have the Equivalent circuit of HVDC line as shown below,

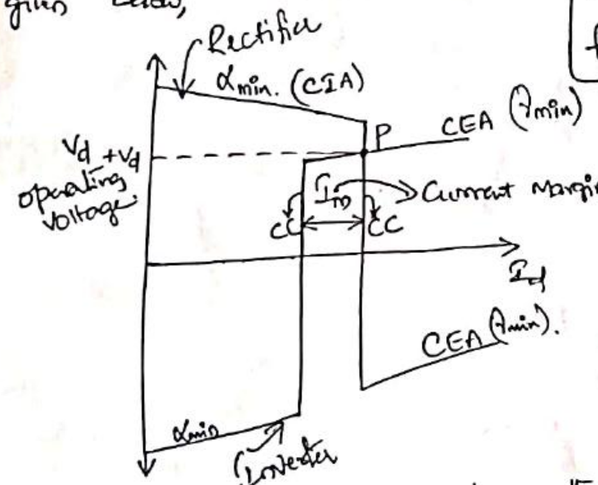


from the above basic equivalent circuit diagram.

$$\boxed{I_d = \frac{V_{dor}\cos\alpha - V_{dop}\cos\gamma}{R_{cr} + R_L + R_{ci}}} \text{ — Ⓐ}$$

$$\left[\because V_d = V_{doi} = V_{dor} = \frac{3\sqrt{3}E_n}{\pi}\right.$$

Now, the complete characteristics of both stations control are given below,



[CIA → Constant Ignition Angle Control for 'α']

[CC → Constant Current Control]

[CEA → Constant Extinction Angle Control for 'γ']

To draw this characteristics we have the equations of 'V_d' from the equivalent circuit as below

for Rectifier, $V_d = V_{dor}\cos\alpha - R_{cr} I_d$ —— ①

for Inverter, $V_d = V_{doi}\cos\beta + R_{ci}. I_d$

But it is always convenient to work with γ rather than β

So, the V_d equation for the Inverter will be,

$$\boxed{V_d = V_{doi}\cos\gamma + R_{ci}. I_d} \text{ — ②}$$

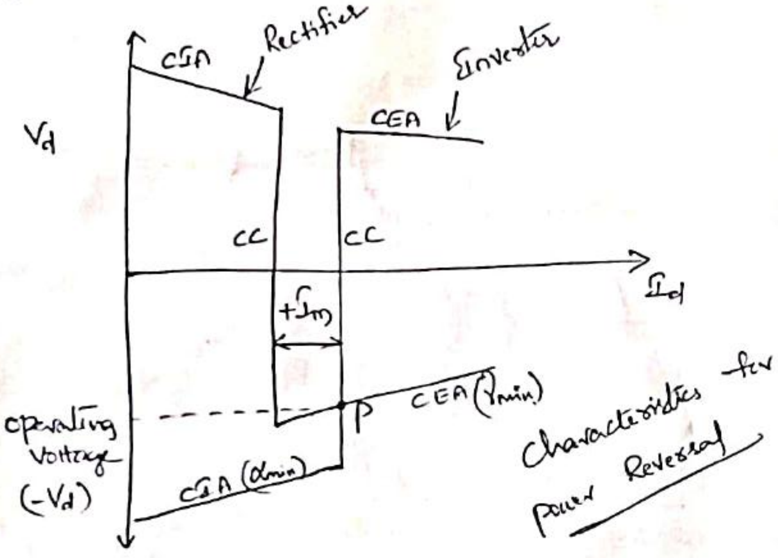
Since, ① and ② are same output DC voltage V_d for Rectifier & Inverter Respectively, for the analysis purpose assuming the Inverter Voltage as Reference, then the link Resistance R_L will be get added to the Equivalent Resistance of the Rectifier then the ① will becomes

$$① \Rightarrow \boxed{V_d = V_{dor}\cos\alpha - (R_{cr}+R_L)\, I_d} \text{ — ③}$$

Based on above equations ② & ③ we can observe the Resistance in the Rectifier circuit is high compared to the Resistance on the Inverter circuit Equation. Due to the Resistance on the inverter circuit equation. Due to the Resistance i.e, $(R_{cr}+R_L)$ the slope will be increase of Resistance i.e, $(R_{cr}+R_L)$ the slope will be more than the inverter slope due to R_{ci}, which was shown in the above characteristics.

In Normal operating condition, i.e, power transfer takes from Rectifier to Inverter the above characteristics will be applicable. But, for Power Reversal operating condition this is not suitable, because there is no intersecting point as like that of 'P' in the negative quadrant. So, no operating point for V_d will determined then no power transfer will takes place from Inverter to Rectifier.

To overcome this difficulty, the Current Margin will be changed from positive Margin to Negative margin with slight changes and the characteristics as shown below,



This is the basic Complete characteristics of Converter Control under Normal operating conditions and under power Reversal operating condition.

Now, depends upon the above characteristics we can say that each Station i.e, Rectifier (or) Inverter has "three" operating Regions. For Rectifier, it is initially the Constant α Control, followed by Constant Current Control and next the Constant Extinction angle Control. Similarly, for Inverter it is initially the CEA, followed by CC and Constant α Control.

In above both the Characteristics I_m is nothing but Direct Current margin which should be upto 10% of the Rated DC Current in the link.

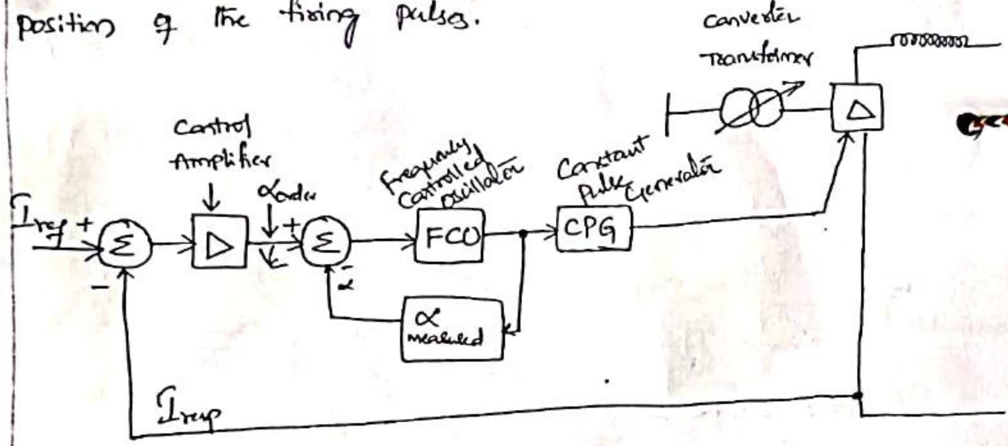
Now, if this Current margin is in first quadrant then we can say as basic operating characteristics. Similarly, if this Current margin is in fourth quadrant then that type of characteristics is for power Reversal operating Condition.

Note:– Basically, to avoid the clash of two Current Controllers of both stations, the Current Reference at the Inverter is kept low that of Rectifier at Normal operating conditions. This Margin is typically about 10% of the Rated Current in DC link.

In Case of power Reversal Condition, the Current Reference of Rectifier is kept low Compared to the Inverter. Again the I_{margin} is typically about 10% of Rated Current

* Constant Current Control :-

The below figure shows the simplified block diagram for a Current Control System of a Converter. A Control Voltage V_c is derived from the difference between Current Reference and the Current response in a Control Amplifier. This Control Voltage V_c Controls the phase position of the firing pulses.



The Control Amplifier should have a high enough gain to attain agreement between Current order and Current response and Suitable dynamics to make the Current control System Stable and fast.

The gain and time Constant of the Current Control System in Rectifier and Inverter operation have to be tuned to meet the dynamic behaviour of the HVDC System.

Note:- The Rectifier Normally Controls the direct Current (Id

→ Constant Current Control which may be at Rectifier (a) at Inverter

* Constant Extinction Angle (CEA) Control:-

Since, Current Reference in the Inverter is reduced by a fixed amount called Current Margin (I_{margin}). The direct Current determined by the Rectifier in the other end of the line will be more than the Current Reference at the Inverter This gives a Constant Error which forces the Current Controller to go to Saturation at the Inverter, and leave the Inverter with Constant Extinction angle Control. This is the usual mode of operation for an Inverter. The Current and γ control Systems are shown below,

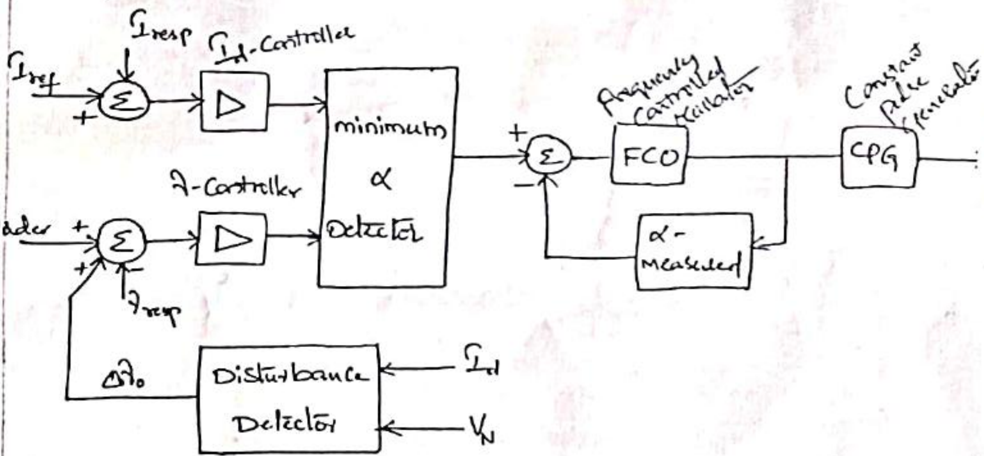


Fig. Current and Extinction Angle Control System

In Constant Extinction angle Control, the γ (extinction angle) of the thyristors is Controlled in a close loop. The Actual value of gamma is evaluated from the Time interval between the valve Current extinguishing Point to zero Crossover point of the Commutating Voltag. The Controller must act fast in the direction of the enlarging gamma (γ). Dynamic stabilisation is needed to improve the Recovery from Commutating failure.

The Constant Extinction angle Control is a device that Consists of Separate Computer for each group of Valves Connected to the same phase. Providing Computer to each grou separately is necessary because Complete balance between the phase voltages must not be taken for granted for after symmetrical fault Conditions. Each Computer Continously calculates and provides an output pulse when the Correct instant for firing a valve has approached, for Safe Commutation.

The Commutation voltage is nothing but, the voltage between two successive phases, namely the phase to which the Conducting valve is Connected and the other phase to which the next valve is to be fired, in an order of the same group.

By Controlling the Extinction angle the power factor is going to be maintained.

* Constant Ignition Angle Control :-

Ignition Angle (α) is the angle at which valves of Rectifier Can be turned ON. In Case if it is desired to have Constant minimum Ignition angle $\alpha = 0$, no provision is to be needed.

Sometimes multi anode valves may Require greater minimum angle delay. under such circumstances, Ignition angle Can be Controlled by various methods

* Converter Firing Angle Control :-

The operation of Constant Current (CC) and the Constant Extinction Angle Control (CEA) are closely linked with the method of generating of pulses (gate) 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 by at the ground potential and the firing signals sent to the individual thyristors by light signals through fiber-optic cables.

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

Basically, there are two types of Firing Controls.

I, Individual Phase Control (IPC)

II, Equidistant pulse Control (EPC).

* Individual phase Control :-

This scheme was used in early HVDC Stations. In this scheme, firing instant is determined individually for each Valve so that a Constant delay (or) Extinction angle is maintained for all the Valves in steady state with respect to the instant of zero crossing of voltages. In other words, the phase position of the Control pulses is determined Separately for each Valve and is directly Synchronized to Commutation voltages by relating the firing to "zero Crossing" of the Commutation Voltages.

As this Scheme (IPC Scheme) is characterised by a seperate control of phase delay angle α for each Valve, it Requires 6 parallel delay circuits.

There are two basic approaches for IPC scheme,

ⓘ Inverse Cosine Control

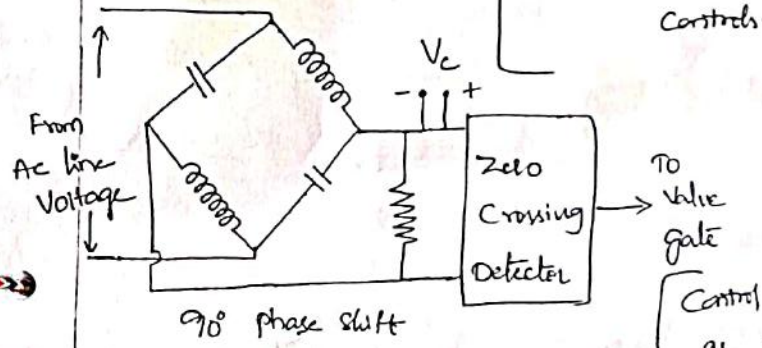
ⓘⓘ Linear Control of phase delay (or) Constant 'α' Control,

* ⓘ Inverse Cosine Control :-

There are Several Versions of this method. In this Scheme, a Control Voltage (V_c) Common to all the delay circuits, generates pulses at the Crossing point of the control voltage and the appropriate Ac line Voltage.

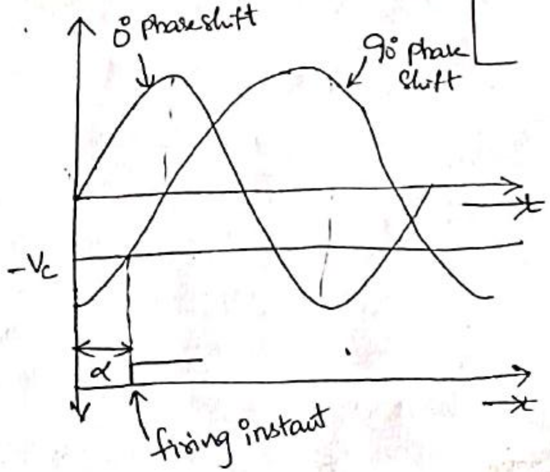
The are Common arrangement in all the Several versions, the six timing Voltages, are each phase shifted by 90° and added Separately to a Common Control voltage V_c as illustrated below,

The Control voltage (V_c) is determined by either Constant Current (or) Constant Extinction Angle (CEA) Controls.



Control voltage is determined as, $V_c = V_m \cos\alpha$

$\Rightarrow \alpha = \cos^{-1}\left(\frac{V_c}{V_m}\right)$



The phase delay angle is given by

$$\boxed{\alpha = \cos^{-1}\left(\frac{V_c}{V_m}\right)} - ①$$

where V_c = Control voltage
V_m = Max. (or) peak voltage

The output Voltage of the Converter is given by

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

$$= V_{do}\left(\frac{V_c}{V_m}\right) \Rightarrow V_d = \left(\frac{V_{do}}{V_m}\right) \cdot V_c$$

$$\Rightarrow \boxed{V_d = K V_c} - ②$$ ⟹ Linear Characteristic but In Accurate

From the above two Equations we can say the delay angle α is proportional to inverse Cosine of Control Voltage. It also depends on the AC System Voltage amplitude & shape

The main advantage of this scheme is the average DC Voltage Varies linearly with the Control Voltage (V_c).

However, as the firing angle approaches to zero, ∴ V_c approaches to the Peak value V_m and also 'α' becomes Very Sensitive to both V_c & V_m and a small error in either of the voltages leads to high inaccuracy.

✱ If $\alpha = 5°$ Then to fire T_1 ⇒ it takes a delay of 5°
for to fire T_2 ⇒ it may (or) may not Equal to 65° } 60° difference
iii) for T_3 ⇒ it may (or) may not Equal to 125° } 60° difference

This is the great disadvantage in Cosine (or) Inverse Cosine & Linear Control of Phase delay Control. So we have to move for 6 delay circuits for 6 Thyristors. To overcome this, moving to EPC ✱

(ii) Linear Control of Phase delay (or) Constant α Control :-

In this Scheme, a Common Control Voltage (V_c) to all the delay circuits, and Six timing (Commutation) Voltages are derived from the Converter AC bus via Voltage transformer and Six gate Pulses are generated at nominally identical delay times from the Zero Crossings of AC Voltages. The instant of zero crossing of a particular Commutation Voltage Corresponds to $\alpha = 0°$ for that value.

The firing angle is Proportional to Common Control Voltage and is given by

$$\alpha = K_1 \cdot V_c$$

∴ o/p Voltage $V_d = V_{do} \cos\alpha$

$$\boxed{V_d = V_{do} \cos(K_1 \cdot V_c)}$$

from the above equation, we can say the transfer characteristic is Non-linear. But accuracy of ±1°.

The Six delays are Produced by independent delay circuits and Controlled by a Common Control Voltage (V_c) derived from CC (or) CEA Controllers.

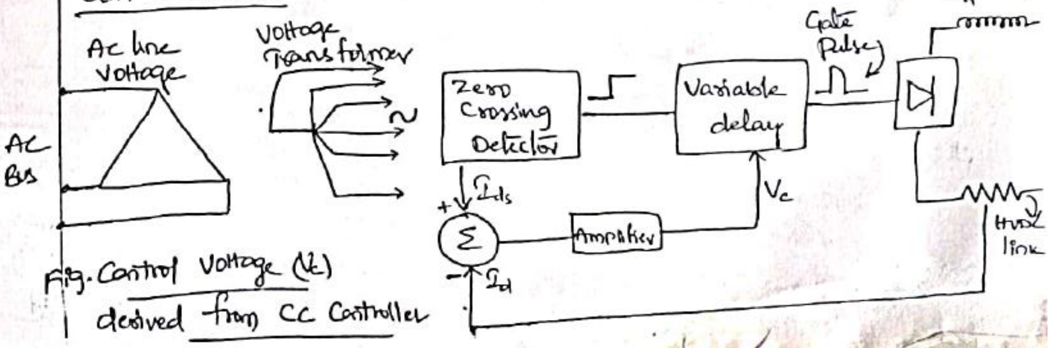


Fig. Control Voltage (V_c) derived from CC Controller

* Drawbacks of IPC system :-

The major drawback of IPC Scheme is, the firing delay angle for each thyristor is dependent on the Corresponding line voltage Therefore any distortion in AC voltages will results in different Phase angle delays for different values and hence the firing intervals will differ from 60°. This inaccurate Pulse spacing will Produce noncharacteristic harmonics in the AC line Current apart from Normal harmonics.

It is so expensive to filter out the lower order Harmonics. In a weak AC System this may lead to harmonic instability. This is also one of the reason for not using IPC Scheme in Modern HVDC Systems.

* Equidistant Pulse Control (EPC) :-

In this scheme, no direct Synchronisation of Control Pulse to the AC Voltage is applied and so, is Used in all Modern HVDC Systems It is primarily useful for Successful operation of weak AC System. The Basic principle is to produce a Single pulse spacing at Equal intervals of $\frac{1}{Pf}$ through a ring Counter. where, P=pulse number and f is the Nominal frequency.

	IPC	EPC
Symmetry will not be achieved IPC is Highly in accurate	for $T_1 \Rightarrow \alpha = 5°$ for $T_2 \Rightarrow \alpha \neq 65°$ $T_3 \Rightarrow \alpha \neq 125°$	for $T_1 \Rightarrow \alpha = 5°$ for $T_2 \Rightarrow \alpha = 65°$ $T_3 \Rightarrow \alpha = 125°$:

60°

60°

Symmetry will be Then for EPC

EPC is accurate upto ±1°.

Basically, There are 3 Controls in EPC Schemes

i, Pulse Frequency Control (PFC)
ii, Pulse period Control and
iii, Pulse phase Control (PPC).

EPC Scheme was Suggested by 'Ainsworth' Using a Phase locked oscillator to generate the firing Pulses.

i. Pulse Frequency Control (PFC) :-

In this Control Scheme, a Voltage Controlled oscillator (VCO) is used, the frequency of which is determined by the Control voltage (V_c) which belongs to the Error in the Quantity $[(I_{d_{ref}} \sim I_{d_{meas}})$ (a) $(\gamma_{meas} \sim \gamma_{ref})]$ being Regulated. The frequency in the steady state operation is equal to Pf_0 where, f_0 is fundamental freq. of the AC System. PFC System has an Integral characteristic and has to be Used along with a feedback Control System for Stabilization.

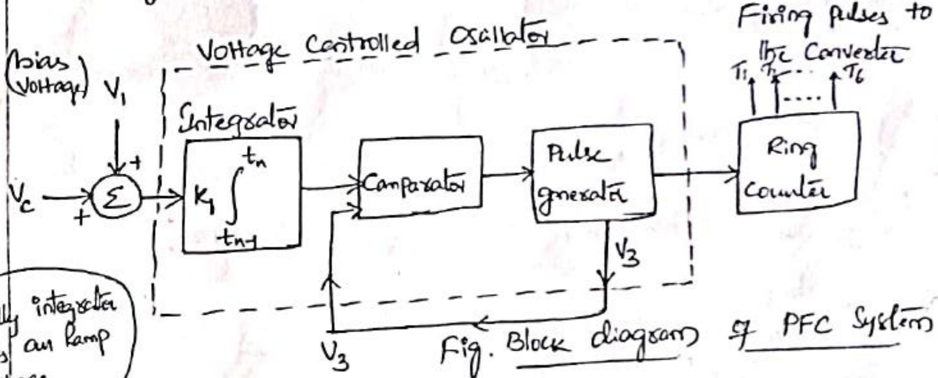


Fig. Block diagram of PFC System

Basically integrator produces an Ramp voltage

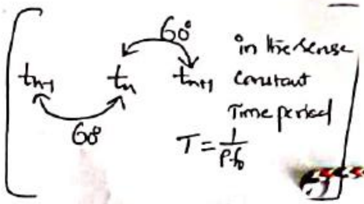
The above figure shows the Simplified block diagram of PFC System. The voltage Controlled oscillator Consists of an integrator, Comparator and pulse generator. The output Pulses of the generator drives the Ring Counter and also Reset the Integrator.

The instant 't_n' of the firing pulse is to be determined from the following equations

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

where, V_1 = constant voltage and V_3 is proportional to the system period. In the steady state, $V_c = 0$ and the above equation will become,

$$K_1 V_1 (t_n - t_{n-1}) = V_3 \quad \text{—②}$$

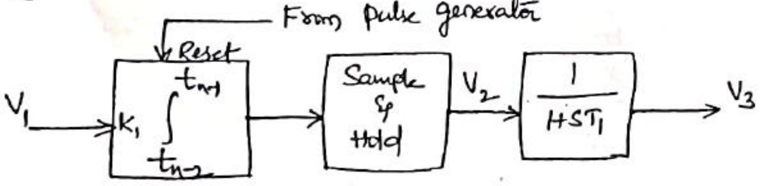


Since $t_n - t_{n-1} = \frac{1}{Pf_0}$

$\therefore$ ② ⇒ $K_1 = \frac{Pf_0 V_3}{V_1.}$ —③

where, K_1 is the gain of the integrator in the steady state condition.

Now, the above circuit is not suitable for frequency correction (when the system freq. deviates from f_0). Therefore, the frequency correction according to Ainsworth is obtained by deriving V_3 from the below fig.

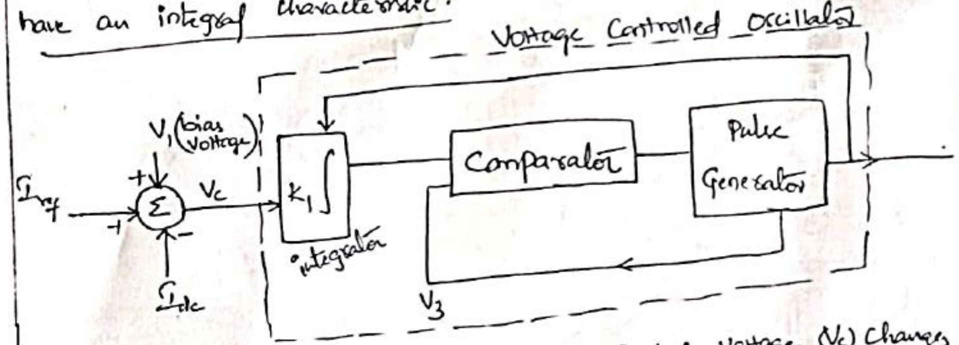


From the above fig. $V_3 = \frac{V_2}{(1+ST_1).}$ and

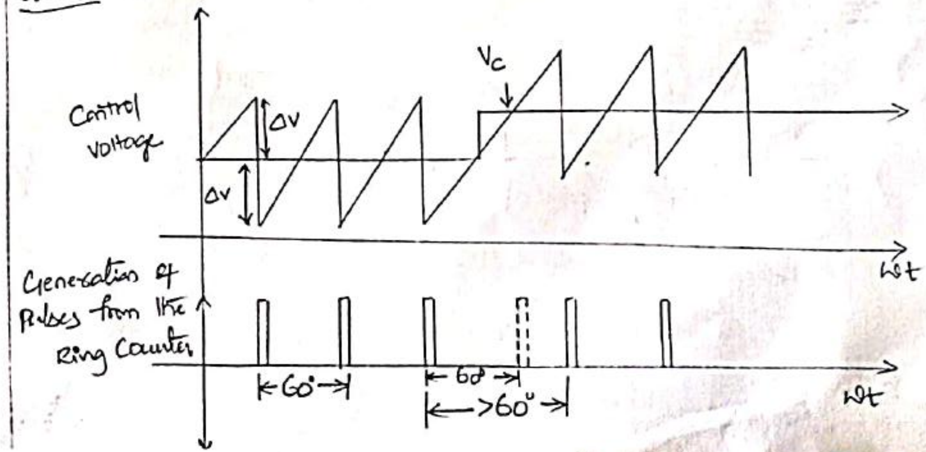
$$V_2 = \frac{K_1 V_1}{(t_{n-1} - t_{n-2})}.$$

(ii) Pulse Phase Control :-

The basic block diagram is shown below, which consists of a voltage controlled oscillator that produces a pulse-train depends on charging and discharging voltage of a capacitor. This is maintained between a fixed limit ±ΔV around the control voltage. The response of this system is fast because it does not have an integral characteristic.



Due to any changes in I_{dc} the control voltage (V_c) changes which causes a proportional change in the control angle 'α' which is shown below. To overcome this a control loop for the converter control angle α is required that can be achieved by constant current (or) constant Extinction Angle Controls.



* Starting and stopping of HVDC link :-

In general, the HVDC line can be started with the two methods using short pulse (60) gate pulses and long (120) gate pulses.

i, Starting with Long Pulse firing :-

In this case, the current extinction during the start up is not a problem. The starting sequence in this case as follows,

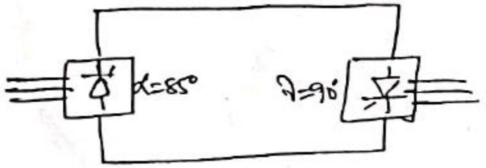
ⓐ Deblock the inverter at about $\gamma = 90^\circ$.

ⓑ Deblock the Rectifier at $\alpha = 85^\circ$ to establish the low DC current

ⓒ Ramp up the Voltage by inverter control and current by Rectifier Control,

The sequence of operation is as follows,

for Eg:-



Initially, both stations are at non-conducting mode

Now, first deblock the inverter with $\gamma = 90^\circ$.

That means just deblocking the inverter and just giving $\gamma = 90^\circ$, then it (inverter) will be ON. Similarly, deblock the Rectifier and give $\alpha = 85^\circ$ which means not $\alpha \neq 90^\circ$ because, earlier when inverter is ON then no overlap angle (μ) will comes into picture; then if we take $\alpha = 90^\circ$ then due to the overlap angle (μ) the Rectifier Voltage may becomes Negative So, we try to give positive Voltage at Rectifier by igniting the α somewhere at 85°, then a small voltage will exist across the Rectifier and at inverter the voltage is zero. Then a small amount of current will flows through the link.

Now, to transmit the power we can increase the voltage and the current simultaneously. But, it is always preferable to raise the voltage first which maintains the minimum DC current in the link.

If we initially increase the 'current' there may be chance of insulation failure (or) may be some flashovers across the insulators etc. To overcome this, we have to increase the voltage first and then current. For this (to increase voltage) both Rectifier and Inverter angles are to be varied accordingly.

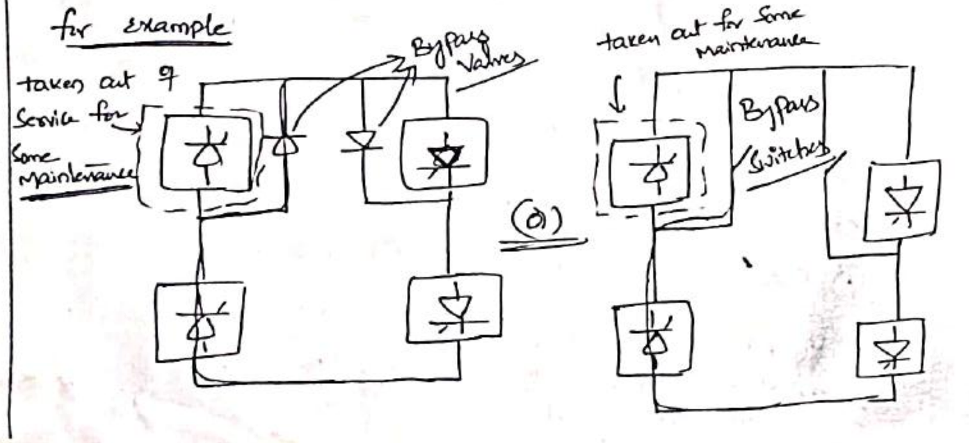
By increasing the voltage we can check the status of Tr.line, whether it is operating quite good (or) not. If not operating as desired we can immediately stop the loading of transmission line as the current was minimum initially. If it is operating good then continue to increase the voltage and then current to maintain the rated power transmission.

ii, Start up with Short pulse firing :-

Consider N Series Connected bridges at a Converter Station. If one of the bridge is to be taken out of Service, there is need to not only to block, but bypass the ~~Current~~ bridge. This is because of the fact that just blocking the pulses does not extinguish the Current in the pair of Valves that are left Conducting at the time of blocking. The Continued Conduction of this pair injects AC Voltage into the link which Can give rise to Current and Voltage oscillations.

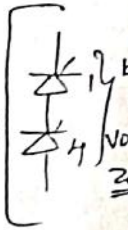
The bypassing of the bridge Can be done with the help of Seperate bypass Valve (or) by bypassing Switch. The bypass Valve Used with mercury arc. Valves where the possibility of arc, makes it impractical to use. Bypass pairs (or) Bypass Switch is the practice as it saves the Cost of an extra Valve.

for example



In Case of Bypass Switch, we Cannot take Simply the Converter out for maintenance. First we have to maintain the Voltage across the ~~Bypass Switch~~ Converter ZERO and then the Converter to be taken out, by closing the Switch. This Can be achieved (Getting Zero voltage across Switch) by Conducting 1 pair of Valves to be Conducted then voltage will be zero across the Converter, after that close the Switch, then take out the Converter

⇒ In the short pulse firing Case the Current extinction is present as the forward bias is not in Conduction. The Sequence for this Case as follows;



both are conducting, ∥ Voltage is Zero

ⓐ open bypass Switch at one terminal

ⓑ Deblock that terminal and lead to minimum Current in the Rectifier mode.

giving pulses to Converter is nothing but Deblocking

** The Converter which is Deblocking. that Should act as Rectifier initially, Because, in Short pulse, there is a problem of Commutation failure **

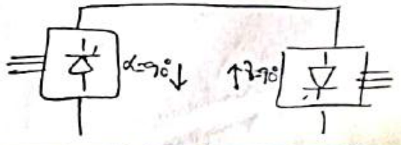
ⓒ open Bypass Switch at Second terminal and Commutate Current to the Bypass pair

ⓓ Start the Second terminal also in the Rectifier mode

ⓔ The Inverter terminal is put into the Inversion Mode

ⓕ Ramp up the Voltage and then the Current.

*initially both acts as Rectifiers and then decrease α and increase γ to make one in Rectifier operation and other in



In this Case also, the Voltage is normally raised before raising the Current. This permits the Insulation of the line to be Checked before raising the power. (13)

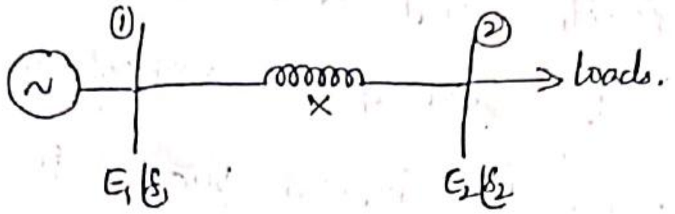
This type of increasing of power avoids stresses on the generator shaft. The Switching Surges in the line are also Reduced. The permissible Ramping (increasing voltage) rates may vary from 2 to 10 pu per second, implying a Start-up time of more than 100 to 500 msec.

* It is to be noted that to avoid operation at high delay (or) extinction angles, the deenergization (stopping) of a bridge at the Rectifier (or) Inverter Station is accompained by the deenergization at the Inverter (or) Rectifier.

Unit - IV.

FACTS - I

The major problem in AC Transmission System is to maintain the power flow in the line from one end to another end. A simplified case of power flow on a transmission line will be represented as below,



The above tr. line is assumed to have only inductive Reactance X and line Resistance and capacitance are ignored. Now, the power transfer capability of a given Tr. line will be given Mathematically as,

$$P = \frac{E_1 E_2}{X} \sin\delta$$

Where, E_1 and E_2 are the Magnitudes of bus voltages, with an angle δ (the difference b/w two angles) between the two.

If the angle (δ) b/w the two bus voltages is small, the current flow largely represents the Active power. Increasing (or) Decreasing the inductive impedance of a line will greatly affect the Active power flow. Thus, the impedance control which in reality provides the ~~control~~ current control, can be the most cost effective means of controlling the power flow.

power (or) Current flow Can also be Controlled by Regulating the Magnitude of Voltage Phasor E_1 (or) E_2. The Regulation of Voltage magnitudes E_1 (or) E_2 has much more influence over the Reactive power flow than the Active power flow

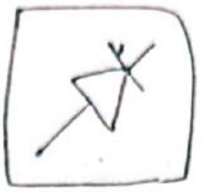
Current flow and hence the power flow Can also be changed by Injecting the voltage in Series with the line. When the injected voltage is in phase quadrature with the Current, It directly influences the magnitude of Current flow and Substantially the power flow. Therefore by varying the magnitude & phase angle of the injected voltage, both Active & Reactive Current flow Can be influenced.

Therefore, voltage injection Methods forms the most important Portfolio of the FACTS Controllers.

* Basic Types of FACTS Controllers :-

In General, FACTS devices are Classied Into,

i, Shunt Controllers
ii, Series Controllers
iii, Series- Series Controllers
(iv) Shunt - Series Controllers.



Basic Symbol of FACTS device

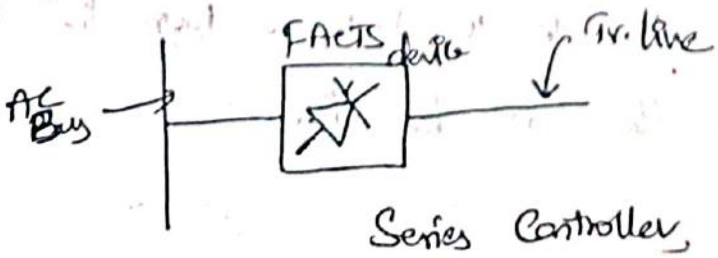
Definition

"The devices which incorporates the power Electronic based and Other Static Controllers to enhance the controllability and to increase the power transfer Capability" are known as FACTS devices.

Static Controllers — devices which are not based on power Electronic components.

i, ~~Shunt~~ Series Controllers :-

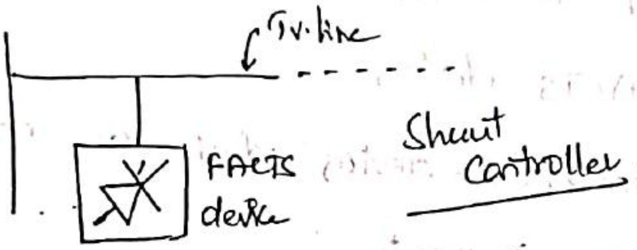
The Series Controller could be a Variable impedance such as Capacitor, Reactor etc. in principle, all Series Controllers inject voltage in Series with the line. As long as the Voltage is in Phase with the line Current, the Series Controller only Supplies (or) only Consumes Variable reactive power. Any other phase Relationship will involve handling of Real power as well



Series Controller,

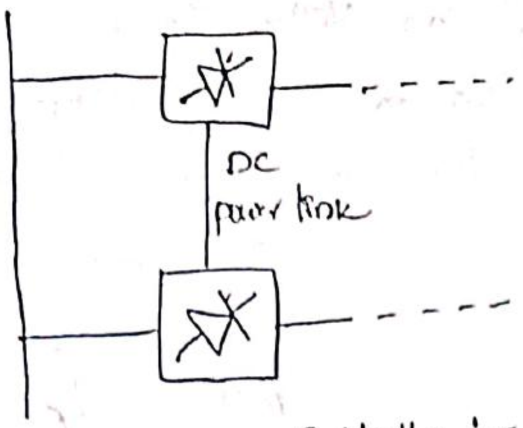
ii, Shunt Controller :-

Same as to that of Series Controllers, the Shunt Controllers also be a Variable impedance. In principle all Shunt Controllers inject Current into the sim at the point of Connection. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies (or) only Consumes Variable Reactive power. Any other phase Relationship will involve handling of Real power as well.



iii, Combined Series-Series Controller :-

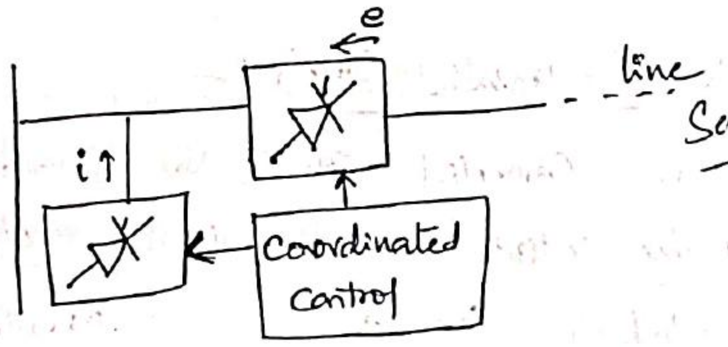
This Could be a Combination of Seperate series Controllers, which are Controlled in a Coordinated manner, in a multiline transmission System. or it Could be a "Unified Controller", in which Series Controllers provide Independent Series reactive Compensation for each line but also transfer Real power among the lines via-DC link. The Real power transfer Capability of Unified Series-Series Controller, Referred to as Interline power-flow Controller (IPFC), makes it possible to balance both the Real & Reactive power flow in the lines.



Series- Series Controller

(iv) Combined Series- Shunt Controller :-

This Could be a Combination of Seperate Shunt and Series controllers, which are Controlled in a Coordinated Manner. In principle, this device inject the Current with the Shunt part and the voltage with the Series part of the Controller. Here also there can be a Real power exchange between the Series and Shunt Controllers via the power link.



Series- Shunt Controller

* Description of FACTS Controllers :-

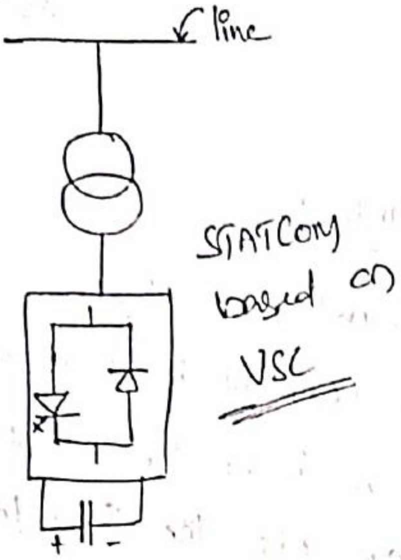
(i) Shunt Controllers :-

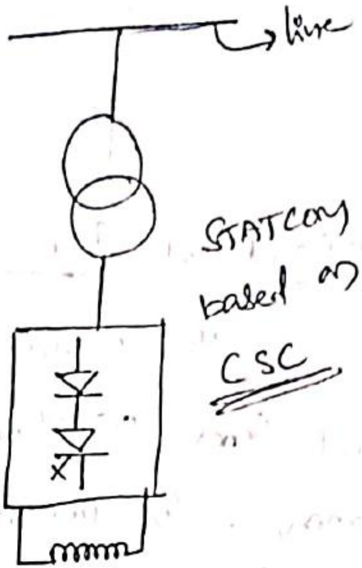
ⓐ Static Synchronous Compensator :- (STATCOM) :

A Static Synchronous generator operated as a Shunt Connected Static Var Compensator whose Capacitive (or) Inductive output Current Can be Controlled independent of the AC system voltage.

STATCOM is one of the Key device of FACTS Controllers.

It can be based on Voltage Source (or) Current Source Converter. STATCOM can be designed to also act as an Active filter to absorb the System Harmonics.

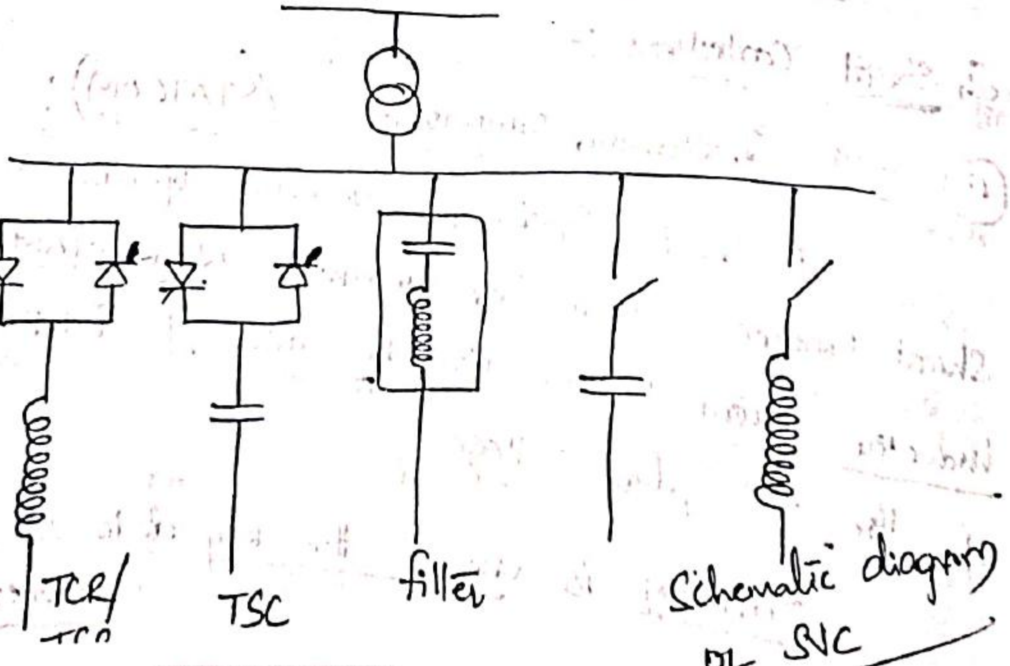




Generally, STATCOM based on Voltage Source Converters will be preferred and will be the basis for presentations of most Converter based FACTS Controllers.

ⓑ Static Var Compensator (SVC) :-

A Shunt Connected Static Var generator (or) absorber whose output is adjusted to exchange the Capacitive (or) Inductive Current so as to maintain (or) control specific parameters of Electrical power System.



Schematic diagram of SVC

SVC based on thyristors without the gate Turn-off Capability as shown above. It includes Seperate Equipment for leading and lagging Vars; the Thyristor Controlled (or) Thyristor Switched Reactor (TCR/TSR) for absorbing the Reactive power and Thyristor Switched Capacitor (TSC) for Supplying the Reactive power.

SVC is Considered as the lower cost alternative to STATCOM.

→ TCR :-

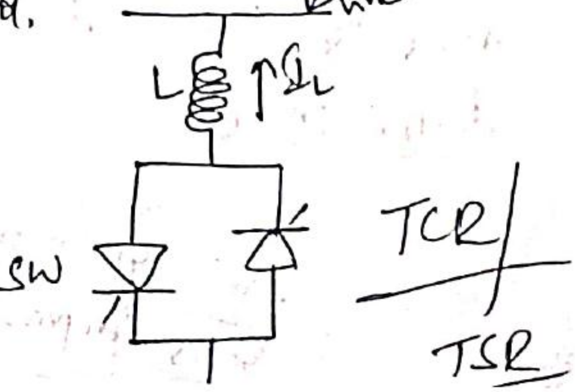
A Shunt Connected, Thyristor controlled inductor whose effective reactance is Varied in a continous manner by Partial Conduction control of Thyristor Valve.

This device is a Subset of SVC in which Conduction time, and hence, Current in a Shunt Reactor is Controlled by a Thyristor based AC Switch with firing angle control.

→ TSR :-

A Shunt Connected, Thyristor Switched Inductor whose effective reactance is Varied in step wise manner by full (or) zero conduction operation of the thyristor valve.

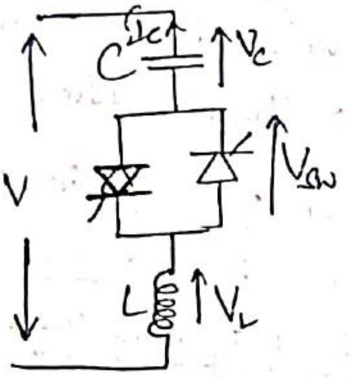
As like that of TCR, TSR also a Subdevice of SVC. TSR is madeup of Several Shunt Connected inductors which are Switched ON and OFF by thyristor switches without any firing angle Control.



→ TSC :-

A Shunt Connected, thyristor switched Capacitor whose effective Capacitive reactance is varied in step-wise manner by full (or) zero Conduction operation of the thyristor valve.

TSC also a Sub-device of SVC in which Thyristor based AC Switches are used to Switch ON and OFF the shunt Capacitor units. Shunt Capacitors Cannot be switched Continuously with variable firing angle Control.

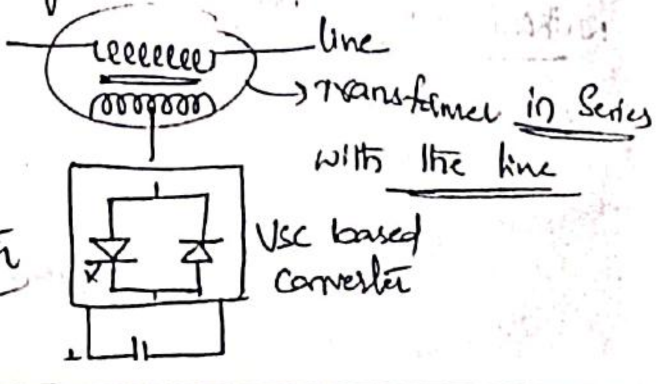


Basic Thyristor Switched Capacitor

(ii) Series Controllers :-

(a) Static Synchronous Series Compensator (SSSC) :-

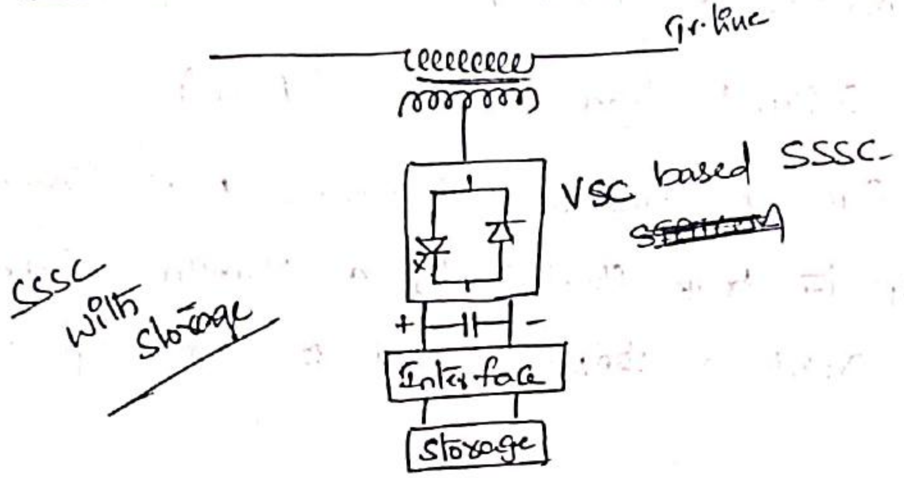
A static Synchronous generator operated without an external electric Source as a Series Compensator whose output voltage is in quadrature with and Controllable independently of the line Current for the purpose of increasing (or) decreasing the overall reactive voltage drop across the line and thereby Controlling the transmitted electric power.



Static Synchronous Series Compensator

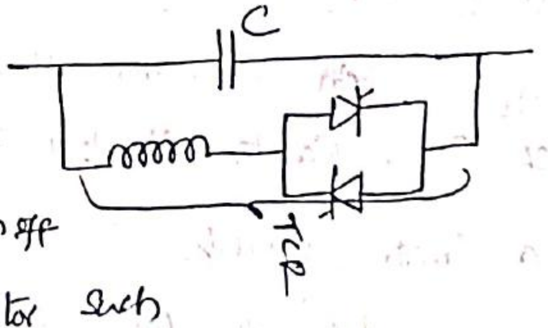
SSSC is one of the most Important FACTS Controller. It is like a STATCOM, except that the output AC voltage is in Series with the line. SSSC can be based on Voltage (or) Current Source Converter.

Without an Extra energy Source, SSSC can only inject a Variable Voltage, which is 90° leading (or) lagging Current. Battery storage (or) Super Conducting magnetic storage can also be Connected to a Series Controller to inject a Voltage of Variable angle in Series with the line.



(b) Thyristor Controlled Series Capacitor :-

A Capacitive Reactance Compensator which Consists of a Series Capacitor bank Shunted by a Thyristor Controlled Reactor (TCR) in order to provide a Smooth Variable Series Capacitive Reactance.



TCSC is based on the thyristors without gate turn off capability. A Variable Reactor such as TCR is Connected across the Capacitor. When the TCR firing angle is 180°, the Reactor becomes non-Conducting and the series Capacitance has its normal impedance. As the firing angle advances from 180° to less than 180° the capacitive impedance decreases. when the TCR firing angle is 90°, the Reactor becomes fully Conducting and the total impedance becomes inductive. with exactly 90° TCSC helps in limiting the fault Current.

The TCSC may be single large unit (or) may consists of several equal (or) different sized Smaller Capacitors in order to achieve a superior performance.

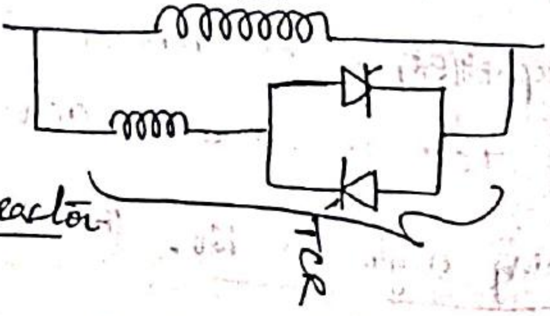
ⓒ Thyristor Switched Series Capacitor :- (TSSC)

A Capacitive Reactance Compensator which Consists of a Series Capacitor bank shunted by a Thyristor Switched Reactor to provide a stepwise control of Series Capacitive reactance.

Instead of Continous Control of Capacitive impedance, this approach of switching inductors at firing angle of 90° (or) 180°, but without firing angle control.

ⓓ Thyristor Controlled Series Reactor (TCSR) :-

An Inductive Reactance Compensator which Consists of Series Reactor shunted by TCR in order to provide a smooth variable Series Inductive Reactance.



when the firing angle of the TCR is 180°, it stops conducting and uncontrolled reactor acts as a fault current limiter. Now as the angle decreases below 180° to 90°, the net Inductance value decreases because, the Net Inductance is the parallel combination of two Reactors.

(c) Thyristor Switched Series Reactor :-

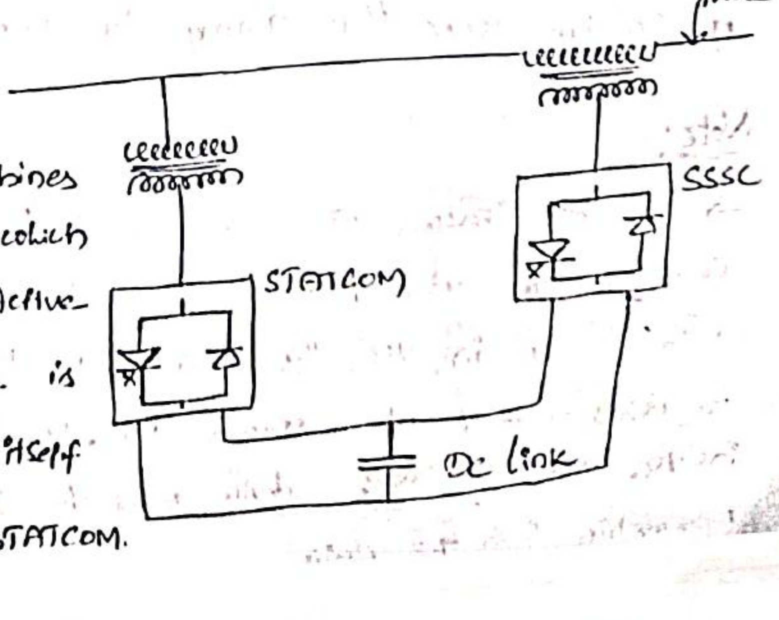
An Inductive Reactance Compensator which consists of a Series reactor shunted by TSR in order to provide a stepwise control of Series Inductive Reactor.

This is simply the Complement of TCSR, but the thyristors fully ON (or) OFF to achieve a Combination of stepped Series Inductance.

(iii) Combined Shunt & Series Controllers :-

(a) Unified power flow controller :- (UPFC)

A Combination of SSSC and STATCOM which are coupled via a Common DC link, to allow bidirectional flow of Real power between the Series o/p terminals of SSSC and Shunt o/p terminals of STATCOM, and are Controlled to provide Concurrent Real and Reactive line Compensation.



UPFC which combines a STATCOM and SSSC which is shown in fig. The Active power for the Series unit is obtained from the line itself via the Shunt Unit STATCOM.

the latter (STATCOM) also used for voltage control with the control of its Reactive power. This is a Complete Controller for Controlling Active & Reactive power through the line as well as the voltage control.

→ Other devices in this classification are
- i, Thyristor Controlled phase shifting Transformer (TCPST)
- ii, Interphase power Controller (IPC).

But, the best suited one was UPFC.

(iv) Combined Series - Series Controllers :-

(a) Interline power Flow Controller :-

The IPFC is a Recently introduced controller and thus has no IEEE definition yet.

This is a Combination of two (or more) Static Synchronous Series compensators which are Coupled via a dc link to facilitate bi-directional flow of Real Power between the AC terminals of the SSSC's, and are Controlled to provide independent reactive Compensation for the adjustment of Real power flow in each line and maintain the desired distribution of Reactive power flow among the lines.

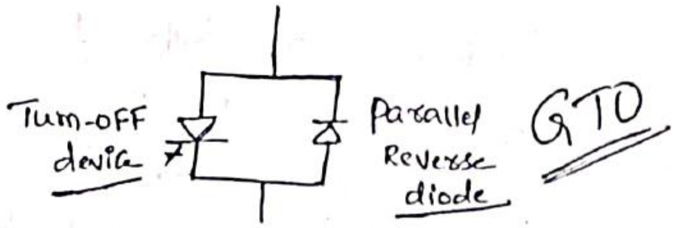
Note:-

→ For the Reasons of economics & Performance, Voltage Source Converters are often preferred over Current Source Converters.

→ In general in VSC the Current is bidirectional, and the voltage is unidirectional, which means the DC voltage no need to Reverse in VSC. Now, the Turn off devices used for VSC's are known as Asymmetric Turn-off device

Converter Operation :-

→ Therefore, the Voltage Source Converters are made up of an Asymmetric Turn-OFF device such as GTO. as shown below.



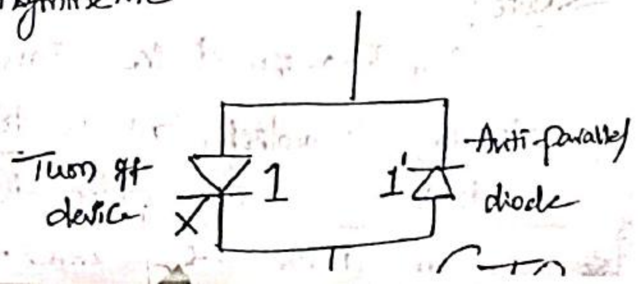
* Basic Concepts of Voltage Source Converters :-

The Converters applicable to FACTS Controllers would be of Self Commutating type. There are two basic Categories of Self Commutating converters;

i, Voltage Source Converter in which DC voltage has one Pollarity and the power Reversal takes place through the Reversal of DC Current pollality

ii, Current Source Converters in which DC Current always has one pollarity and power Reversal takes place through the Reversal of DC voltage pollarity

For reasons of economics and performance VSC's are often preferred than CSC's for FACTS applications. Since the DC Current flows in either direction in case of VSC's, the Converter valves have to be ~~di~~ bi-directional. Also, the DC voltage does not Reverse, the turn-off devices need not have reverse voltage Capability. Such turn off device is known as Asymmetric turn-off device. Thus, a voltage Source Converter (VSC) valve is made up of an Asymmetric turn-off device such as GTO.



The principle of operation of this turn off device is explained with the help of single valve operation.

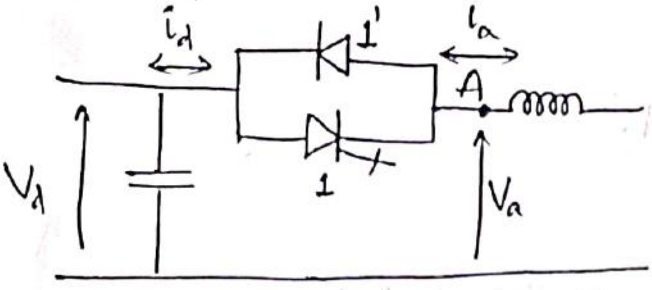


Fig. Single valve operation

When turn off device 1 is turned ON, the positive DC terminal is connected to ac terminal A, and the ac voltage would jump to $+V_d$.

It the current happens to flow from $+V_d$ to A, the power would flow from DC side to AC side (inverter action). However, if the current happens to flow from A to $+V_d$ it will flow through the Diode 1', even if the device 1 is turned ON, and the power flows from AC to DC (Rectifier)

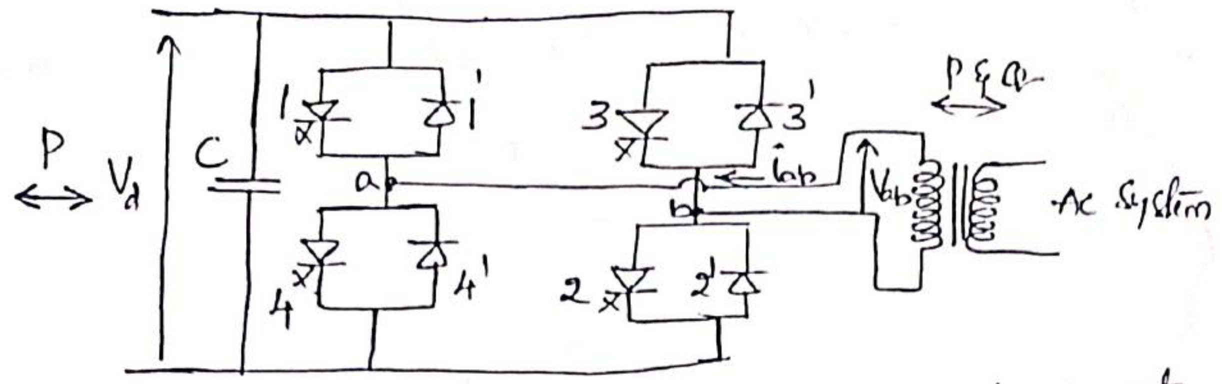
* Thus, a valve with a combination of turn-off device and diode can handle power flow in either direction, with the Turn-off device handling Inverter action, and the Diode handling Rectifier action.

Thus, the valve combination and its capability to act as a Rectifier (or) as an Inverter with the instantaneous current flow in positive (ac to dc) (or) Negative (dc to ac) direction respectively, is the basic to the voltage source converter.

⇒ Note:-

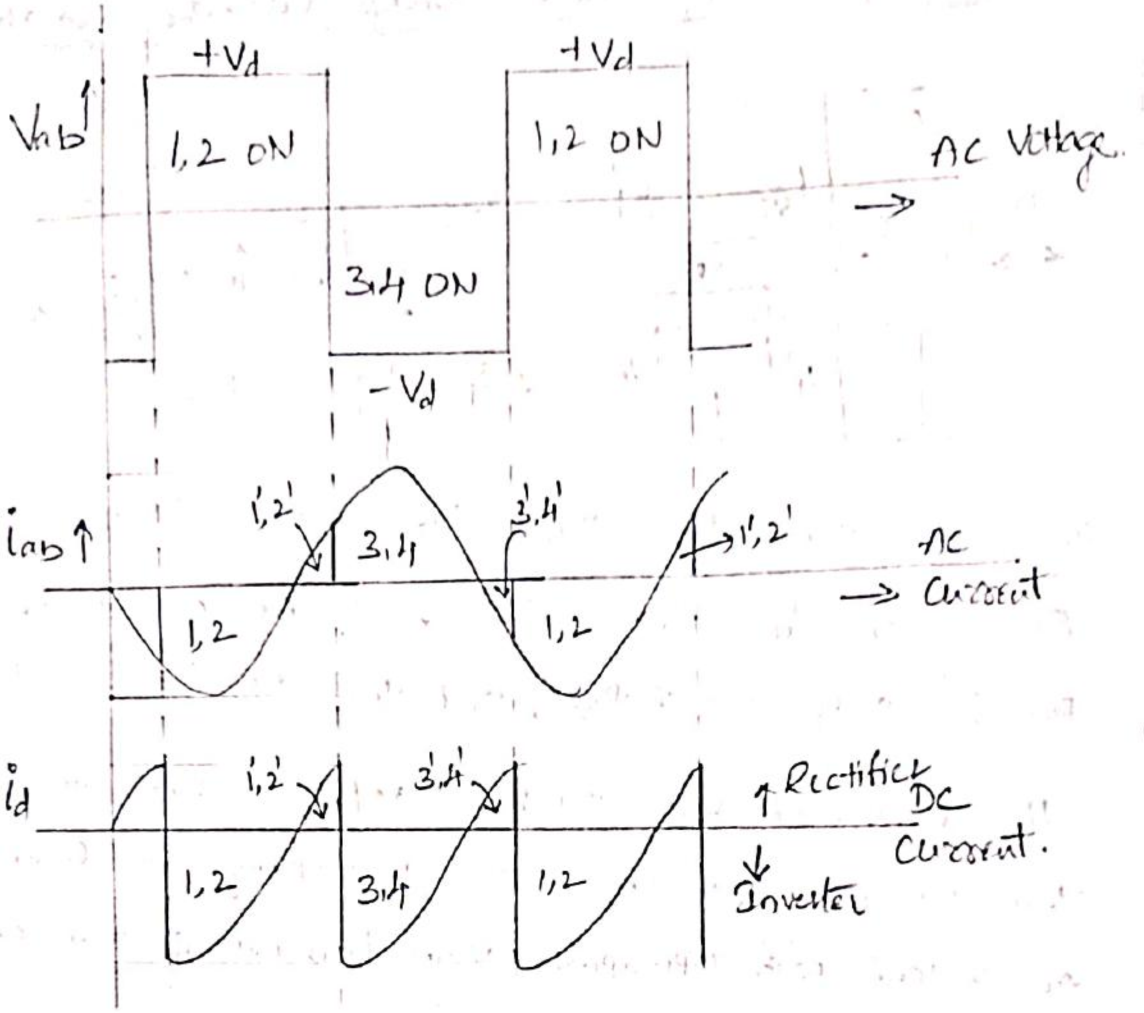
Any Turn-off device turns off, the AC bus current is not actually interrupted, but is transferred from a turn off device to diode when power factor is "not unity" and to another turn-off device when power factor is 'unity'.

* Single Phase Full Wave Bridge Converter Operation :-



The above figure shows 1ϕ- full wave bridge converter Consists of four Valves (1-1') to (4-4'). A DC Capacitor to Provide stiff DC Voltage, and two AC Connection points a & b. The designated valve numbers represent their Sequence of turn-ON and turn-OFF. The DC Voltage is Converted to AC Voltage with appropriate valve turn-ON & turn-OFF Sequence is given below,

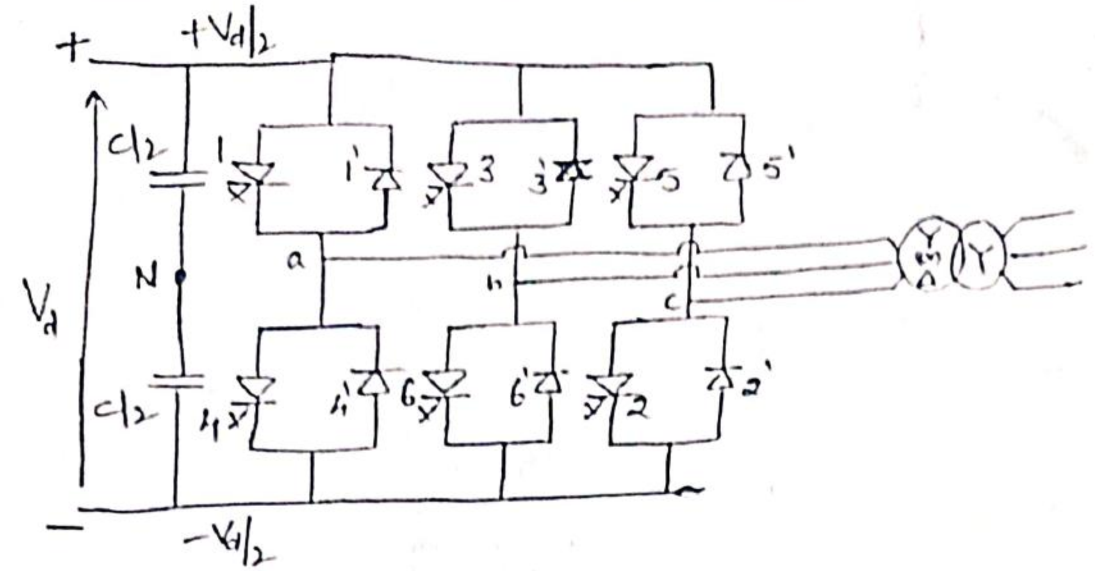
with Turn-OFF devices 1 and 2 turned ON, Voltage V_{ab} becomes $+V_d$ for one half cycle and with 3 & 4 turned ON and devices 1 and 2 turned OFF, V_{ab} becomes $-V_d$ for another half cycle. This voltage waveform occurs regardless of the phase angle, magnitude & wave form of Ac Current flow. The AC Current is the Result of Interaction of Converter generated AC Voltage with the AC System, angle θ, leading with respect to the Square wave Voltage waveform.



In the above waveform of Current flow i_d in the DC bus with the positive side flowing from AC to DC (Rectifier) and the Negative side flowing from DC to AC (Inverter). Clearly, the Average DC Current is "negative". Now, Depends upon the net Current, we can say the Voltage Source Converter is Convinient to operate as Inverter, rather than Rectifier, even though it has the Capability to operate as Rectifier.

Rectifier:

* 6-pulse full wave Bridge Converter :-



The above figure shows a 3φ-full wave Converter with 6 Valves (1-1') to (6-6'). The designated order 1 to 6 represents the Sequence of Valve operation in time. It consists of three Phase-legs, which operate at 120 apart. The three Phase legs operate in a Square wave Mode. Each Valve alternately closes for 180° as shown in wave-forms. These Three Square wave forms are the Voltages of AC buses a.b.c with respect to a thay hypothetical DC Capacitor Mid-point 'N', With Peak Voltages of $+V_d/2$ and $-V_d/2$.

The three phase-legs have their timing 120° apart with respect to each other. Phase-leg 3-6 Switches 120° after Phase leg 1-4, and phase leg 5-2 Switches 120° after Phase leg 3-6, thus completing the cycle. The three Phase-to Phase voltages V_{ab}, V_{bc}, V_{ca}, where, $V_{ab} = V_a - V_b$, $V_{bc} = V_b - V_c$ and $V_{ca} = V_c - V_a$.

For example, the wave-form for V_{ab} shows voltage V_d when turn-off device 1 Connects AC bus 'a' to the DC bus '$+V_d/2$' and turn-off device 6 Connects AC bus 'b'

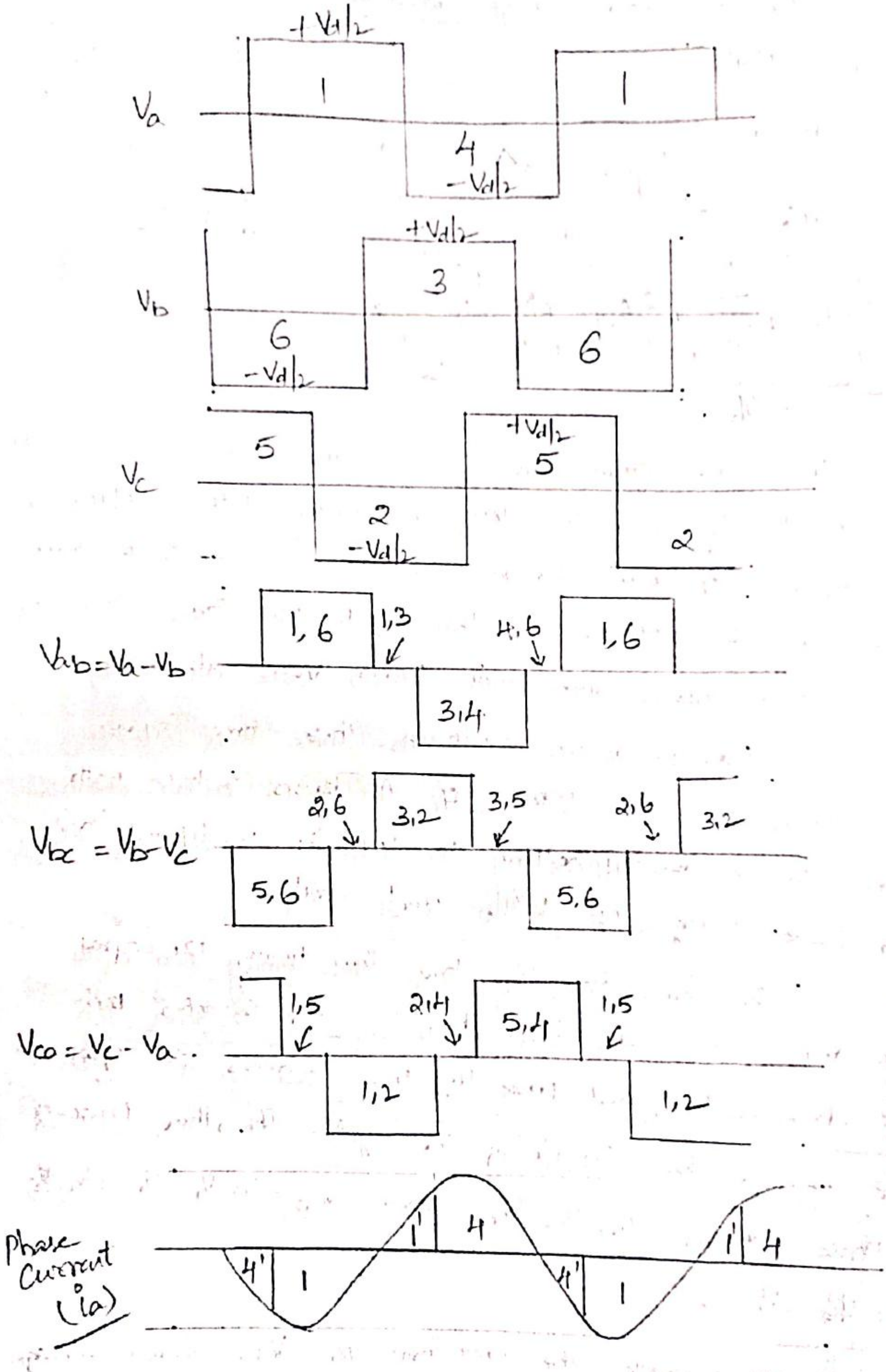


Fig.: Ac Waveforms of a 3ϕ full wave Converter to the DC bus $-V_d/2$, giving a total voltage of $V_{ab} = V_a - V_b = V_d$. It is seen that 120° later, when turn-off device-6 is turned off and turn-off device-3 is turned ON, both the AC buses a and b, become connected to the same DC bus $+V_d/2$ giving zero voltage between a and b.

Another 60° later, as turn off device 1 turns off and turn-off device 4 connects bus a to $-V_d/2$, V_{ab} becomes $-V_d$. Another 120° later, turn-off device-3 turns off and turn off device 6 connects to $-V_d/2$ giving $V_{ab} = 0$. Now, the cycle is completed when, after another 60° turn-off device 4 turns off, and turn off device 1 turns ON. Similarly, the other two voltages V_{bc} and V_{ca} have the same sequence 120° apart.

The turn-ON and turn-OFF of the devices establish the waveforms of the AC bus voltages in relation to the DC voltage, the current flow itself is the result of the interaction of the AC voltage with the AC system. It can be seen that when comparing the phase a voltage with the waveform of the phase a current, that when turn-off device 4 is ON and turn off device 1 is off and the current is negative, the current would actually flow through diode 4' ~~to device 1~~ But later, when device 4 is turned off and device 1 is turned ON, the negative current flows through device 1, the current having transferred from diode 4' to device 1.

characteristics.

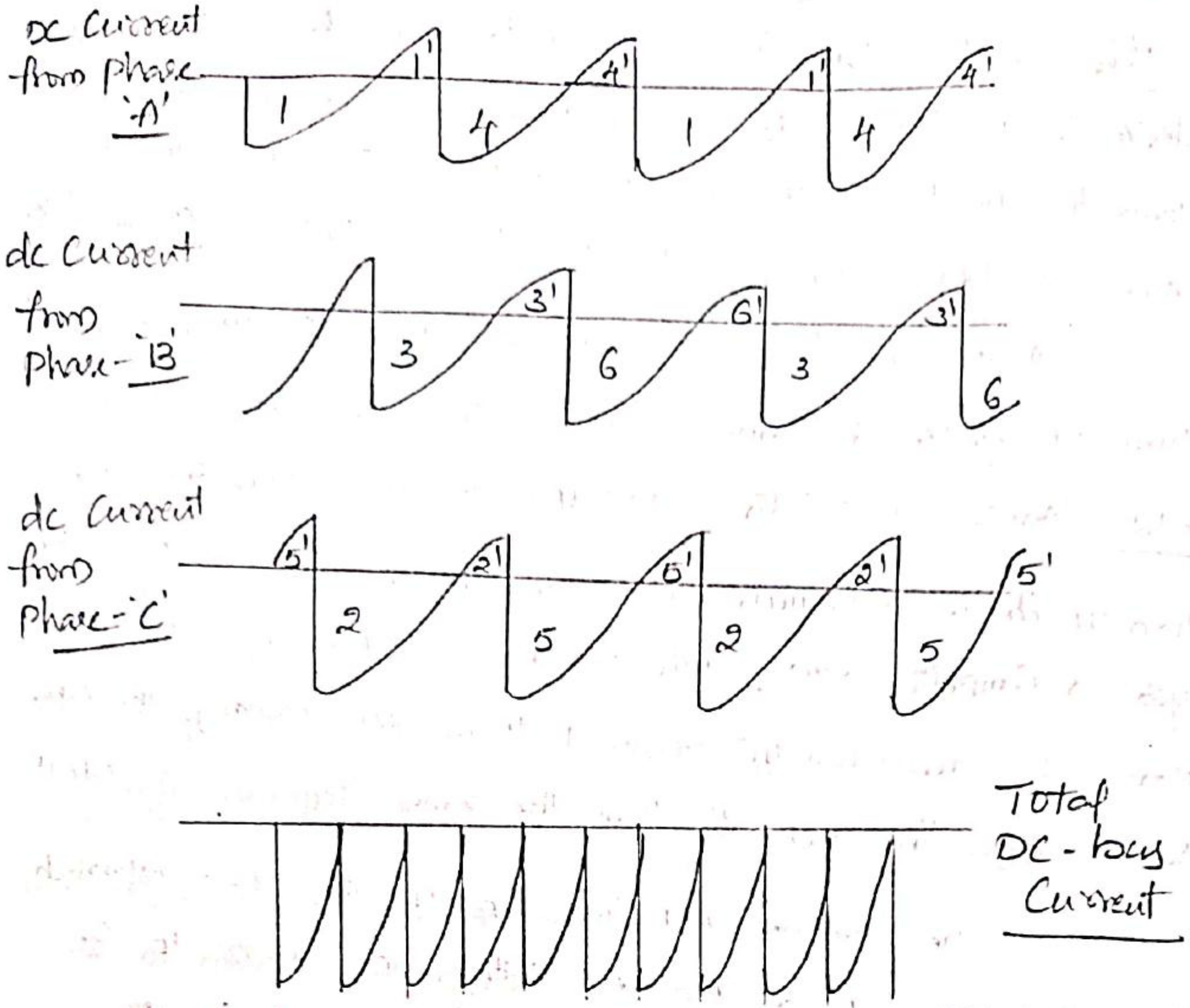


Fig. DC Current wave forms of 3φ full wave VSC

* Fundemental & Harmonics for a 3φ Bridge Converter :-

From the previous Section, it is to be noted that the Square wave forms of Va, Vb & Vc are the phase Voltages with respect to hypothetical Mid-point 'N' of the DC voltage and not the neutral point of AC side. These Voltages would be Phase to neutral AC voltages only if AC neutral is physically Connected to the mid-point of the DC voltage, in which Case the Converter would in effect becomes a Series Combination of three phase three pulse half bridge Converter and not a six pulse full-wave Converter.

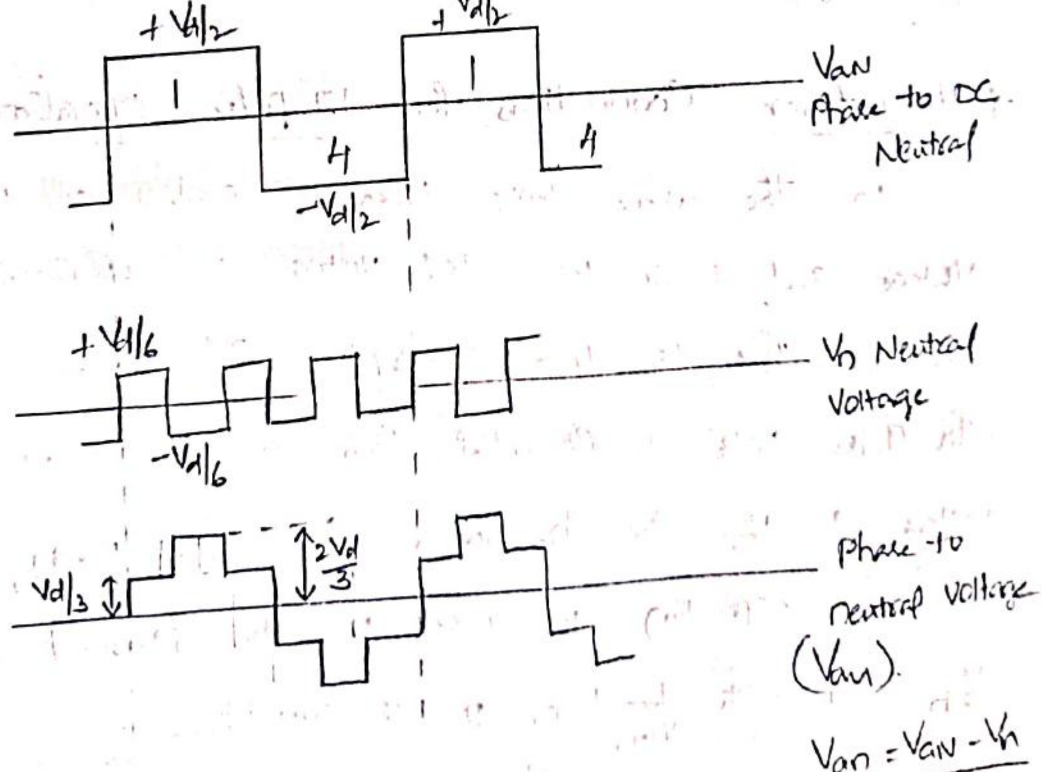
For a square wave with amplitude $\frac{V_d}{2}$, the instantaneous voltages of V_a, V_b & V_c based on Fourier analysis is given by,

$$V_a = \frac{4V_d}{2\pi}\left[\cos\omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\cos 7\omega t + \cdots\right]$$

V_b is obtained by Replacing ωt by $\omega t - \frac{2\pi}{3}$ and

V_c is obtained by Replacing ωt by $\omega t + \frac{2\pi}{3}$.

Since the AC neutral in a bridge Converter is floating, it is necessary to work out phase to neutral voltages, which appear across the transformer secondaries. If it is assumed that the three phases are connected to wye transformer secondary with floating neutral, then the floating neutral will acquire a potential w.r.t DC mid-point which is $\frac{1}{3}$rd of sum of all the voltages of phase terminals a, b & c. Below fig. shows the V_n, a square wave magnitude of $V_d/6$.



$V_{an} = V_{aN} - V_n$

characteristics.

Subtracting V_n from the phase voltages w.r.t. DC neutral gives the phase voltages across the wye-connected transformer secondaries, as shown only for Van. Similarly for Vbn and Vcn would be same except the phase shift by 120° and 240° for phases b & c respectively.

Van can be mathematically represented as,

$$V_{an} = \frac{4V_d}{2\pi}\left[\cos\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t + \cdots\right]$$

Similarly, $V_{ab} = V_{an} - V_{bn}$

$$\Rightarrow V_{ab} = \frac{2\sqrt{3}}{\pi}V_d\left[\cos\omega t - \frac{1}{5}\cos 5\omega t + \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \cdots\right]$$

Now, the two equations determined above are 30° out of phase.

Now, to overcome this phase difference and to reduce the lower order harmonics we need different transformer connections and to increase the pulse number of converters respectively.

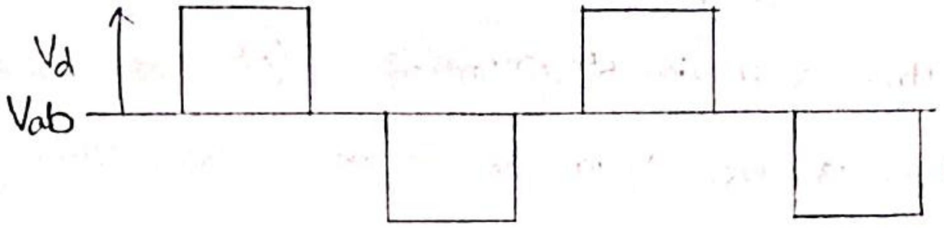
* Transformer Connections for 12-pulse operation :-

In the above topic, harmonic content of phase to phase voltage and phase to neutral voltage was discussed, and was mentioned that the two voltages were 30° out of phase. If this phase shift is corrected, then for the phase to neutral voltage i.e. Van, the harmonics other than 12n±1, would be in phase opposition to those of the phase-to-phase voltage Vab and with $\frac{1}{\sqrt{3}}$ times of the amplitude.

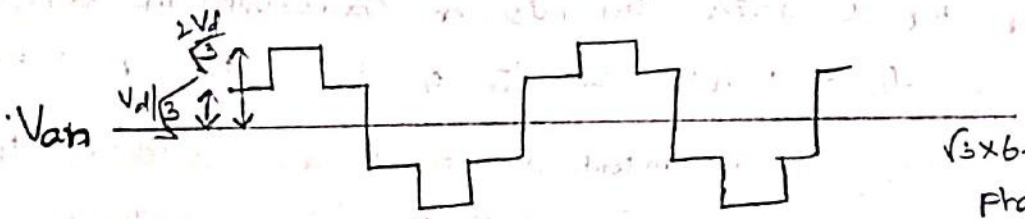
To achieve this, the phase-to-phase voltages of a second converter were connected to the Delta-connected

Secondaly of a second transformer, with √3 times the turns compared to the wye-connected secondaly and the pulse train of one converter was shifted by 30° with respect to other (inorder to bring Vab and Van to be in phase).

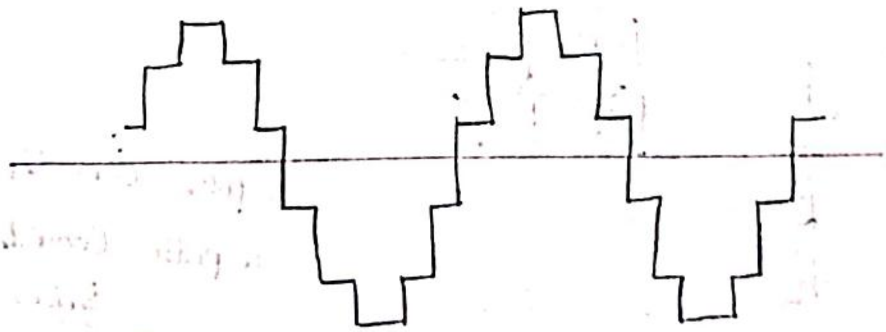
Below figure shows the waveforms of Van and Vab adjusted for the transformer ratio and one of them phase displaced by 30°. These two waveforms are then added to give the third waveform, which is seen to be a 12-pulse waveform.



6-pulse phase to phase



√3×6-pulse phase to phase



12-pulse voltage waveform

The below figure shows the transformer connection to arrange the phase difference of 30°, in which two 6-pulse converters, involving a total of 6 phase legs are connected in parallel on the same DC bus and work together as a 12-pulse converter.

characteristics.

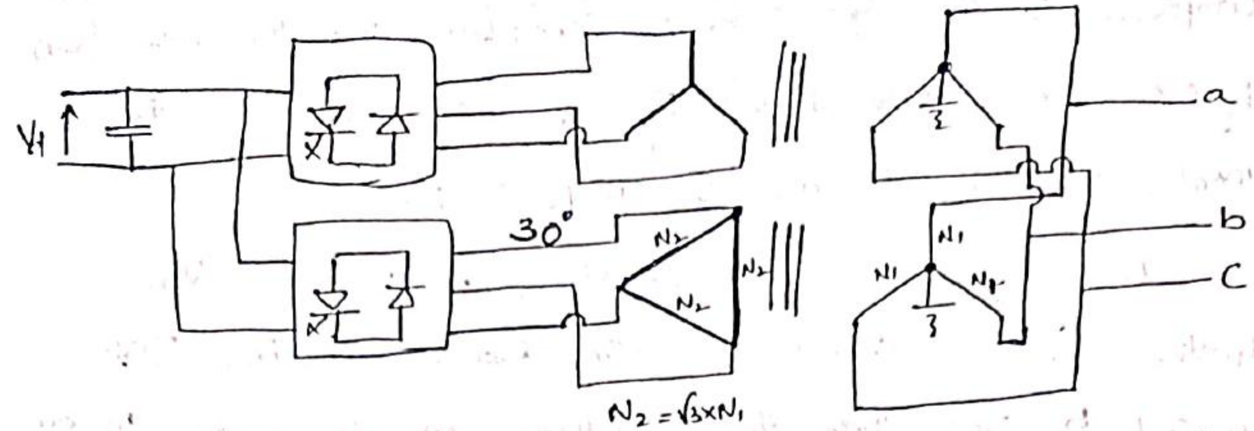
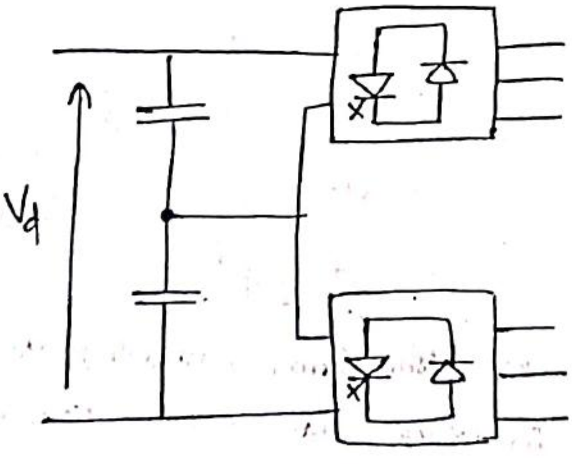


Fig. 12 pulse Converter with two Parallel Connected 6-pulse Converters

→ It is necessary to have two seperate transformers, Otherwise Phase Shift in 5th, 7th, 17th, 19th ... (other than ~~non~~-12-pulse harmonics i.e, 11,13, 23,25...) in the secondaries will result in large circulating current.

The two Converters can also be connected in Series on the DC Side for a 12-pulse Converter of twice the DC Voltage. In such a case, it is important to provide a control to ensure that the two buses (Capacitors) have equal voltages.



12-pulse Converter with two 6-pulse Converters in Series

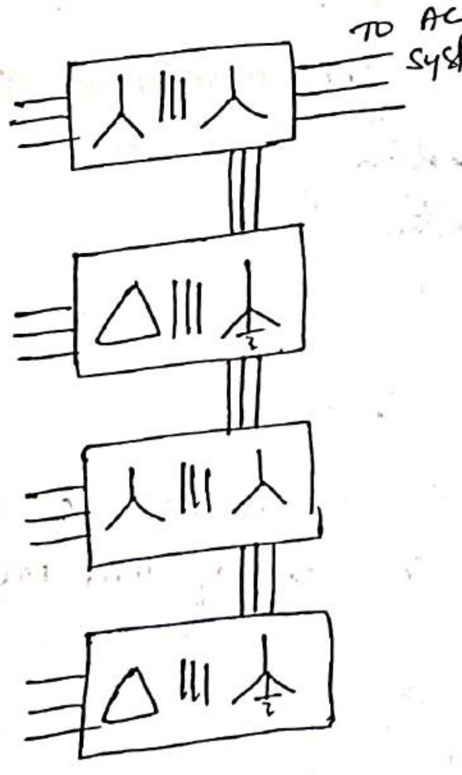
* For 12-pulse Converter; 5th,7th order harmonics are Eliminated.

* 24 and 48 pulse operation :-

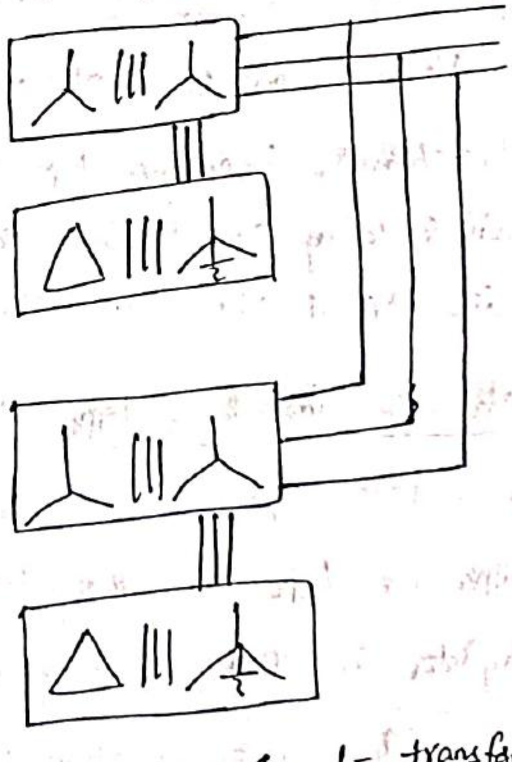
Two 12-pulse Converters, phase shifted by 15° from each other, Can provide a 24-pulse Converter, obviously with much lower harmonics on both AC & DC side. Its AC output Voltage would have 24±1 order harmonics. i.e, 23, 25, 47, 49 . . . harmonics with magnitudes of $\frac{1}{23^{rd}}$, $\frac{1}{25^{th}}$, $\frac{1}{47^{th}}$, $\frac{1}{49^{th}}$ - - - respectively of the fundamental AC Voltage.

One approach is to provide 15° phase shift wdgs on the two transformers of one of the 12-pulse Converter.

Another approach is to provide phase shift wdgs for +7.5° on the two transformers of one-12 pulse Converter and on the two transformers of other 12-pulse Converter -7.5° on the two



24-pulse Converter transformer Connections with two 12-pulse Converters in Series.



24-pulse Converter transformer Connections with two 12-pulse converters in parallel

The Alternative, of Course is go to 48-pulse Operation with 8 6-pulse Converters, with one Set of transformers of one 24-pulse Converter phase-shifted from the other by 7.5° (or) one Set shifted by +3.75° and the other by ~~-3.75°~~ -3.75°. Logically, all 8 transformers primaries are to be Connected in Series, but because of the Small Phase-shift, the primaries of the two 24-pulse Converters may be Connected in parallel if the Consequent circulating Current is in acceptable limits.

* For 48-pulse operation, AC filters should not be necessary.

* Types of Controllable Shunt Var Generation :-

Various types of Controllable Shunt Var-Generation are given as
i, Variable impedance type Var Generation
ii, Switching Converter type Var Generation
iii, Hybrid Var Generation.

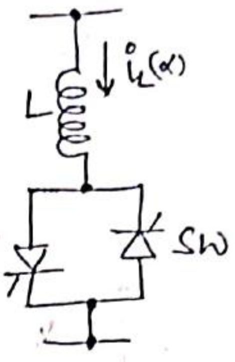
(i), Variable impedance type Var Generation :-

The performance and operating characteristics of the impedance type Var generation are determined by their Major Thyristor-Controlled Constituents:

ⓐ Thyristor Controlled Reactor
ⓑ Thyristor Switched Capacitor

ⓐ Thyristor Controlled Reactor & Thyristor Switched Reactor (TCR & TSR) :-

The basic block diagram is shown below, It consists of a fixed Reactor of inductance 'L', and a bidirectional thyristor valve 'SW'. Currently available large thyristors can block the voltages upto 4000 to 9000 volts and conducts current upto 3000 to 6000 ~~volts~~ amperes. Thus, in practical valve many thyristors are connected in series to meet the required blocking voltage levels.



A thyristor valve can be brought into conduction by Simultaneous application of a gate pulse to all the thyristors of the same pollarity. The valve will automatically block immediately after the AC current crosses the Zero, unless the gate signal is reapplied.

The current in the Reactor can be controlled from maximum ($\alpha=0$) to zero ($\alpha=90°$) by the method of firing delay angle control. The conduction period of the thyristor valve is controlled by delaying the thyristor valve with respect to the peak of the applied voltage in each half cycle. when $\alpha=0$, the valve sw closes at the peak value of voltage and resulting the current in the Reactor, that (current) will be the same as that obtained in steady state with a permanently closed switch. when the gating of the valve is delayed by an angle α $(0 \leq \alpha \leq \pi/2)$. the current in the Reactor can be expressed as given below.

applied Voltage across the TCR $v(t) = V\cos\omega t$ ①

and Current passing through inductor (L) is,

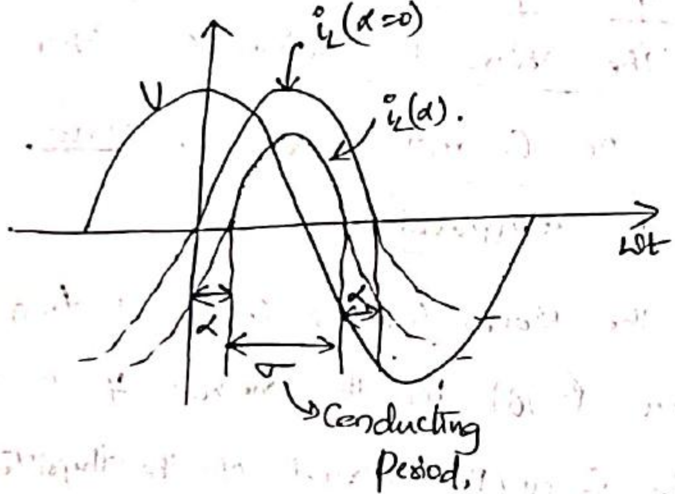
$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt$$

$$= \frac{1}{L}\int_{\alpha}^{\omega t} V\cos\omega t$$

$$= \frac{V}{\omega L}\Big[\sin\omega t\Big]_{\alpha}^{\omega t}$$

$$\therefore \boxed{i_L(\alpha) = \frac{V}{\omega L}\left(\sin\omega t - \sin\alpha\right)} \quad ②$$

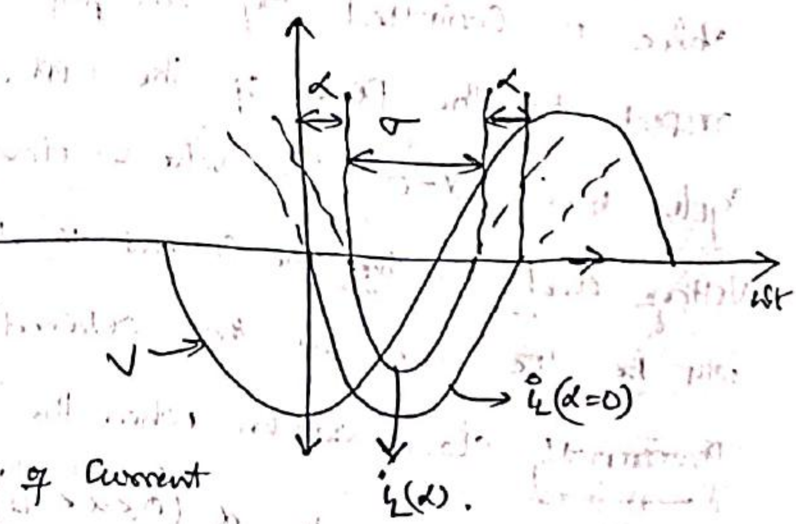
The method of Current Control is illustrated for positive and Negative half cycles below,



for positive half cycle the above Equation ② will holds good.

for Negative half cycle the above Equation ② will be,

$$\boxed{i_L(\alpha) = \frac{V}{\omega L}\left(\sin\omega t + \sin\alpha\right)}$$



Therefore the magnitude of Current in the reactor Can be Varied Continously by this method of delay angle control, from maximum ($\alpha = 0$) to zero ($\alpha = 90$).

where, $i_L(\alpha)$ is together with the fundemental Component $i_{LF}(\alpha)$.

Nao, to adjust the Current in the Reactor it is important to Calculate the fundemental component of Current.

Now, the fundemental Current $i_{LF}(\alpha)$ is given as,

$$I_{LF}(\alpha) = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} i_L(\alpha)\sin\omega t \, d\omega t$$

$$= \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} \frac{V}{\omega L}(\sin\omega t - \sin\alpha)\, d\omega t \cdot \sin\theta \quad (\because \omega t = \theta)$$

$$= \frac{2V}{\pi\omega L}\int_{\alpha}^{\pi-\alpha}(\sin\theta - \sin\alpha)\, d\theta \cancel{t} \cdot \sin\theta$$

$$= \frac{2V}{\pi\omega L}\int_{\alpha}^{\pi-\alpha}(\sin^2\theta - \sin\alpha\sin\theta)\, d\theta$$

$$= \frac{2V}{\pi\omega L}\left[\int_{\alpha}^{\pi-\alpha}\sin^2\theta\, d\theta - \int_{\alpha}^{\pi-\alpha}\sin\alpha\sin\theta\, d\theta\right]$$

$$= \frac{2V}{\pi\omega L}\left[\int_{\alpha}^{\pi-\alpha}\left(\frac{1-\cos 2\theta}{2}\right) d\theta - \sin\alpha\int_{\alpha}^{\pi-\alpha}\sin\theta\, d\theta\right]$$

$$= \frac{2V}{\pi\omega L}\left[\int_{\alpha}^{\pi-\alpha}\frac{1}{2}d\theta - \int_{\alpha}^{\pi-\alpha}\frac{\cos 2\theta}{2}\, d\theta - \sin\alpha\int_{\alpha}^{\pi-\alpha}\sin\theta\, d\theta\right]$$

$$= \frac{2V}{\pi\omega L}\left[\left[\frac{\theta}{2}\right]_{\alpha}^{\pi-\alpha} - \left[\frac{\sin 2\theta}{4}\right]_{\alpha}^{\pi-\alpha} - \sin\alpha\left[-\cos\theta\right]_{\alpha}^{\pi-\alpha}\right]$$

$$= \frac{2V}{\pi\omega L}\left[\left(\frac{\pi-\alpha-\alpha}{2}\right) - \left(\frac{\sin(2\pi-2\alpha)}{4} - \frac{\sin 2\alpha}{4}\right) - \sin\alpha\left(-\cos(\pi-\alpha) + \cos\alpha\right)\right]$$

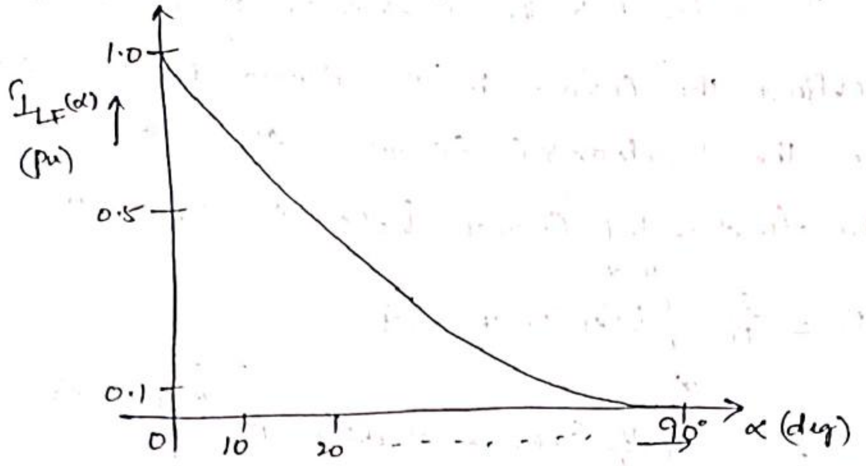
$$= \frac{2V}{\pi\omega L}\left[\frac{\pi-2\alpha}{2} - \left(\frac{-\sin 2\alpha}{4} - \frac{\sin 2\alpha}{4}\right) - \sin\alpha(2\cos\alpha)\right]$$

$$= \frac{2V}{\pi\omega L}\left[\frac{\pi-2\alpha}{2} + \cancel{2}\frac{\sin 2\alpha}{\cancel{4}_2} - 2\sin\alpha\cos\alpha\right]$$

$$= \frac{2V}{\pi\omega L}\left[\frac{\pi}{2} - \alpha + \frac{\sin 2\alpha}{2} - \sin 2\alpha\right]$$

$$\boxed{I_{LF}(\alpha) = \frac{2V}{} \left[\frac{\pi}{2} - \alpha - \frac{\sin 2\alpha}{2}\right]} \quad \text{—— ③}$$

The characteristics of $I_{LF}(\alpha)$ (Vs) α is shown below,

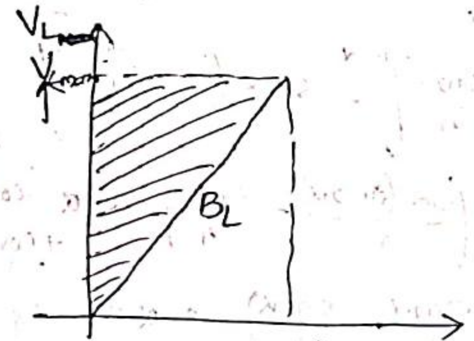


It is clear from above characteristic that the TCR can control the fundamental current continously from zero to maximum as if it was a Variable Reactive Admittance

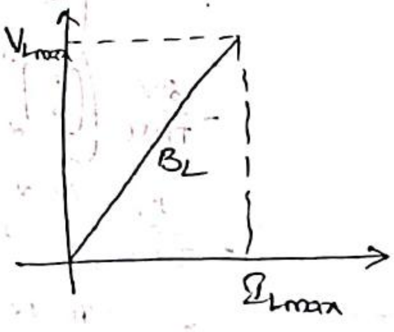
for TCR, the effective Reactive Admittance is defined as $B_L(\alpha)$, Mathematically,

$$\boxed{B_L(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right)} \text{ — } (4)$$

Also the V-I characteristics of TCR is given as,



Ⓐ for TCR



Ⓑ for TSR

* where TSR can provide fixed inductive Reactance to the System either zero (or) Maximum, either switches ON (or) OFF.

(b) Thyristor Switched Capacitor :-

A single phase TSC is shown in figure. It consists of a Capacitor, a bidirectional Thyristor Valve, and a relatively small Surge Current limiting Reactor. This reactor is needed primarily to limit the Surge current in the thyristor Valve under abnormal operating conditions. Current limiting Reactor is also be used to avoid Resonance condition with the AC System impedance at particular frequencies.

Under steady state operating conditions, when the thyristor valve is closed and the TSC is connected to the sinusoidal AC voltage $v = V\sin\omega t$, and the current in the branch is given by,

$$\left[\because X_c = \frac{1}{2\pi f C} = \frac{1}{\omega C} \Rightarrow \omega C = \frac{1}{X_c}\right]$$

$$i = C\frac{dv}{dt}$$

$$= C\frac{d}{dt}(V\sin\omega t)$$

$$= V\cdot C\cos\omega t\cdot\omega$$

$$i = \frac{V\cos\omega t}{X_c}$$

$X - X_L$

X

$X\left(1 - \frac{X_L}{X}\right)$

again $X_c = X_c - X_L$

$$\therefore i = \frac{V\cos\omega t}{X_c - X_L}$$

$$\left[\because n = \sqrt{\frac{X_c}{X_L}}\right]$$

$$= \frac{V\cos\omega t}{X_c\left(1 - \frac{X_L}{X_c}\right)}$$

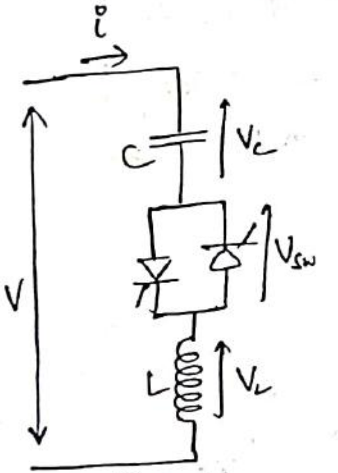
$$\therefore i = \frac{V\cos\omega t}{X_c\left(1 - \frac{1}{n^2}\right)} = \frac{V\cos\omega t}{X_c\left(\frac{n^2-1}{n^2}\right)} \qquad \left[\because \frac{1}{X_c} = \omega C\right]$$

$$\therefore \boxed{i = \frac{n^2}{n^2-1} V\omega C\cos\omega t}$$

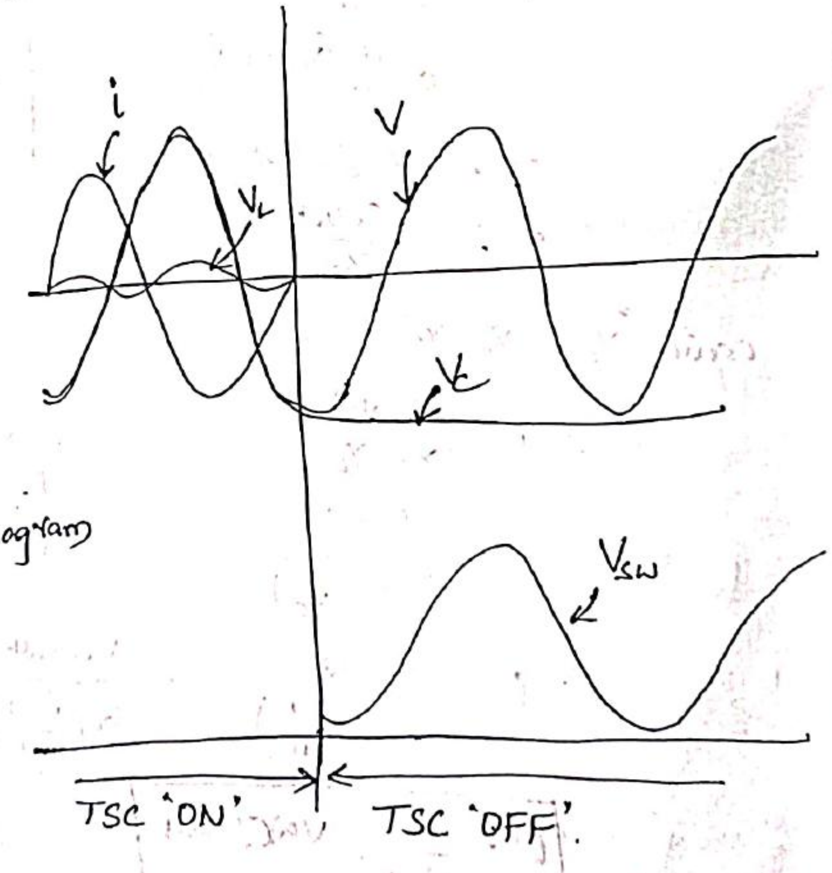
Now, the Amplitude of the voltage across the capacitor is, $\boxed{V_c = \frac{n^2}{n^2-1} \cdot V}$

The TSC branch operates on Thyristor delay angle control technique. This can be disconnected at any current zero by prior removal of the gate drive to the thyristor valve. At the point of current zero crossing, the capacitor voltage is at its peak value i.e $V_c = \frac{n^2}{n^2-1} . V.$

The disconnected capacitor stays charged to this voltage and consequently, the voltage across the non-conducting thyristor valve varies between zero and the peak-to-peak value of the applied AC voltage as given below,



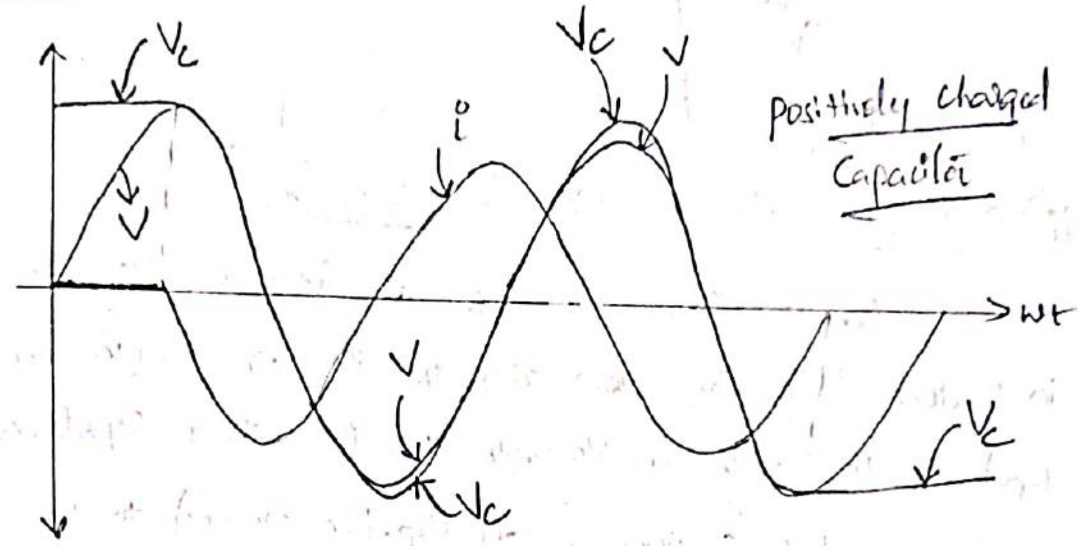
Fig(a)
Fig. Basic Block diagram of TSC

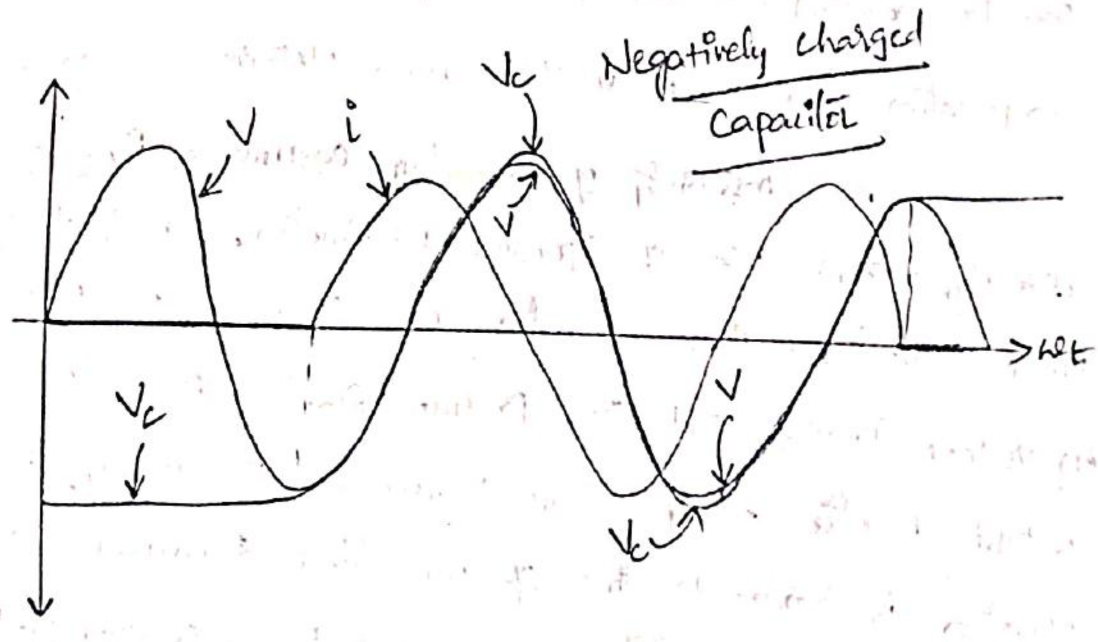


Fig(b) Associated waveforms of TSC.

If the voltage across the disconnected capacitor remains uncharged, the TSC bank could be switched "IN" again, without any transient, at the appropriate peak of the applied AC voltage, as illustrated for positively & negatively charged capacitor in below figure.

Normally, the capacitor bank is discharged after the disconnection.

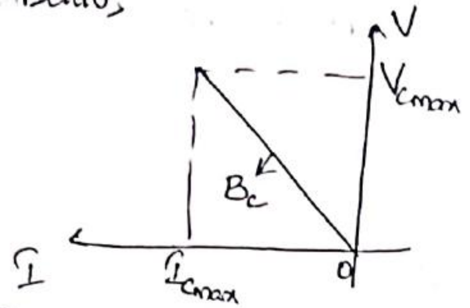




Simply, The TSC branch represents a single capacitive admittance which is either connected to (or) disconnected from AC system. The max. applicable voltage and corresponding current is limited by the ratings of TSC components.

To approximate Continous Current Variation, Several TSC branches in parallel may be Employed. The TSC branch have to be Complemented with a TCR.

The operating V-I characteristics of TSC are given below,



(ii) Switching Converter type Var Generation :-

Variable impedance type Var Generators has been seen in previous topic. The main aim of this approach (Variable impedance type) is to provide a Variable Reactive Shunt impedance that can be adjusted (Continously (or) step-like manner) to meet the compensation requirements of transmission Network.

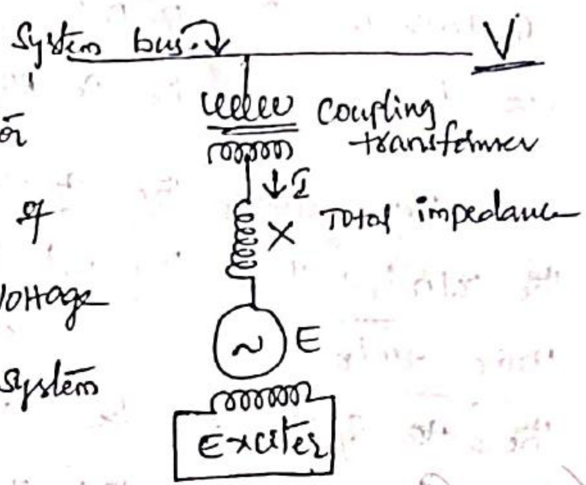
The possibility of generating Controllable Reactive power directly, without use of Capacitors (or) Reactors, by Various Switching power Converters. These Converters are operated as Current Sourced (or) Voltage Sourced and they produce Reactive power essentially without Reactive energy storage Components. Functionally, their operation is Similar to that of an ideal Synchronous machine whose Reactive power output is Varied by Excitation Control. Because of this, a Rotating Synchronous generator also known as Static Synchronous Generator (SSG).

When SSG is operated without an energy Source, and with appropriate Controls to function as a Shunt-Connected

Reactive compensator, then that type of device can be termed as Static Synchronous Compensator (STATCOM), based on Voltage Sourced Converter.

Basic operating principle :-

The basic principle of Reactive power generation by Voltage Source Converter is same to that of Conventional Rotating Synchronous machine, as shown in below figure.



Now, the Reactive Current drawn by the Synchronous Compensator is determined by the Magnitude of system voltage V, and internal voltage E, and total impedance of the system as below,

$$\boxed{I = \frac{V-E}{X}}$$

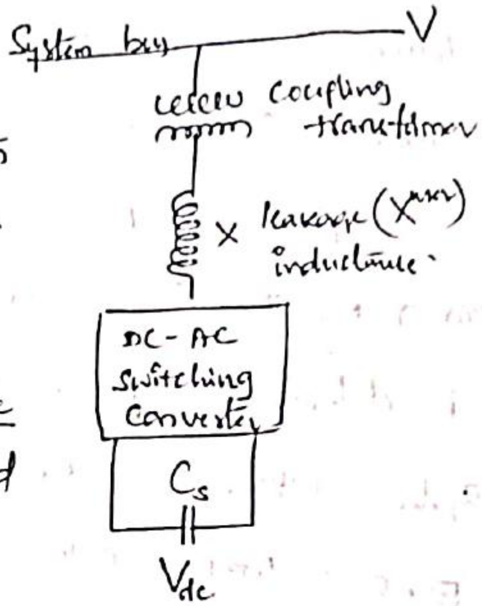
and Reactive power $\boxed{Q = \frac{1-\frac{E}{V}}{X} V^2}$

By controlling the excitation of the Machine, the Reactive power flow can be controlled. Increasing E above V results in a leading Current, that is, Machine is 'seen' as 'Capacitor' by the AC System. Decreasing E below V produces a lagging Current, that is Machine 'seen' as Reactor by the AC System. Under either operating condition a small amount of Real power flows from the AC System to Machine to supply its Mechanical and Electrical losses. Note that if the excitation of machine is controlled so that the corresponding

Th [illegible]

Reactive output maintains (or) varies a parameter of the AC system, then that machine is known as Rotating Synchronous Compensator.

The basic VSC scheme for Reactive power generation is shown schematically below,



The converter produces a set of controllable 3ϕ output voltages with the frequency of the AC power system.

By varying the amplitude of the output voltage produced, the Reactive power exchange b/w the converter and the AC system can be controlled in a manner similar to that of the synchronous machine.

That is, if the amplitude of output voltage increased above that of AC system, the converter generates capacitive Reactive power to AC system. Similarly, if the amplitude of output voltage decreases below that of AC system. then the converter generates Reactive (inductive) power to AC system.

If the amplitude of o/p voltage is ~~zero~~ equal to that of the AC system voltage, then the Reactive power exchange is zero.

STATCOM basically works with the help of VSC, so, the device STATCOM categorised under switching converter type Var Generator.

* Types of Controllable Series Var Generation :-

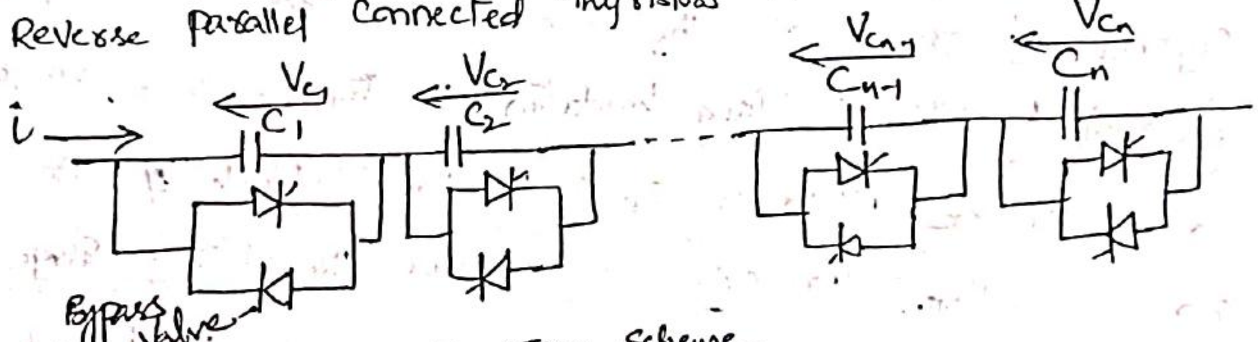
The basic Controllable Series Var Generation has been Classified into,

i, Variable impedance type Series Var Generation
ii, Switching converter type Series Var Generation

(i) Variable impedance type Series Var Generation :-

*(a) Thyristor Switched Series Capacitor (TSSC) :-

The basic circuit arrangement of TSSC is shown below It Consists of Capacitors, each shunted by an appropriately rated 'Bypass Valve' composed of a string of Reverse parallel connected thyristors in series.



Fig(a) Basic TSSC Scheme.

The operating principle of TSSC is straight forward: the degree of series Compensation is Controlled in a step like manner by increasing (or) decreasing the number of series capacitors inserted. A capacitor is inserted by turning off, and it is bypassed by turning ON of thyristor valve.

A thyristor valve commutates "naturally," that is, it turns off when the Current crosses zero. Thus, a Capacitor can be inserted into the line by the thyristor valve only at the zero crossing of the line current.

since, the Insertion takes place at the line Current zero, a full half cycle of the line Current will charge the Capacitor from zero to maximum and the Successive, opposite pollarity half cycle of the line Current will discharge it from maximum to zero, as shown below.

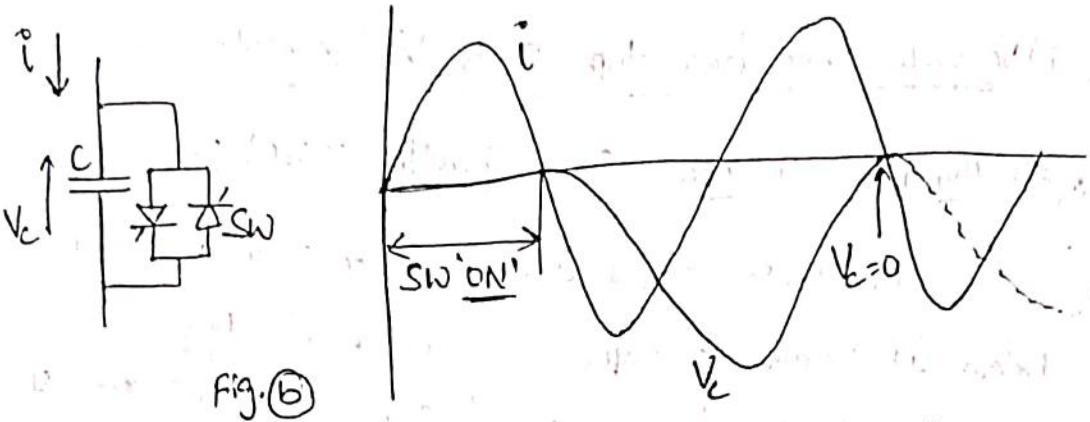


fig. ⓑ

From the above figures as we have seen that the Capacitor insertion at the line Current zero, neccessitated (తప్పనిసరి) by the Switching limitation of thyristor valve, results in DC voltage which is Equal to the amplitude of AC Capacitor Voltage. In order to minimize the Initial Surge Current in the valve, the thyristor valve should be turned "ON" for bypass, only when the Capacitor Voltage is "zero".

This Requirement Can Cause a delay of up to one full cycle, which would set the theorittical limit for the Response time of TSSC.

The TSSC Can Control the degree of Series Compensation by either inserting (or) bypassing Series Capacitors but it Cannot change the natural characteristic of Capacitor Compensated line. That is, TSSC Could Cause a Subsynchronous Resonance just like an ordinary capacitor.

Therefore, the pure TSSC scheme of Fig. ⓐ would not be applied for critical applications where a high degree of compensation is required and the danger of sub-synchronous resonance is present.

Nevertheless, TSSC could be applied for the power flow control and for damping power oscillations where the required speed of response is moderate.

The basic V-I characteristic of the TSSC with four operates to control the series connected compensator modules compensating voltage as shown below.

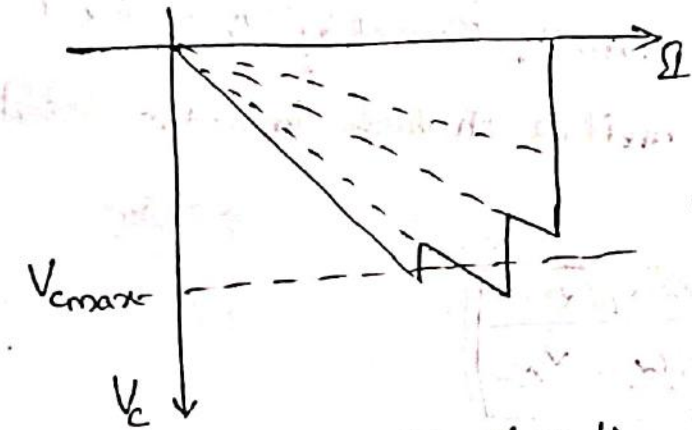


Fig. ⓒ. V-I characteristics when 4 modules are operating

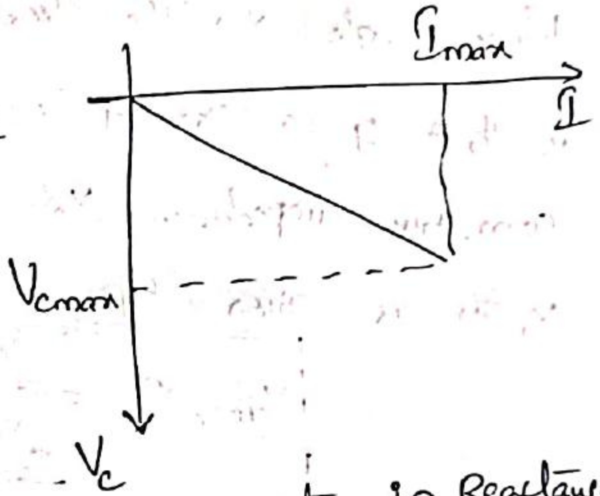


Fig. ⓓ operating in Reactance control Mode

*ⓑ Thyristor Controlled Series Capacitor :- (TCSC) :-

The basic Thyristor controlled Series Capacitor scheme was proposed in 1986 as a method of "Rapid adjustment of Network impedance". It consists of the series compensating capacitor shunted by Thyristor controlled Reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating

This arrangement is similar to the TSSC and, if the impedance of the Reactor, X_L, is sufficiently smaller than that of the Capacitor, X_C. It can be operated in ON/OFF manner like the TSSC. However, the basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially cancelling the effective compensating capacitance by the TCR.

Now, the TCR at the fundamental frequency is a continuously variable Reactive impedance, controllable by the delay angle α. The steady state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, X_C and a variable inductive impedance $X_L(\alpha)$ is given by,

$$\boxed{X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}}$$

Where, $X_L(\alpha) = X_L \dfrac{\pi}{\pi - 2\alpha - \sin\alpha}$

$$\therefore X_L(\alpha) = X_L \frac{\pi}{\sin\alpha\left(\frac{\pi}{\sin\alpha} - \frac{2\alpha}{\sin\alpha} - 1\right)}, \quad X_L \leq X_L(\alpha) \leq \infty.$$

The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source. As the impedance of the controlled Reactor, $X_L(\alpha)$, is varied from its maximum (∞) towards its minimum (ωL), the TCSC increases its minimum

Capacitive impedance $X_{TCSC\,min} = X_C = \frac{1}{\omega C}$, untill parallel Resonance at $X_C = X_L(\alpha)$. when this Condition occurs and $X_{TCSC}(\alpha)$ theoritically becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of TCSC, $X_{TCSC}(\alpha)$ becomes the Inductive, where the Capacitor is in effect bypassed by the TCR..

Therefore with the usual TCSC arrangement in which the the impedance of TCR Reactor, X_L, is smaller than that of the Capacitor X_C, the TCSC has two operating ranges, one is $\alpha_{Clim} \leq \alpha \leq \pi/2$ where $X_{TCSC}(\alpha)$ is Capacitive and the Other is $0 \leq \alpha \leq \alpha_{Llim}$ where $X_{TCSC}(\alpha)$ is Inductive as shown below,

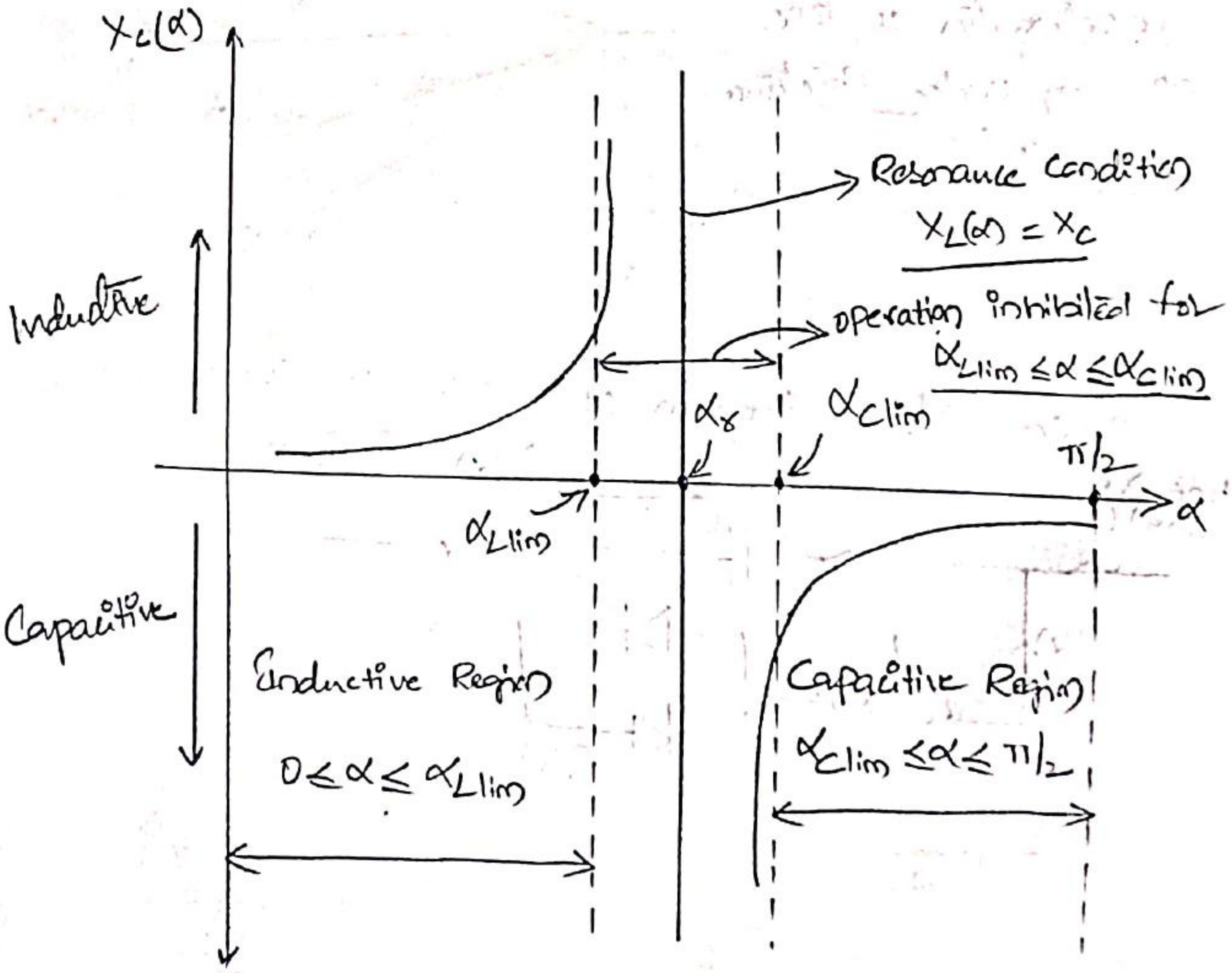


Fig. Impedance (Vs) delay angle (α) characteristics of TCSC.

The basic V-I characteristics of TCSC when operated in voltage control (Fig.ⓐ) and operated in Reactance control (Fig.ⓑ) as shown below,

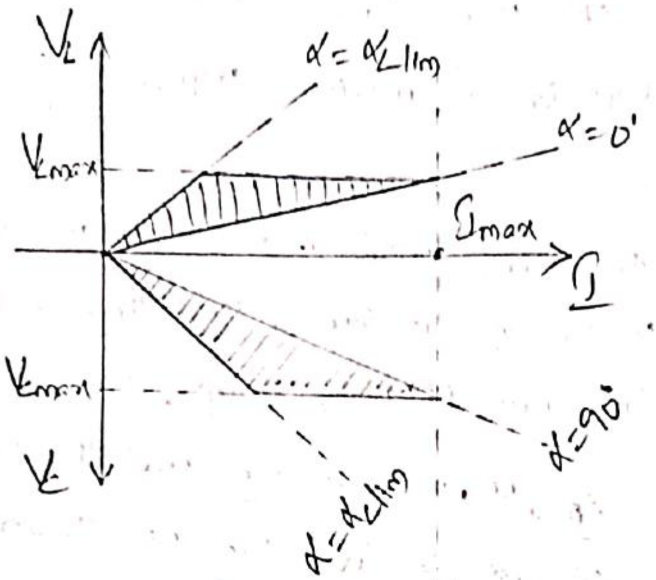
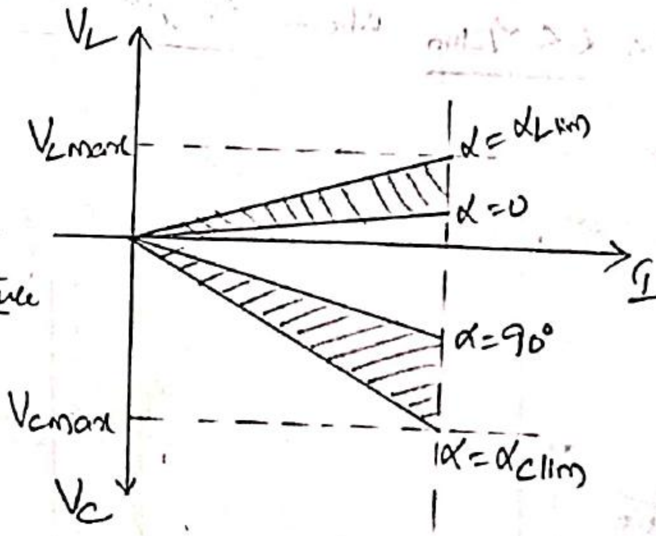
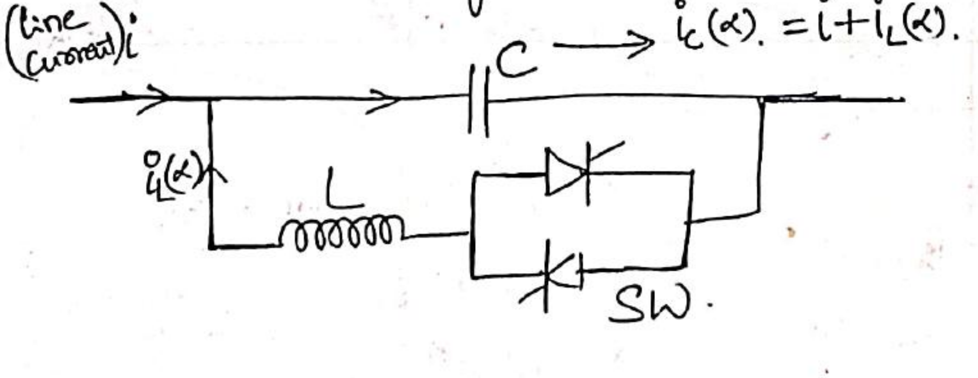


Fig.ⓐ V-I Characteristics of TCSC ~~under~~ operating in voltage control.

Fig.ⓑ V-I characteristics of TCSC operating under Reactance control,



Basic Block diagram of TCSC is shown below,



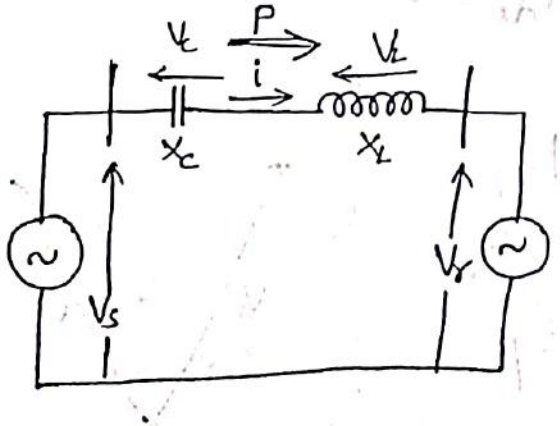
(ii) Switching Converter type Series Var Generation :-

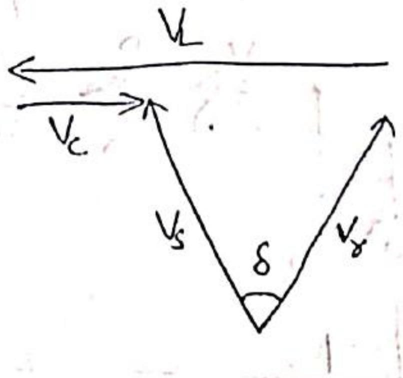
As like that of Shunt Compensation, a Voltage Source Converter with its internal Control can be considered as Synchronous Voltage Source (SVS). It can produce a set of alternating Sinusoidal Voltages at desired frequency with controllable amplitude, Phase angle; generate (or) absorb the reactive power and exchange Real power with the AC system when its DC terminals are connected to a Suitable Electric DC energy source (or) storage.

ⓐ Static Synchronous Series Compensator (SSSC) :-

The Voltage Sourced Converter based Series Compensator, called Static Synchronous Series Compensator (SSSC) was proposed by GYUGI in 1989 with the Concept of using converter based technology uniformly for shunt and Series Compensation, as well as transmission angle control.

The basic operating principle of SSSC can be explained with Reference to the Conventional Series Capacitive compensation shown in below figure together with the Related Voltage Phasor diagram.



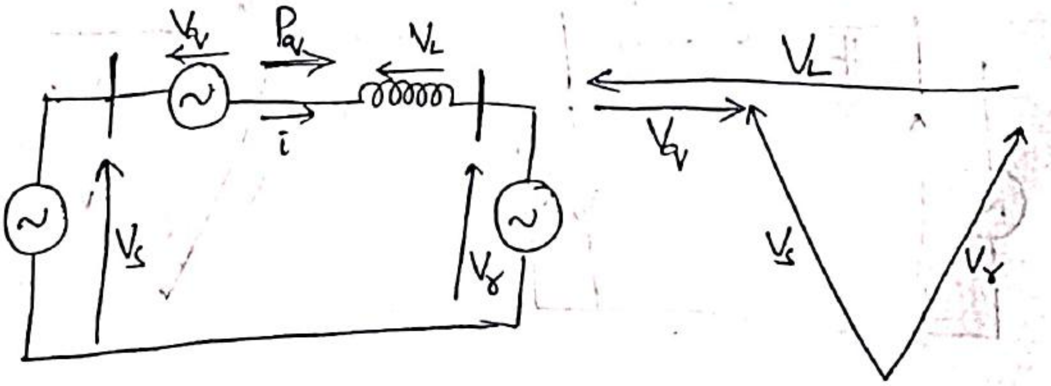


Trcr when OPNAL=1

The Phaser diagram clearly Shows that at a given line Current the Voltage across the Series Capacitor forces the Voltage across the Series line ~~Capacitive~~ the opposite Pollarity voltage across the Series line Capacitor Reactance to increase by the magnitude of the Capacitor Voltage. Thus the Series Capacitive Compensation works by ~~the magnitude of the Capacitor voltage~~ increasing the voltage across the impedance of the given physical line, which inturn increases the Corresponding line Current and the transmitted power.

While it may be Convinient to Consider Series Capacitive Compensation as a means of Reducing the line impedance, in Reality it is really a means of increasing the voltage across the given impedance of the physical line. It follows therefore that the same steady state power transmission can be established if the series compensation is provided by a Synchronous AC voltage Source as Shown in below figure, whose output Precisely matches the voltage of the series Capacitor.

Mathematically, $V_{qv} = V_c = -jX_cI = -jkXI$



where as before V_c is injected compensating voltage phasor, I is the current, X_c is the Reactance of series capacitor, X is the line Reactance, $k = \frac{X_c}{X}$ is the degree of series compensation, and $j = \sqrt{-1}$. Thus by making the output voltage of the synchronous voltage source a function of the line current, as specified in above equation, the same compensation as provided by the series capacitor is accomplished.

However, in contrast to the Real series capacitor, the SVS is able to maintain a constant compensating voltage in the presence of variable line current, or control the amplitude of the injected compensating voltage independent the amplitude of the line current.
of the amplitude of

For Normal capacitive compensation, the output voltage lags the line current by 90°. For SVS, the output voltage can be Reversed by simple control action to make it lead or lag the line current by 90°. In this case, the injected voltage decreases the voltage across the inductive line impedance and thus the series compensation has the same effect as if the Reactive line impedance was increased.

with the above observations a generalised expression for injected voltage V_q can simply be written as

$$V_q = \pm j V_q(\tau) \frac{\hat{I}}{i}$$

where τ. - Control Parameter for injected voltage

Date
13/9/15

Combined Compensators

Unit - V UPFC

Introduction :-

In general, the FACTS Controllers are acting on one of the transmission lines operating Parameters which determines the transmitted Power i.e, Voltage, (Magnitude & Phase angle) and impedance. Depends upon the Controllable Capability the FACTS Devices are categorised into two groups.

The First group consists of Variable impedance type such as ~~SSA~~ SVC and TCSC. The Second group employs self - Commutated, voltage sourced Converters. The most significant difference between the two groups is Related to the Capability to generate Reactive Power and exchange the Real Power.

In the first group SVC (or) TCSC are either Reactive Compensators which are unable to exchange the Real Power with the AC System (or), which Can exchange Real power but are unable to generate the Reactive power for the Reactive power Compensation.

The Second group of Controllers has the inherent Capability like Synchronous machine, to exchange the Real and Reactive power with the ac System. Furthermore, this group automatically generate (or) absorb the Reactive Power, thus provides reactive Compensation with out Capacitors (or) Reactors.

The STATCom and SSSC are each implemented by a Voltage Source Converter to provide effective Voltage and phase angle Control. However in Previous chapter it is seen that voltage (Directly Controlled) and Phase angle (Indirectly Controlled) Control generally involves the exchange of Real and Reactive Power with the AC System.

Thus, in general unRestricted Voltage and Phase angle Regulators are needed to operate in all four quadrants of P+jQ plane. And this unRestricted Voltage and Phase angle Regulators Control required two Voltage Sourced Converters one operating in Series and the other in Shunt with the transmission line from a Common DC Capacitor in Back-to-Back Connection.

The series converter providing the regulation exchanges the total VA corresponding to the injected series voltage and the prevailing line current. It also generates real power component but transfers the real power component to the DC link.

Now it is the shunt converters function to supply & to absorb from the DC link, the real power component, and transfers it back to the AC system that feeds the transmission line. And this arrangement in transmission applications are referred to as unified power flow controller (UPFC).

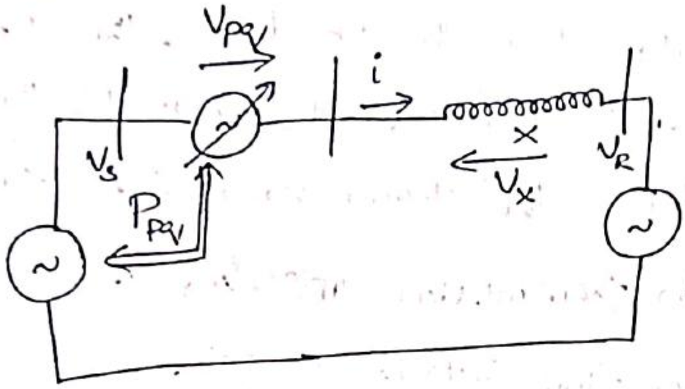
In the UPFC arrangement the STATCOM is used as shunt controller and the SSSC is used as series converter in back to back connection to meet the desired operating conditions.

* Unified Power Flow Controller (UPFC):-

The UPFC was proposed by Gyugi in 1991.
The UPFC can able to control, simultaneously or selectively, all the parameters affecting the power flow in the transmission line, and this unique capability is signified by the adjective "Unified".
Alternatively it can control both Real & Reactive power flow in the tr. line

* Basic Operating principle :-

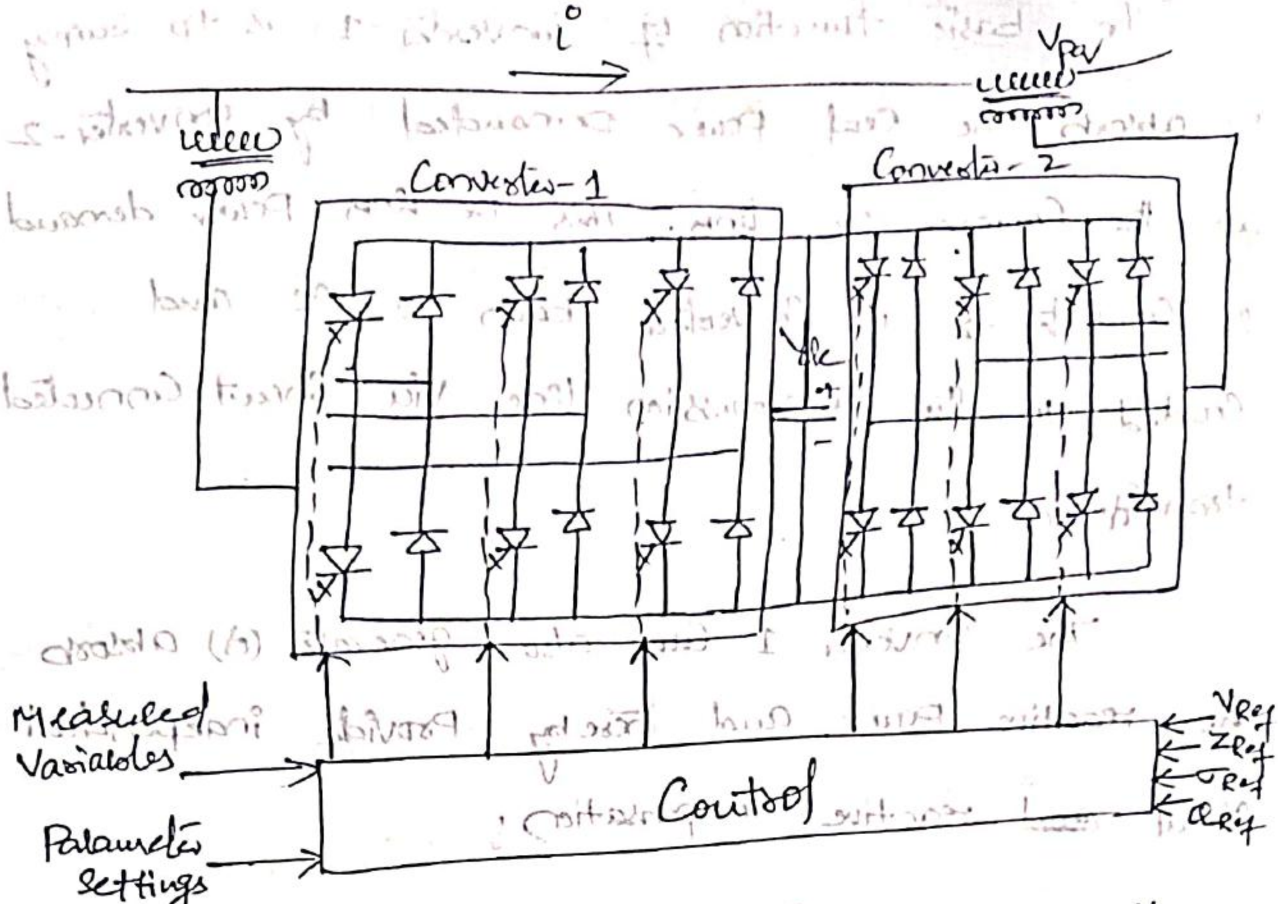
The UPFC is a generalized synchronous voltage Source, represented at fundamental frequency by the Voltage phasor "V_{pq}" and phase angle 'ρ' $(0 \leq \rho \leq 2\pi)$ in series with the line as shown in the figure.



The SVS generally exchanges both the Reactive and Real power with the transmission line. The SVS is able to generate only Reactive power exchanged, the Real power must be supplied to it, (or) absorbed from it by a suitable power supply

In the presently used practical implementation the UPFC consists of two voltage sourced converters. These back to back converters are named as converter 1 and converter 2, and are operated from a common DC link capacitor as shown in the figure.

A simplifi... Represented



From the above UPFC arrangement the Series Converter provides the Series voltage injection V_{pq} with magnitude (V_{pq}) and angle ρ when the transmission line Current flows through this voltage (V_{pq}) will Results in providing the Apparent power (VI) which Consists of both Real and Reactive Powers. The Reactive Power will be exchanged from the Converter to the AC System internally by the Converter. And the Real power will be converted into Dc by the Converter-2 and stores in the Dc link Capacitor.

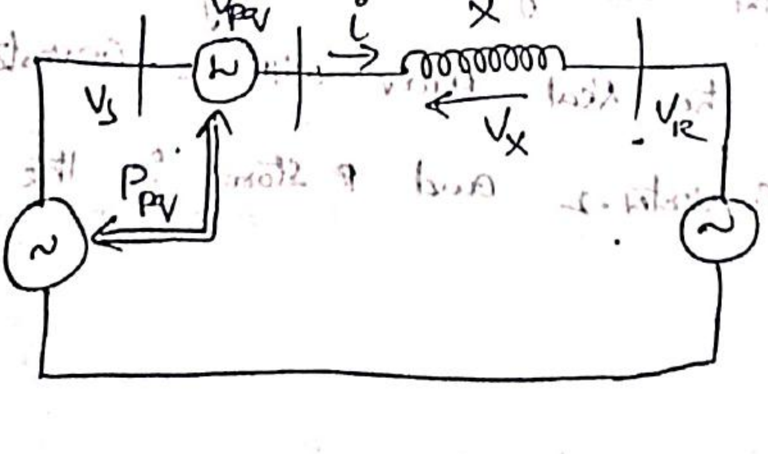
The basic function of Converter-1 is to Supply or absorb the Real Power Demanded by Converter-2 at the Common DC link. This DC link power demand of Converter-2 is Converted back to AC and Coupled to the transmission line via Shunt Connected transformer.

The Converter 1 Can also generate (or) absorb the reactive Power, and thereby Provide independent Shunt ~~and~~ reactive Compensation.

And the Implementation of UPFC with two Converters Connected in Back-to-Back via DC link Capacitor is shown above.

* Independent Real and Reactive power flow Control :-

In order to know the Capability of the UPFC to Control Real and Reactive power flow in the transmission line, refer to the figure below.



let us assume the first, the injected voltage V_{pq} is zero. Then the original Elementary two machine System with V_S, V_R, X, δ can be Restored. with these the Power transmitted and Reactive Power will be,

$$P_0(\delta) = \frac{V^2}{X}\sin\delta$$

$$Q_0(\delta) = \frac{V^2}{X}(1-\cos\delta)$$

The Reactive Power will be $Q_0(\delta) = Q_S(\delta) = -Q_{0r}(\delta)$

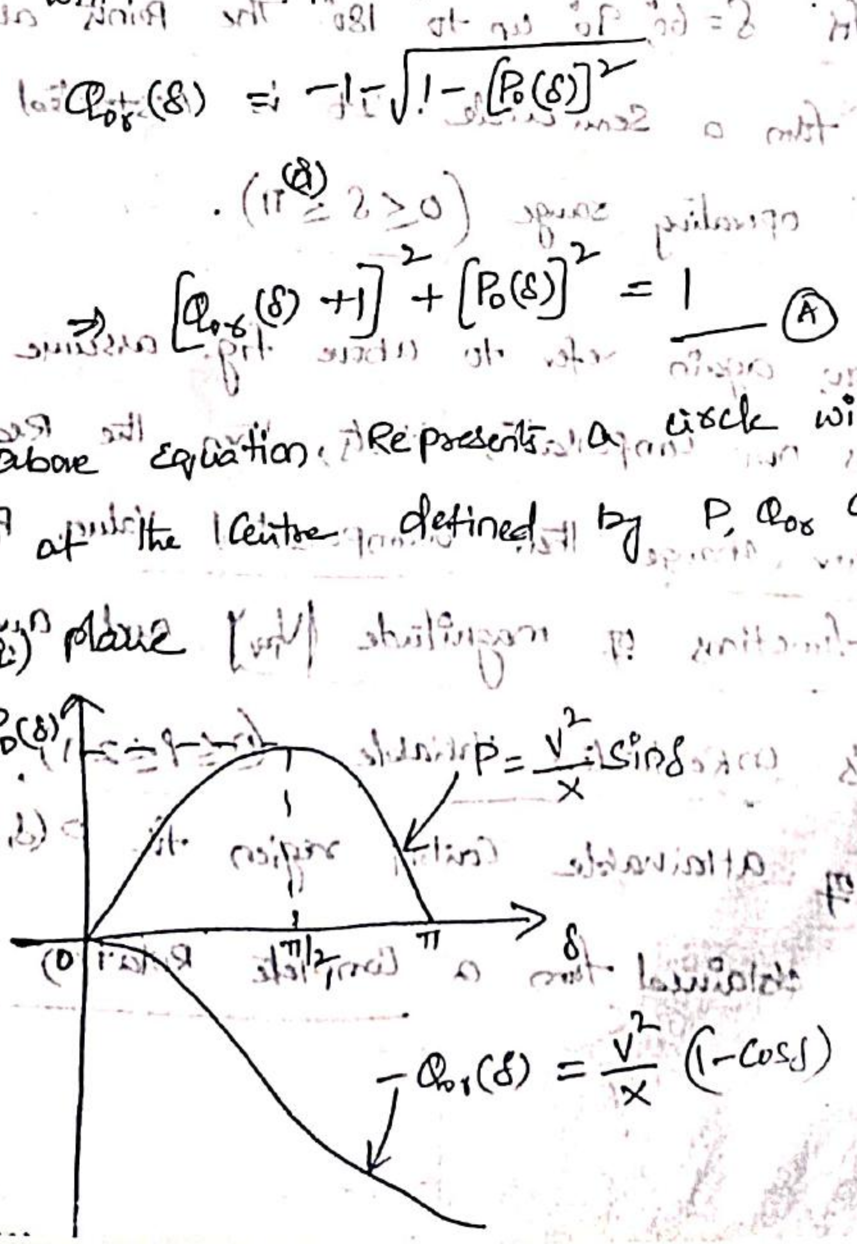
$$\Rightarrow -Q_r(\delta) = \frac{V^2}{X}(1-\cos\delta).$$

Now, the Relationship between the Real and Reactive Powers will be expressed as,

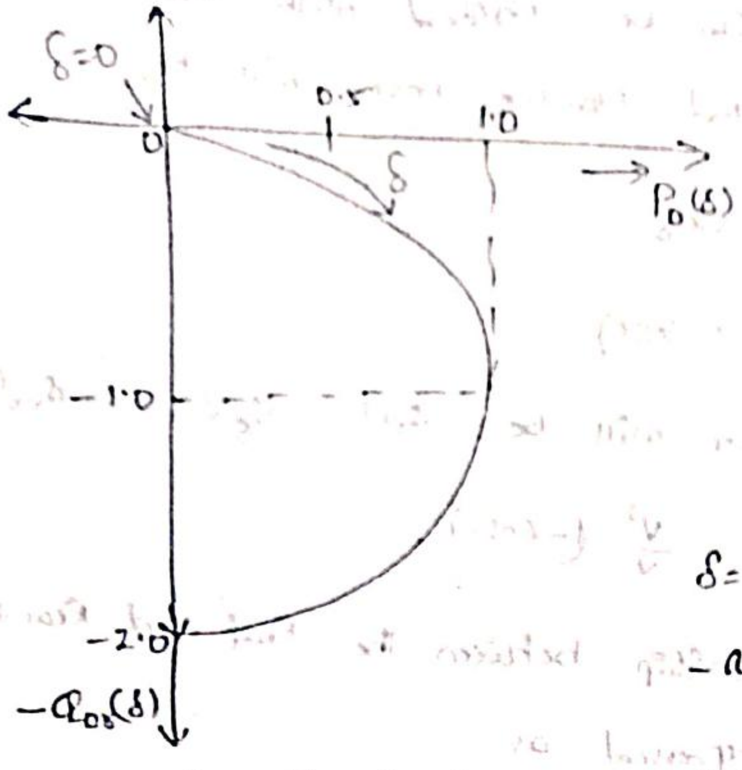
$$Q_{0r}(\delta) = -1 \pm \sqrt{1-[P_0(\delta)]^2}$$

$$\Rightarrow [Q_{0r}(\delta)+1]^2 + [P_0(\delta)]^2 = 1 \quad \text{Ⓐ}$$

The above Equation Represents a circle with a radius of 1.0 at the Centre defined by P, Q_{0r} co-ordinates in (P, Q) plane



From the above equation Ⓐ, describes a circle illustrated in below figure



Eg: $\delta = 0°$

$P = \frac{V^2}{X} \sin 0° = 0$

$-Q = \frac{V^2}{X}(1-\cos 0°)$

$= \frac{V^2}{X}(1-1) = 0$

$\delta = 30°$, $P = \frac{V^2}{X} \sin 30° = 0.5 \frac{V^2}{X}$

$-Q = \frac{V^2}{X}(1-\cos 30°) = \frac{V^2}{X}(1-\frac{\sqrt{3}}{2})$

$= 0.134 \frac{V^2}{X}$

Similarly, for $\delta = 60°, 90°$ up to $180°$. The points are joined to form a semi circle. It is restricted to 180° because 'δ' operating range $(0 \le \delta \le \pi)$.

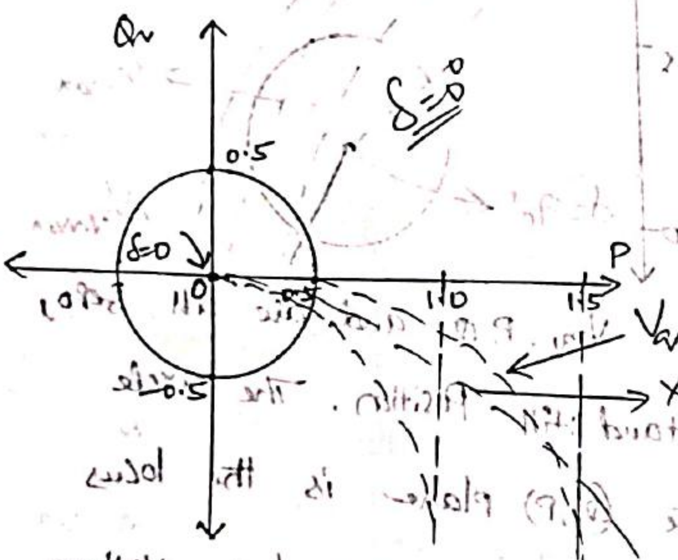
Now again refer to above fig. assume $V_{pq} \neq 0$. which means now compensation starts, then the Real and Reactive power change their uncompensated values $P_0(\delta)$ and $Q_{0r}(\delta)$, as functions of magnitude $|V_{pq}|$ and angle ρ. Since ρ is unrestricted variable $(0 \le \rho \le 2\pi)$, the boundary of attainable control region for $P(\delta, \rho)$ and $Q_r(\delta, \rho)$ is obtained from a complete rotation of V_{pq}

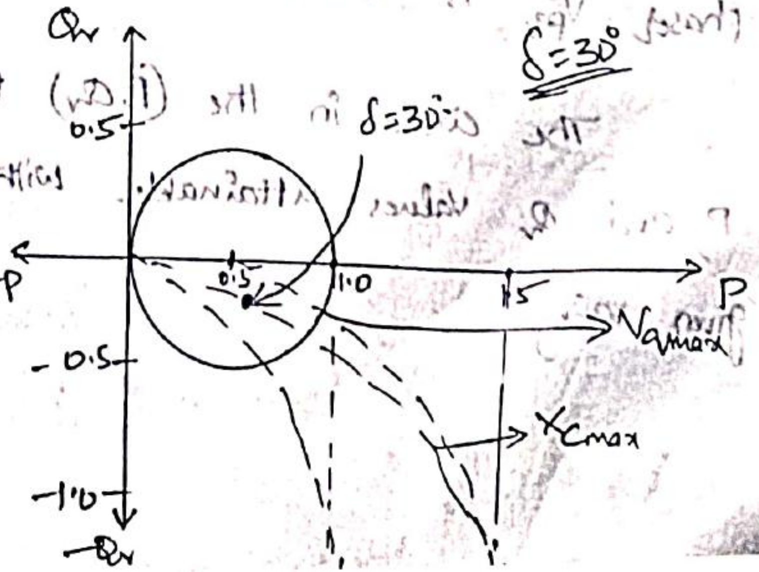
Now, again the Compensated Values of Real and Reactive powers, $P(\delta,\rho)$ and $Q_{0r}(\delta,\rho)$ are related as,

$$\left[P(\delta,\rho) - P_0(\delta)\right]^2 + \left[Q_r(\delta,\rho) - Q_{0r}(\delta)\right]^2 = \left[\frac{V V_{pqmax}}{X}\right]^2 \quad \text{— ⓑ}$$

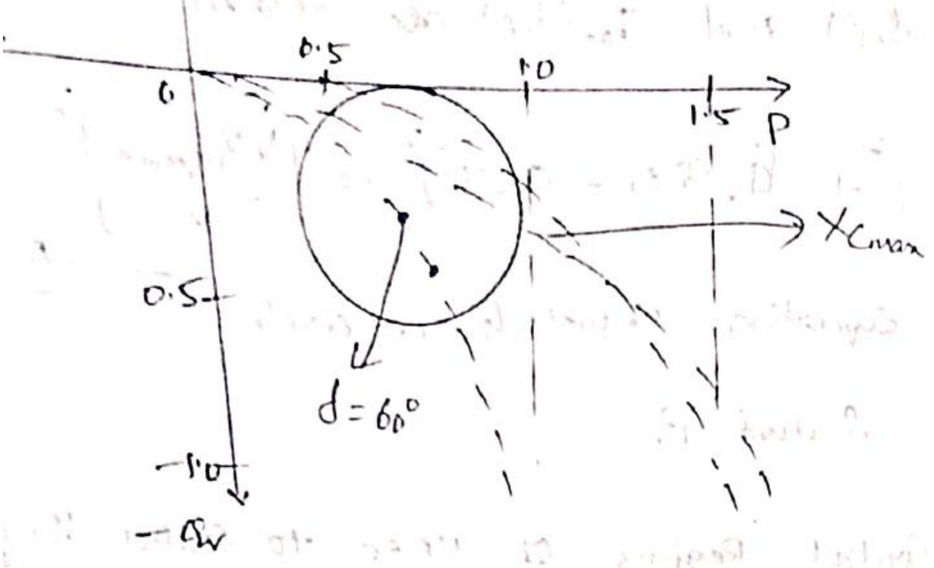
again the above equation Represents a circle as a function of δ and ρ.

The circular Control Regions of UPFC to Control the Real and Reactive Powers at various transmission angles $\delta = 0°, 30°, 60°, 90°$, as shown below,





$\delta = 60^\circ$



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Refer to Text Book for exact figures.

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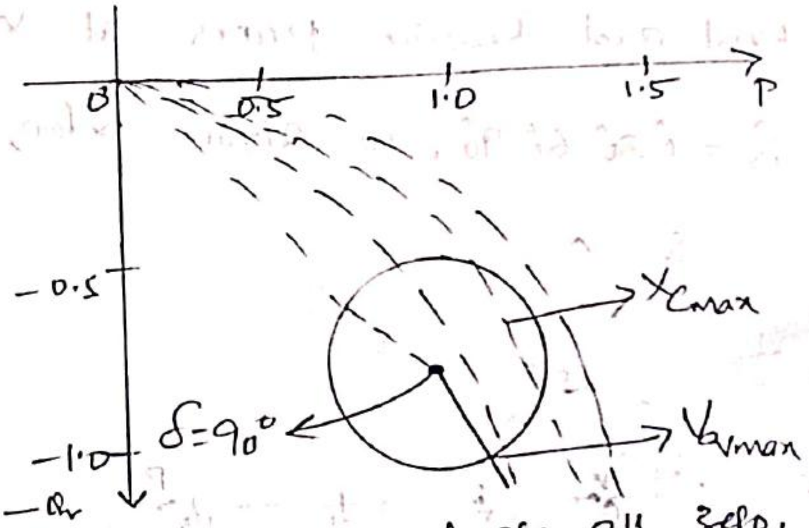
$\delta = 90^\circ$



when the angle $\delta = 0^\circ$, the V_{pq}, P, Q and are all zero, i.e, the system is at stand still position. The circle around the origin of the (Q_r, P) plane is the locus of corresponding Q_r and P values, obtained as voltage phasor V_{pq} is rotated a full revolution $(0 \le \rho \le 360^\circ)$.

The circle in the (P, Q_r) plane defines all P and Q_r values attainable with the UPFC of a given rating.

The figures above ⓐ to ⓓ clearly says that the UPFC, with its capability to control independently Real and Reactive Power flow at any transmission angle.

* Control Structure :-

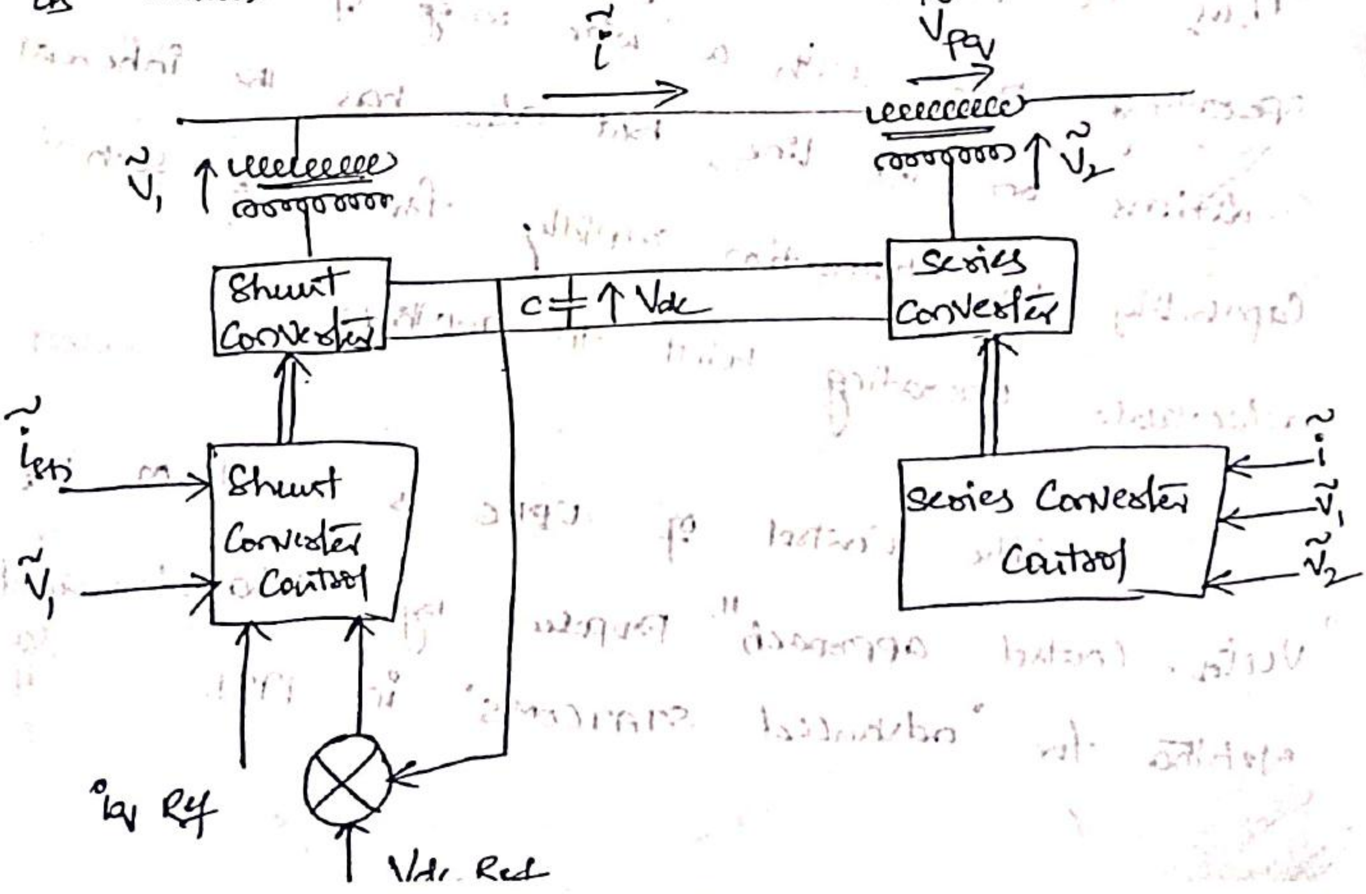
The Superior operating characteristics of the UPFC are due to its unique ability to inject an AC compensating voltage vector with arbitrary magnitude and angle in series with the line, subject to the Equipment rating limits. With suitable Electronic Controls, the UPFC can cause the series injected voltage to vary continuously and angle as desired.

Thus, the UPFC not only able to establish any possible P,Q operating point with a wide range of conditions on the line, but also has the inherent capability to transition rapidly from one such achievable operating point to another.

The Control of UPFC is based on the "Vector - Control approach" proposed by Schauder and Mehtha for "advanced STATCOMS" in 1991.

The term vector instead of phasor, is used to represent a set of 3 instantaneous phase variables that sum to zero. The symbols $\tilde{v}$ and $\tilde{i}$ are used for voltage and current vectors. These vectors are not stationary but changes according to the change in the phase variable, describing various trajectories, which become circles.

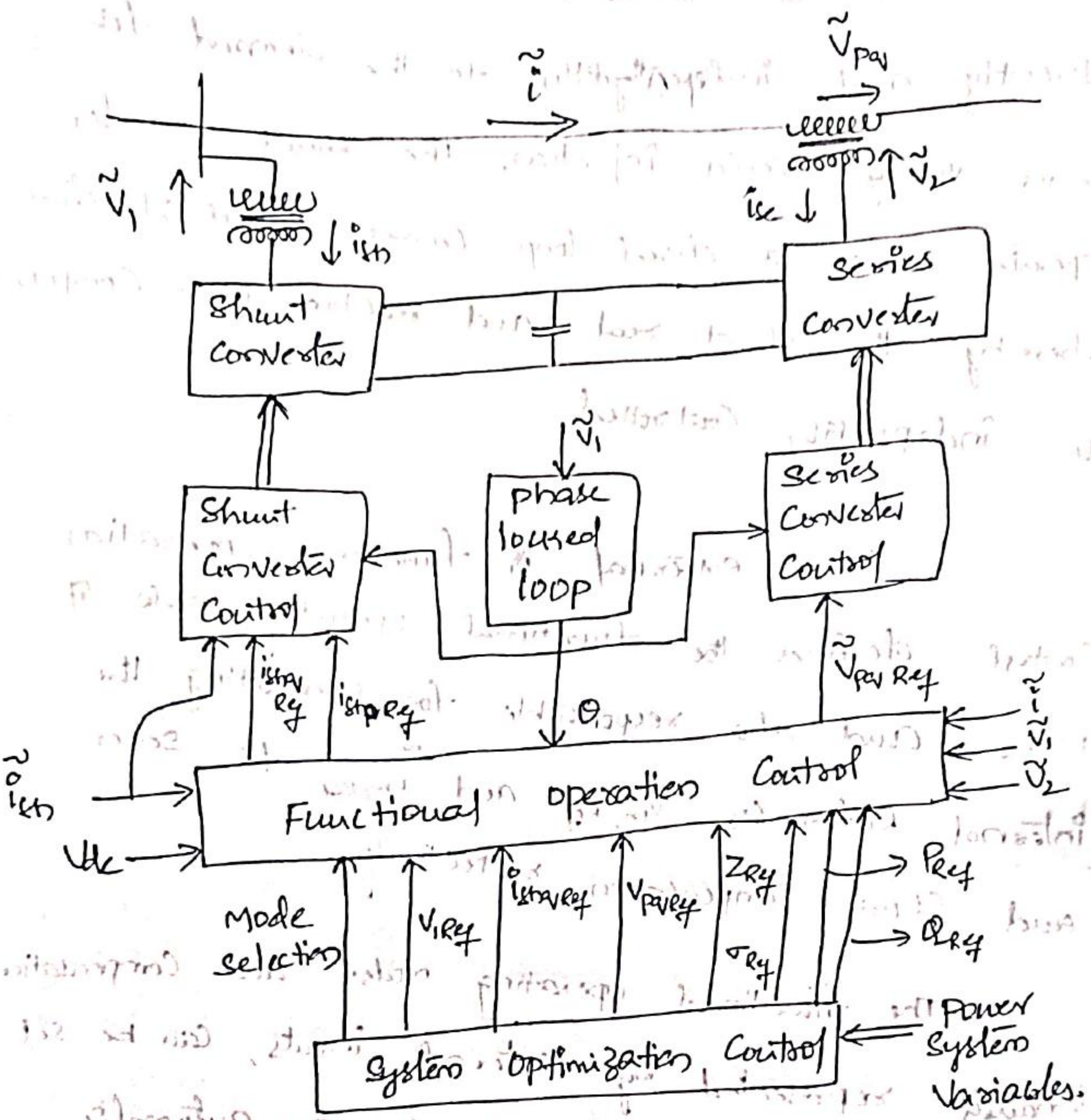
The UPFC control is divided functionally into internal control and functional operation control. The internal (converter) control provides the gating signals to the converter valves so that converter output voltages will properly respond to internal reference variables as shown in figure



It can be observed, the series converter responds directly and indepentydtly to the demand for series voltage vector injection. The shunt converter operates under a closed loop current control structure whereby the shunt real and reactive power components are independtly controlled.

The external or functional operation control defines the functional operating mode of UPFC and also responsible for generating the internal References. $\tilde{V}_{pq Ref}$ and $\tilde{i}_{pq Ref}$ for series and shunt compensation respectively.

The functional operating modes and compensation demands, represented by external inputs, can be set manually by the operator (or) by an automatic operating system. An overall control structure, showing the internal, the functional operation and the system optimization control with the internal and external References as shown below,.



Overall UPFC Control Structure