

HVDC UNIT-II

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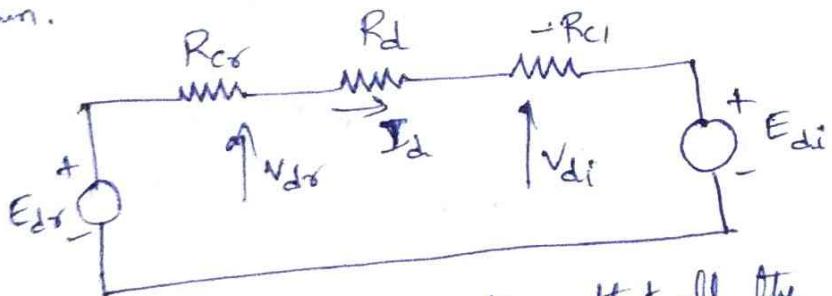
Principles of DC link control:-

one of the major advantages 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 system control in a HVDC link tends to be quite complex with a hierarchy of controllers. high speed microprocessors are being used for many of the control functions including monitoring & supervisory control.

in a two terminal DC link if assumed the control of power in a DC link can be achieved through the control of current or voltage. From minimization of loss considerations, it is important to maintain constant voltage in the link and adjust the current to meet the required power. It is to be noted that the voltage drop along a DC line is small compared to the AC line, mainly because of the absence of the reactive voltage drop.

consider the steady state equivalent circuit of a two terminal DC link as shown.

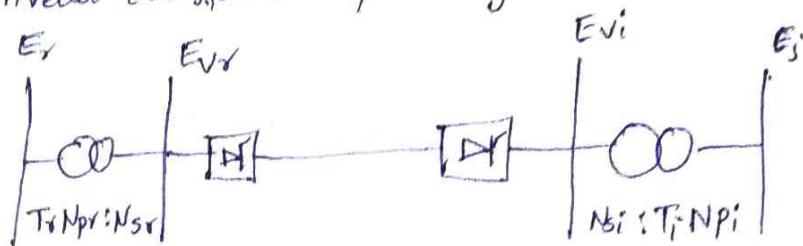


this is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have same delay angles. also the numbers of series connected bridges (n_b) in both stations (rectifier & inverter) are the same. The voltage sources E_{dsr} & E_{dri} are defined by

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

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

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



These voltages can be obtained as $E_{vr} = \frac{N_{sr} E_r}{N_{pr} T_r}$, $E_{vi} = \frac{N_{bi} E_i}{N_{pi} T_i}$

where E_r & E_i are the AC (line to line) voltages of the converter buses on the rectifier and the inverter side. T_r & T_i are the off-nominal tap ratios on the rectifier and inverter sides. we can write

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

$$E_{di} = (A_i E_i / T_i) \cos \gamma_i$$

where A_r & A_i are constants.

It is to be noted E_{di} is defined in terms of the extinction angle γ_i . Rather than B_i , E_{di} can also be written as

$$E_{di} = (A_i E_i / T_i) \cos \beta_i + 2 R_{ci} I_d$$

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

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

The steady-state current I_d in the DC line is obtained as

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

substituting eq? E_{dr} , E_{di} in above eq?

$$I_d = \frac{(A_x E_R / T_R) \cos \alpha_x - (A_i E_i / T_i) \cos \gamma_i}{R_{co} + R_d - R_{ci}} \quad (2)$$

It is to be noted that the control variables are T_R, T_i and α_x, β_i .

Small changes in the voltage magnitudes E_R & E_i can result in large changes in the DC current. It is desirable to control the current and regulate the voltage simultaneously in the link. From considerations given below, it is desirable to have current control at the rectifier station under normal conditions.

- 1. The increase of power in the link is achieved by reducing α_x which improves the power factor at the rectifier, for higher loadings and minimizes the reactive power consumption.

- 2. The inverter can now be operated at minimum γ thereby minimizing the reactive power consumption at the inverter also.

It is to be noted that the current control at the inverter worsens power factor at the higher loadings as ' γ ' has to be increased. Increased ' γ ' also implies higher losses in the valve snubber circuits.

- 3. The operation at minimum extinction angle at the inverter and current control at the rectifier results in better voltage regulation than the operation with minimum delay angle at the rectifier & current control at the inverter.

- 4. The currents during line faults are automatically limited with rectifier station in current control.

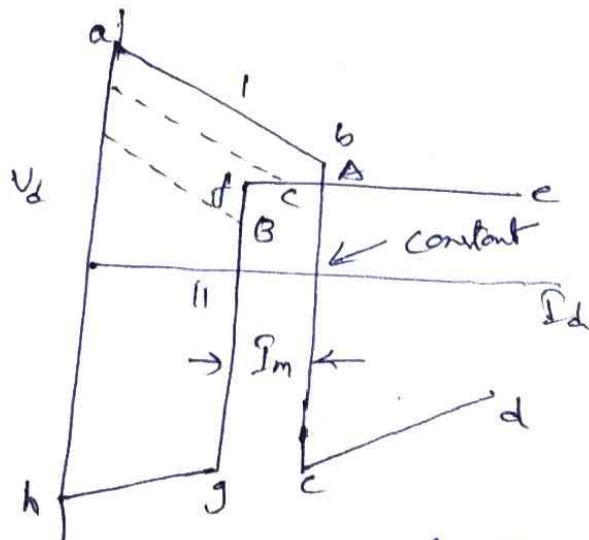
While there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at constant extinction angle (CEA) which is slightly above the absolute minimum required for the commutation margin.

This results in reduced cost at the inverter station, reduced converter losses and reactive power consumption. The constant DC voltage (CDCV) or constant AC voltage control (CACV) are the alternatives that could be used at the inverter. Under normal conditions the rectifier operates at constant current (cc) control and inverter at the CCA controls.

The power reversal on the link can take place by the reversal of the DC voltage. This is done easily by increasing the delay angle at the station initially operating as the rectifier, while reducing the delay angle at the station initially operating as the inverter.

Converter Control Characteristics:-

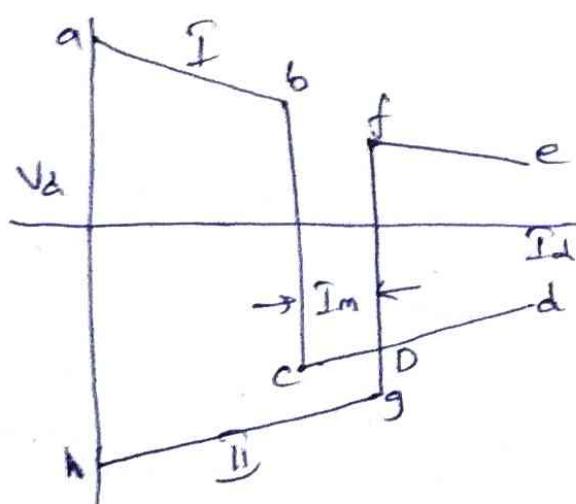
Basic Characteristics :- The basic principles of the control of DC link have been stated. The control characteristics of both stations are shown below.



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

station I	station II	Type
ab	hg	minimum (α)
bc	gf	constant current
cd	fe	minimum (γ)

- (3)
- The intersection of the two characteristics (point A) determines the mode of operation - station I operating as rectifier with constant current control & station II operating at constant extinction angle.
- There can be three modes of operation of the link depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics. These are listed below (operating point A)
- i) CC at rectifier and CEA at inverter* which is the normal mode of operation.
 - ii) with slight dip in the AC voltage the point of intersection drifts to 'C' which implies minimum 'd' at rectifier & minimum 'f' at inverter.
 - iii) with lower AC voltage at the rectifier the mode of operation shifts to point 'B' which implies CC at the inverter with minimum 'd' at the rectifier.
- The characteristic 'ab' has generally more -ve slope than characteristic 'fe' & similar values R_{cr} & R_{ci} . This is because of the fact that the slope of 'ab' is due to combined resistance ($R_L + R_{cr}$) while the slope of 'fe' is due to R_{ci}



The above figure shows the control characteristics for -ve current margin I_m . [where the current reference at station II is less than that at station I]. The operating point shifts now to 'D' which implies power reversal with stations I [acting as Inverter] operating with minimum CEA control while station II operating CC control.

In order to prevent inadvertent power reversal or the due to failure of telecommunication channels, It is necessary to prevent the inverter from transition to the rectifier operation. This can be easily done by putting maximum limits on the delay angle of the inverter (100° to 110°)

Firing angle controls:-

The operation of CC and CEA controllers is closely linked with the method of generation of gate pulses for the valves in a converter. The following are the two basic requirements for the firing pulse generation of HVDC Valves.

1. The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signals through fiber-optic cables. The required gate power is made available at the potential of individual Thyristors for electrically triggered Thyristor (ETT) valves. However for light triggered Thyristor (LTT) valves, the light signal can be used to directly fire individual thyristors.

while the single pulse is adequate to turn-on a thyristor (ii) the gate pulse generator must send a pulse whenever required. If the particular valve is to be kept in a conducting state there are two basic firing schemes.

i) Individual phase control (IPC)

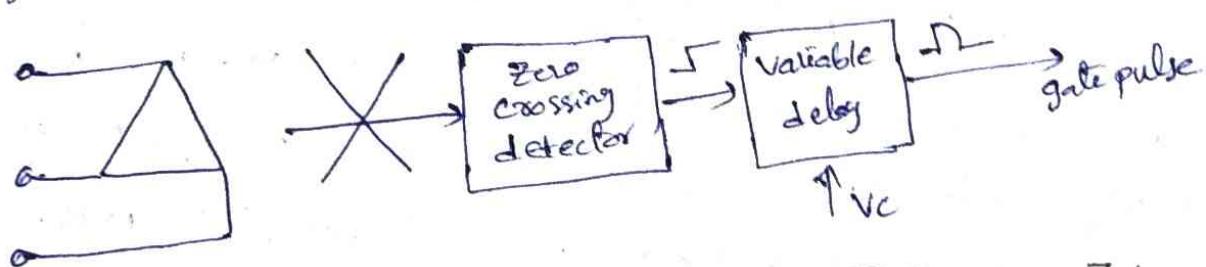
ii) Equidistant pulse control (EPC)

IPC was used in the past and has now been replaced by EPC.

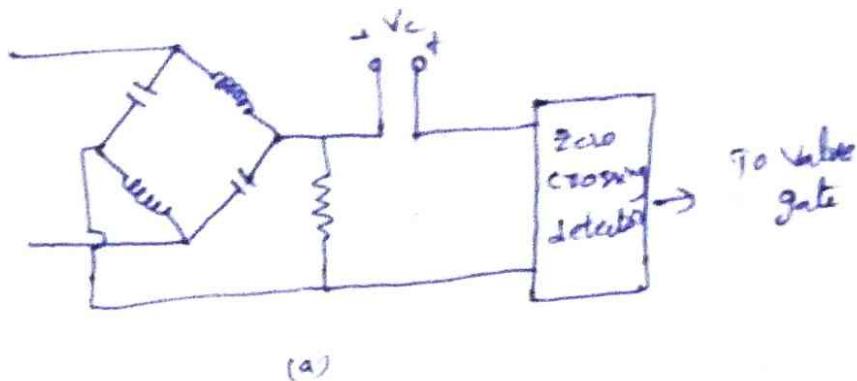
i) Individual phase control:- This was used in early HVDC projects. The main feature of this scheme is, that the firing pulse generation for each phase (valve) is independent of each other and the firing pulses are rigidly synchronized with the commutation voltages. There are two ways on which this can be achieved.

(i) Constant α control (ii) inverse cosine control.

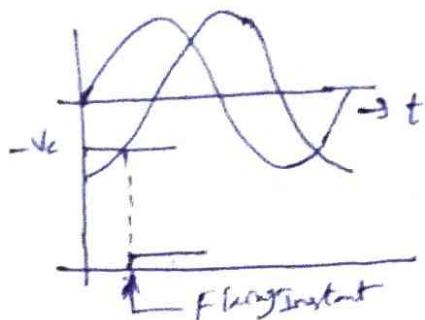
i) Constant α control:- In this scheme six timing (commutation) voltages are derived from the converter AC bus via voltage transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero-crossing of a particular commutation voltage corresponds to $\alpha=0$ for that valve. The delays are produced by independent delay circuits and controlled by a Common Control Voltage V_C derived from the current/extinction angle controllers.



i) Inverse cosine control:- there are several variations of this. One common arrangement is shown below.



(a)



(b)

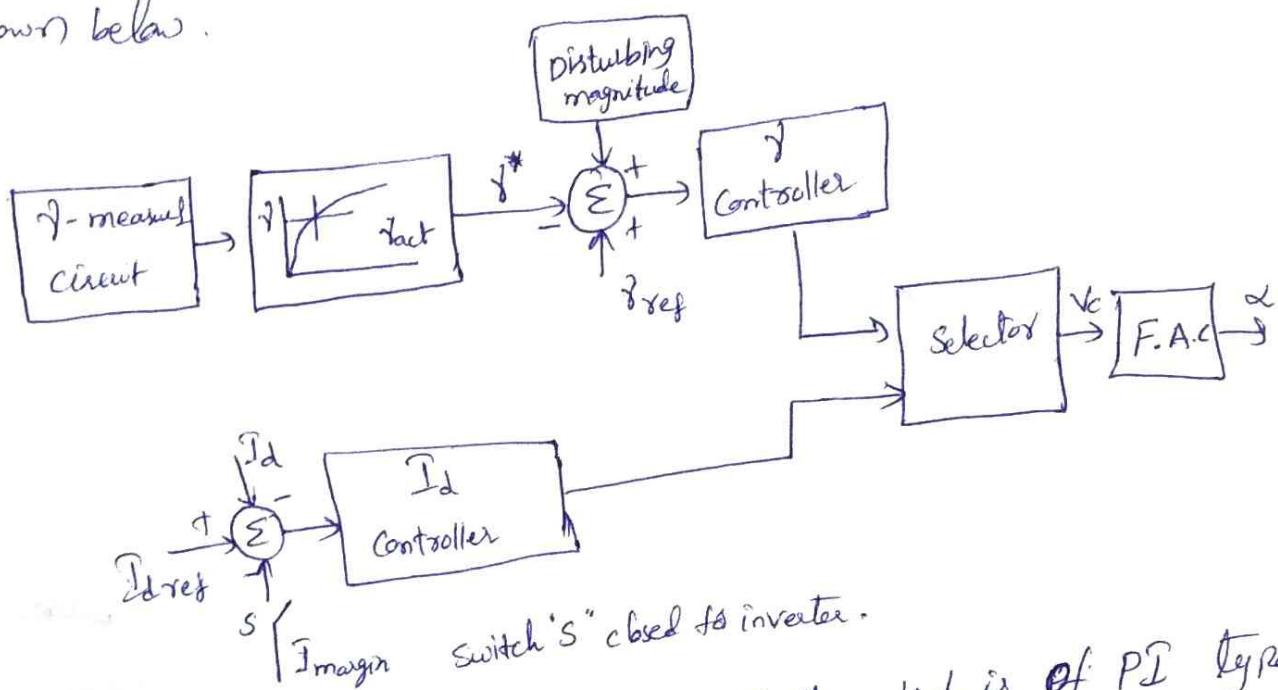
The six timing voltages are each phase shifted by 90° and added separately to a common control voltage V_c . The zero crossing of the sum of the two voltages initiates the firing pulse for the particular valve consider in above 'b' figure. The delay angle ' α ' is nominally proportional to the inverse cosine of the control voltage. It also depends on the AC system voltage amplitude and shape. The main advantage of this control scheme is that the average DC voltage across the bridge varies linearly with the control voltage V_c . It is essential in this scheme to maintain the phase shift at 90° for variations in the supply frequency.

② Equidistant pulse control:- In this scheme, the firing pulses are generated in steady state at equal intervals of $1/p_f$, through a ring counter. This control scheme was first suggested by Ainsworth using a phase locked oscillator to generate the firing pulses.

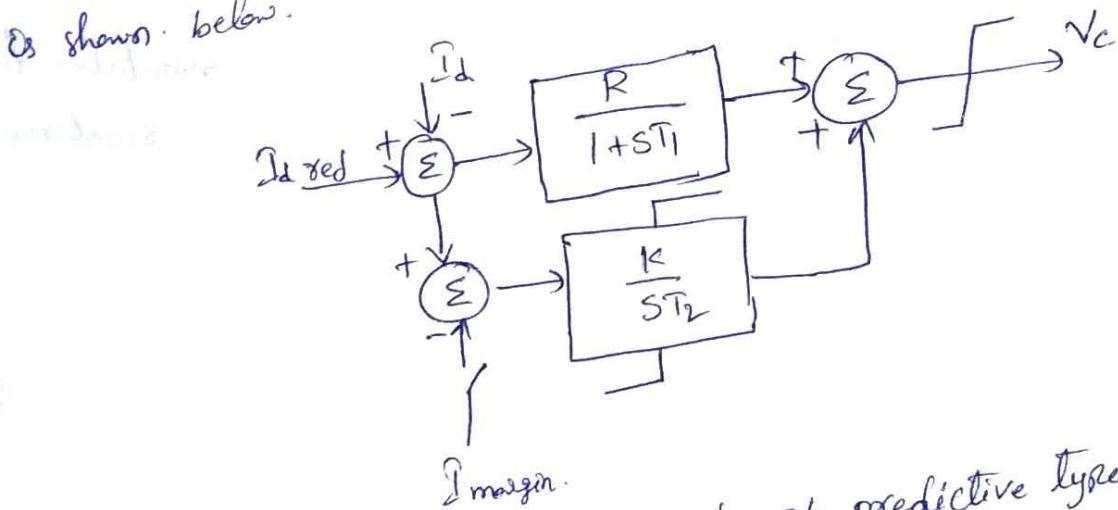
There are '3' variations of EPC schemes

Current and Extinction angle control :-

The current controller is invariably of feedback type as shown below.



The typical block diagram of the controller which is of PI type is shown below.



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

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

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

where e_{cj} is the commutation voltage across valve j

if t_n is the instant of its firing. The prediction of firing angle is based on the eqⁿ $\Rightarrow \beta_j = \beta_{ref} + u_j$

here u_j is the overlap angle of valve j .

In feedback control of extinction angle as shown above figure the measured value of γ passes through a non-linear block. The control is made faster when $\gamma < \vartheta$, & slower when $\gamma > \vartheta$

the fast control reduces the incidence of commutation failure while in the latter case, the instability due to the negative resistance characteristic of fast γ control is avoided.

Starting and stopping of DC Link :-

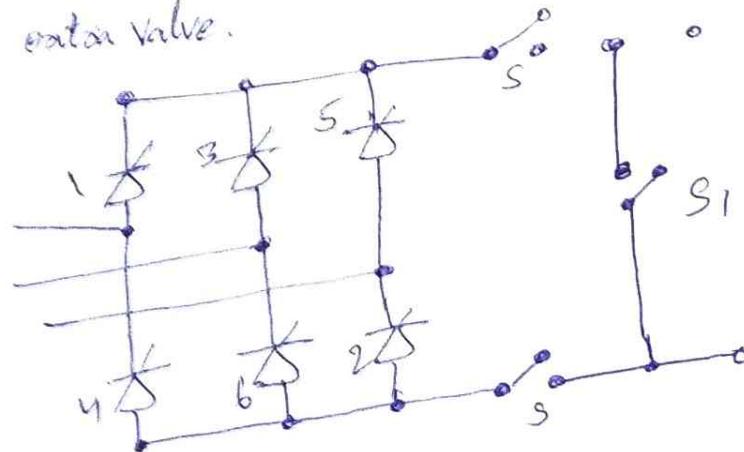
- i) Energization & Deenergization of a bridge
- ii) Start-up of DC link

i) Energization & Deenergization of a bridges -

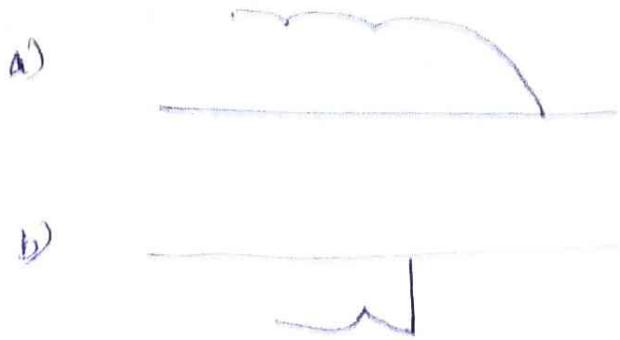
consider 'N' series connected bridges at a converter station. If one of the bridges is to be taken out of service, there is need to not only block, but by pass the bridge.

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pair or because of the fact that just blocking the pulses does not extinguish the current in the pair ~~anywhere~~ ~~anywhere~~ of valves that are left conducting at the time of blocking. the continued conduction of this pair affects AC voltage onto the line which can give rise to current & voltage oscillations due to lightly damped oscillatory circuit in the line formed by shunt reactor & the line capacitance. the bypassing of the bridge can be done with the help of a separate bypass valve or by activating a bypass pair on the bridge. the bypass valve was used with mercury arc valves where the reliability of arc breakers makes it impractical to use bypass pairs. with thyristor valves, the use of bypass pair is the practice as it saves the cost of an extra valve.

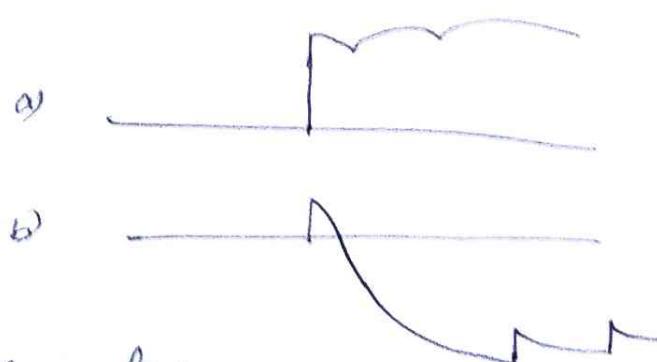


The process of deenergization of a bridge is explained with reference above fig. The valves 2 & 3 are assumed to be conducting initially when the blocking command is given. with the selection of bypass pair 1 & 4 the commutation from valve 2 to 4 is in usual manner. but the commutation from valve 3 to 5 is prevented. In the case of a predetermined choice of the bypass path, the time lag b/w the blocking command & the current transfer to bypass path can vary from 60° to 180° . for rectifier bridge. In the inverter there is no time lag involved in the activation of the bypass pair. The voltage waveforms for the rectifier & inverter are shown below.



The current from the bypass pair is shunted to a mechanical switch S_1 . with the aid of the isolators 'S' the bridge can now be isolated. The isolator pair 'S' & switch S_1 are interlocked such that one (or both) are always closed.

The energization of a blocked bridge is done in two stages. In one stage the current is first diverted from S_1 to the bypass pair. In case the bypass pair fails to take over the current, S_1 must close automatically. In second stage of energization the current is diverted from the bypass pair. For the rectifier this can take place instantaneously neglecting overlap while as the inverter the transition requires some time lag. The voltage waveforms for this case are shown.



i) start-up of DC link :-

There are two different start-up procedures depending upon whether the converter firing controller provides a short gate pulse (δ) long gate pulse.

Startup with long-pulse firing: In this case the current extinction during the start-up is not a problem. The starting sequence in this case is as follows:-

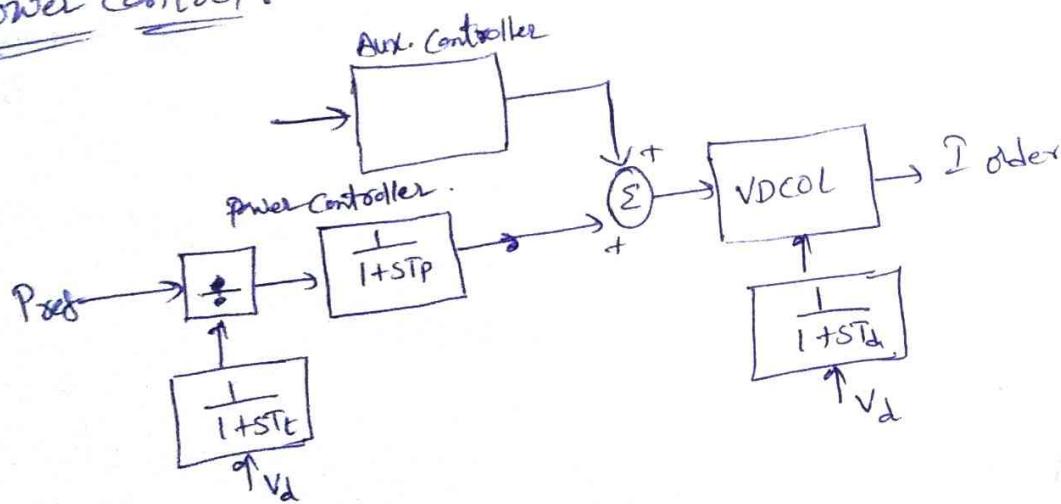
- 1) Deblock inverter at about $\gamma = 90^\circ$
- 2) Deblock rectifier at $\alpha = 85^\circ$ to establish low direct current.
- 3) Ramp up voltage by inverter control & the current by rectifier control.

Startup with short pulse firing: In this case the problem of current extinction during start-up is present as the valve with forward bias is not put into conduction when the current in that falls transiently below holding current.

The starting sequence for this case is as follows:-

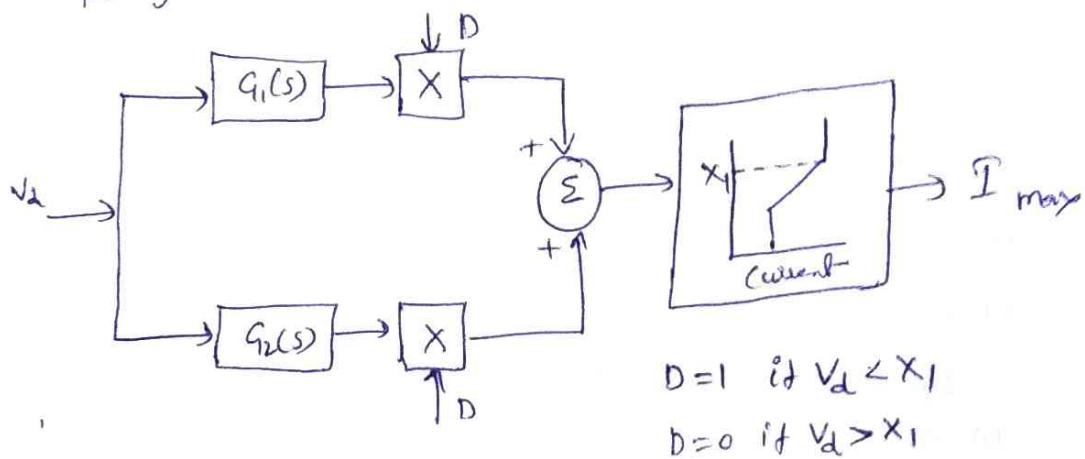
- 1) open bypass switch at one terminal.
- 2) Deblock that terminal and load to maximum current in the rectifier mode.
- 3) open bypass switch at the second terminal & commutate current to the bypass pair
- 4) start the second terminal also in the rectifier mode.
- 5) The inverter terminal is put into the inversion mode.
- 6) Ramp up voltage & current.

Power control:



The above figure shows the basic power and auxiliary controller units. The current order is obtained as the quantity derived from the power order dividing it by the direct voltage. The limits on the current order are modified by the voltage dependent current order limiter (VDCOL). The objective of VDCOL is to prevent individual thyristors from carrying full current for long periods during commutation failures. However, sufficient time delay is given to prevent the action of VDCOL during normal AC system faults, which would otherwise drastically reduce DC power.

The generic model of VDCOL is shown



$G_1(s)$ & $G_2(s)$ are simple transfer functions given by

$$G_1(s) = \frac{1}{1 + ST_{\text{down}}} ; G_2(s) = \frac{1}{1 + ST_{\text{up}}}$$

By providing both converter stations with dividing circuits and transmitting the power order from the leading station in which the power order is set to the trailing station. To get equal calculated current order in the two stations, the measured DC line voltage must be referred to the same point on the DC line by compensation for DC line voltage drop. This is done by adding $\pm R_{\text{th}}$ to the measured voltage.

The term $\pm R_{\text{th}}$ to the measured voltage is large & varies considerably.

When the DC line resistance is very large & varies considerably, the overhead line is very long and exposed to large temperature variations, the DC line voltage drop cannot be compensated.

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individually in the two stations. This problem can be solved by using a current order calculated in one substation only & transmitting it to the other substation.

The use of programmable logic for realization of power flow control function seems to be most appropriate solution for future applications. Standardized computer hardware equipment can be used & the function may be adapted to individual requirement.

The auxiliary controller is designed to provide power modulation for frequency control & stabilization of DC system. The input signal is derived from frequency & other signals.

Reactive power control in HVDC :-

The Reactive power control is very important particularly in weak AC systems, in reducing the dynamic over voltages, in inverters, then the fast reactive power control can help in allowing the increased power at times of need to improve the stability of the receiving end AC system. Although the reactive power requirements for LCC station are primarily met by shunt capacitors & filters, the converters controls can be coordinated with the control of the reactive power source to provide voltage stability & eliminate voltage flicker.

Reactive power requirements in steady state :-

In that the Reactive power requirements in steady state

- es three types
 - i) Conventional control strategies
 - ii) Alternate control strategies
 - iii) Forced commutation

i) Conventional control strategies:- the DC link is operated with current control at the rectifier & minimum extinction angle control at the inverter. under normal conditions. This method of control leads to the minimum reactive power requirement at both ends.

The equations for the reactive power as a function of the active power are conveniently expressed in terms of per unit quantities.

$$\text{The Base Converter voltage } (V_{db}) = (3\sqrt{2}/\pi)V_n$$

where V_n is the rated (line-line) voltage at the valve side operating.

$$\text{Base DC current } (I_{db}) = \text{rated DC current } (I_{dn})$$

$$\text{Base DC power } (P_{db}) = n_b V_{db} I_{db}$$

where n_b is the number of bridges connected in series.

$$\text{Base AC voltage (on the valve side)} \quad V_b = V_n$$

$$\text{Base AC power} = \text{Base DC Power} = (\sqrt{18}/\pi)V_b I_{db} n_b$$

The average DC voltage across a converter bridge is given by

$$\bar{V}_d = \bar{V} \cos \alpha - \bar{R}_c \bar{I}_d \quad \text{--- (1)}$$

$$\text{where } \bar{V}_d = \frac{V_d}{V_{db}}, \bar{I}_d = \frac{I_d}{I_{db}}, \bar{V} = \frac{V}{V_b}, \bar{R}_c = \frac{\bar{x}_c}{2}$$

\bar{x}_c = p.u. leakage reactance of the Transformer

The power factor is given by

$$\cos\phi = \frac{\bar{V}_d}{\bar{V}_{do}} = \frac{\bar{V}_d}{\bar{V}} = \cos\alpha - (\bar{R}_c \bar{I}_d / \bar{V}) \quad \text{--- (2)}$$

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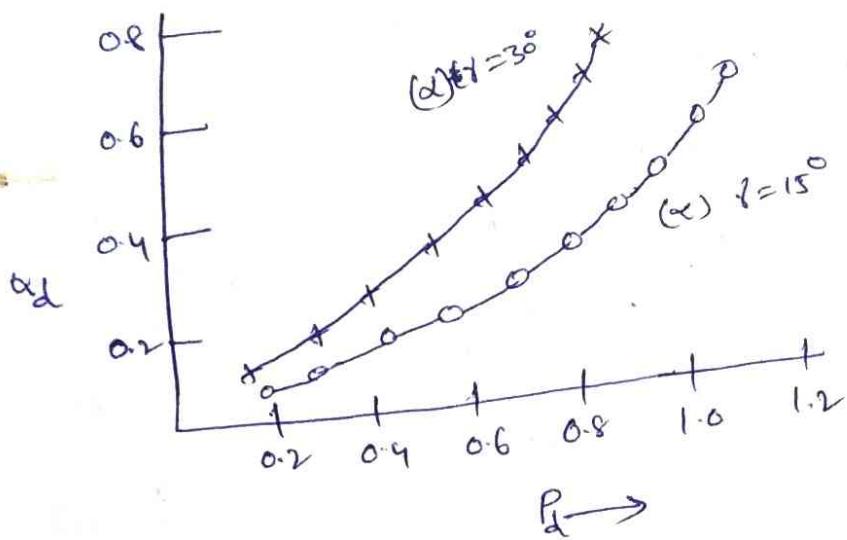
The power & reactive power in per unit are given by

$$\bar{P}_d = \bar{V} \bar{I}_d \cos\phi \quad \text{--- (3)}$$

$$\bar{Q}_d = \bar{V} \bar{I}_d \sin\phi \quad \text{--- (4)}$$

The eq (1) is valid for the converter if ' α ' is replaced by ' γ '

The variation of Q_d vs P_d is shown

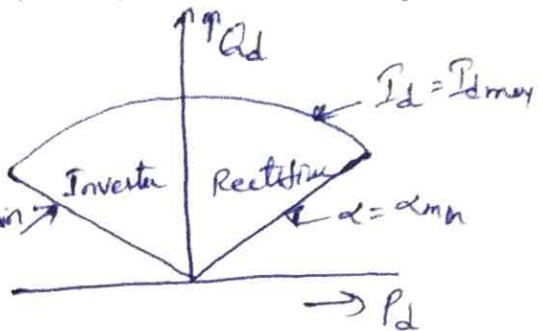


The above figure shows that Q_d increases by about 60% at the rated power. This shows the importance of maintaining low fixing angle in steady state. However, ~~too~~ too low values of α can result increased frequency of mode shifts [transfer of current control from rectifier to inverter] & too low values of ' γ ' can result in increased incidence of the commutation failure. The reactive power is also affected by the magnitude of the AC voltage. The reduction in V leads to increase in Q_d .

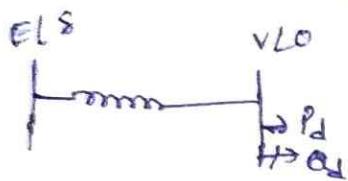
Alternate control strategies:— The region of operation of a converter bridge is bounded by the limits on the DC current and the firing angle. Neglecting the minimum current limit, the operating region of a bridge on P_d - Q_d plane as shown.

This region is bounded by

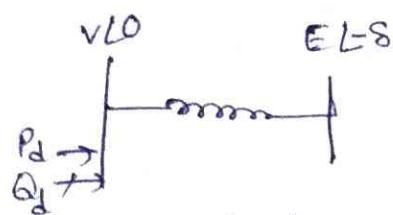
- i) minimum id characteristic
- ii) minimum γ characteristic
- iii) constant rated DC current



The operation at constant DC voltage implies constant power factor characteristic at the converter bus. At the rectifier, the characteristic is that of load with lagging power factor, while at inverter this can be viewed as a generator with leading power factor. operations. If there is no voltage support provided at the converter bus, the stability limit is considerably reduced.

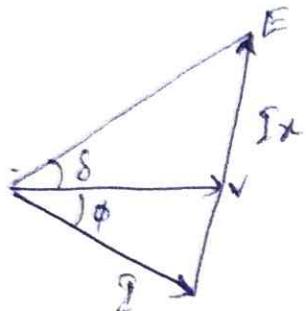


(a) Rectifier

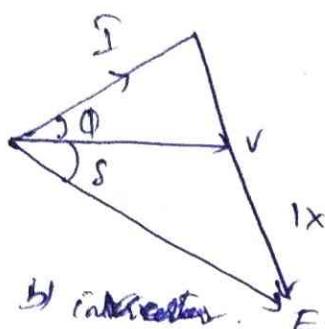


(b) Inverter

from phasor diagram.



(a) Rectifier



(b) Inverter

$$V_L = \frac{E \cos(\delta + \phi)}{\cos \phi} \quad \text{--- (1)}$$

where ϕ is the power factor angle.

The power expression is given by

$$P = V_E B \sin \delta \quad \text{--- (2)}$$

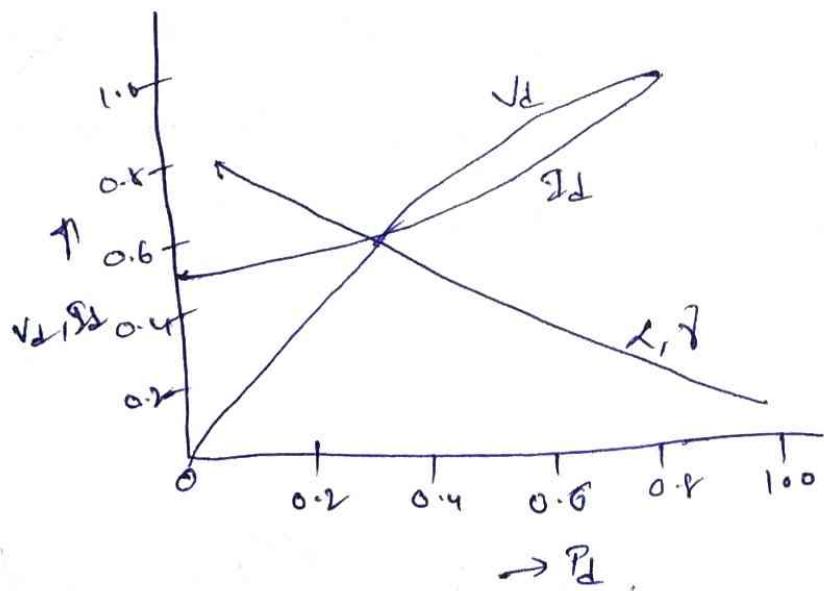
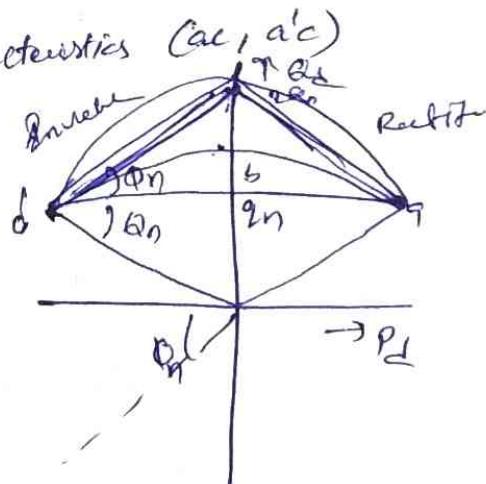
Substituting ① neg ② we get

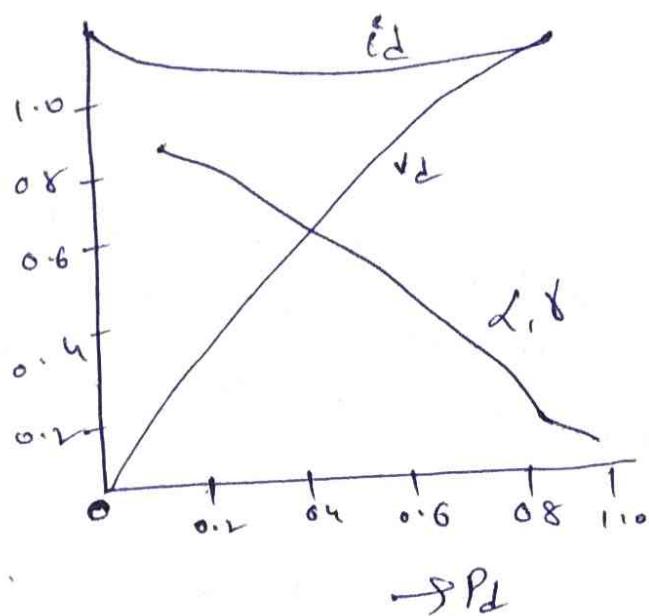
$$P = \frac{E^2 B \cos(\delta + \phi) \sin \phi}{\cos \phi}$$

The above analysis shows that there is a need to modify the reactive power characteristics of the converter stations by either i) choice of the reactive power sources ii) adjusting the converter control characteristics.

When the DC line involves long distance transmission, the minimization of power losses in the line dictates operation at constant DC voltage & flexibility of converter operation is not feasible. However with back-to-back links, the operation at constant voltage is not critical & alternate converter control strategies can be adopted. There are

- i) Constant reactive power characteristics (a_{ab}, a'^{ab})
- ii) constant leading power factor characteristics (a_{ac}, a'^{ac})





iii) Forced Commutation :-

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

Forced commutation involves addition of a voltage component to the normal commutation voltage to shift the zero crossing. One simple method of implementing this is by providing series capacitors. Forced commutation is feasible if gate turn-off (GTO) or MCT devices can be employed in converters. The auxiliary circuits required for forced commutation coupled with increased ratings of thyristor valves can be expensive compared to the cost of reactive power sources required without forced commutation.

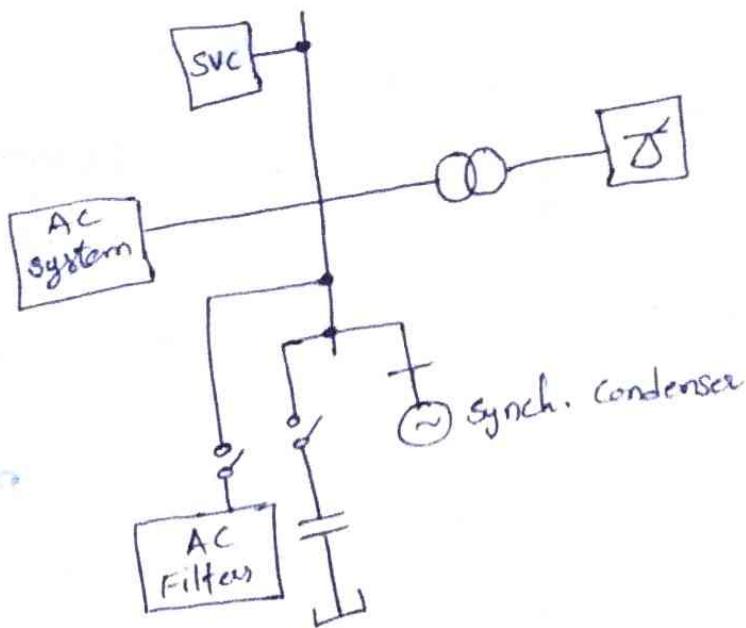
Reactive Power control:- the reactive power control is very important particularly in weak AC systems, in

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Sources of Reactive Power:

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

- i) AC system
- ii) AC filters
- iii) Shunt capacitors
- iv) Synchronous condensers
- v) Static Var Compensator (SVC)
- vi) STATCOM. These are shunt connected FACTS controllers.



The passive AC filters that are provided at the converter bus for filtering out AC current harmonics appear as capacitors at the fundamental frequency and thus provide reactive power. These filters & shunt capacitors are mechanically switched. These devices are less expensive than SVC & Synchronous condensers.

The synchronous condensers are essentially synchronous m.s operating at no load with excitation control to maintain the terminal voltage.

The advantages are as follows-

1. The availability of voltage source for compensation at the inverter if the connection to the AC system is temporarily disrupted. This also implies an increase in SCR as the fault level is increased. The synchronous condenser is essential for providing voltage sources for the line compensation at the inverter.

(ii) Better voltage regulation during a transient due to the maintenance of flux linkages in the rotor winding.

There are also disadvantages of synchronous condensers - there are i) high maintenance of cost. ii) possibility of instability due to the machine going out of synchronism.

The static Var Compensator (SVC) provides fast response following a disturbance. The configuration normally used are

- i) Fixed Capacitor (FC), Thyristor Controlled Reactor (TCR).
- ii) Thyristor Switched Capacitors (TSC)- TCR Combination.

The static Synchronous Compensator (STATCOM) based on voltage source converter (VSC) is an advanced type of SVC that is comparable to a synchronous condenser in terms of its control characteristics.

Actually STATcom was originally named as static condenser (STATCON) with very fast response, reduced maintenance requirements and free from the problems of loss of synchronism. The VSC based HVDC transmission does not require a separate reactive power source as the voltage source converter also functions as a STATcom.

Static VAR Compensators:-

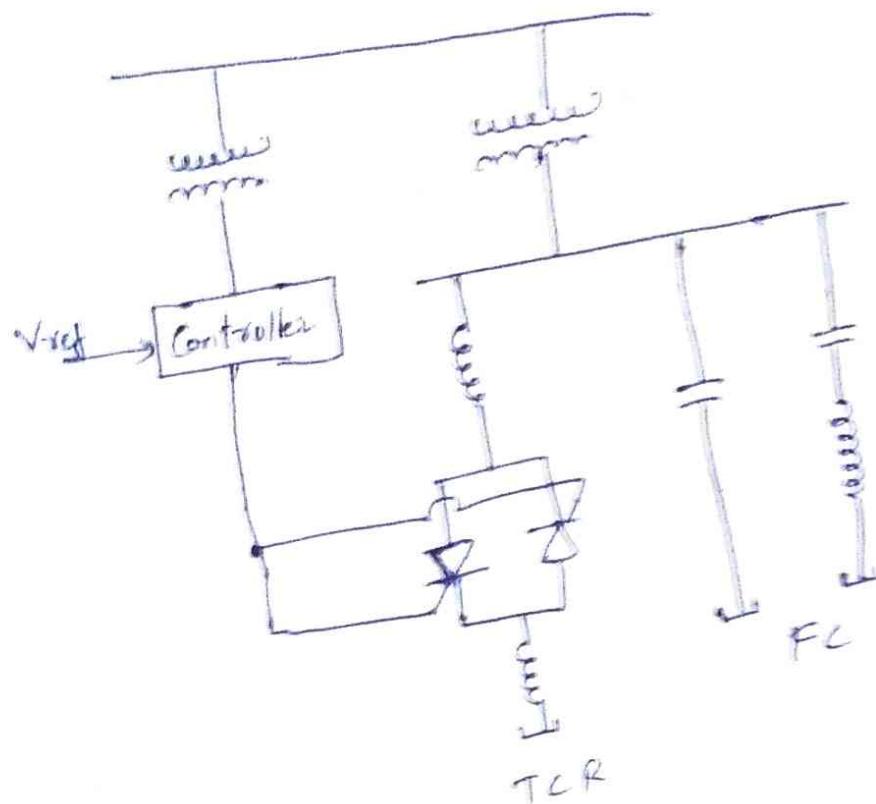
static var compensators are generally two types

- i) SVC ii) STATcom.

i) SVC:- The static var compensators were initially used for load compensation, where the objective is to dynamically control the reactive power demand for large fluctuating loads such as Rolling mills. These are used for voltage control applications in transmission system, where, by maintaining voltage support at specified locations it is possible to provide increased power transfer capability, control of dynamic over voltages, and improve voltage stability. By using auxiliary control signals it is also possible to damp low frequency and Subsynchronous frequency oscillations.

* In HVDC converter stations, the provision of SVC mainly helps to have fast control of reactive power flow, thus by controlling voltage fluctuations and also to overcome the problem of voltage instability.

The schematic diagram of FC-TCR is shown below.

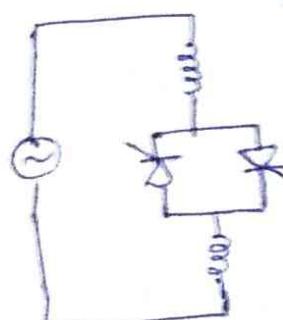


SVC is a variable impedance device made up of FC(TS) and TCR in parallel, while TSC (Thyristor-switched capacitor) provides discrete control over the capacitor impedance. TCR (Thyristor-controlled Reactor) provides continuous control of inductive impedance. here - FC(TS) does not inject harmonics, TCR injects harmonics.

Thyristor controlled reactor (TCR):

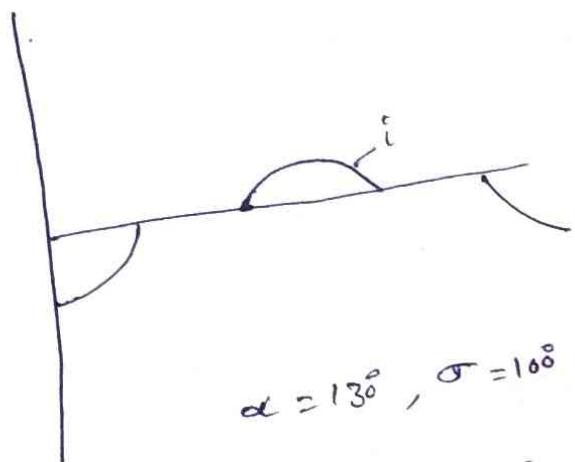
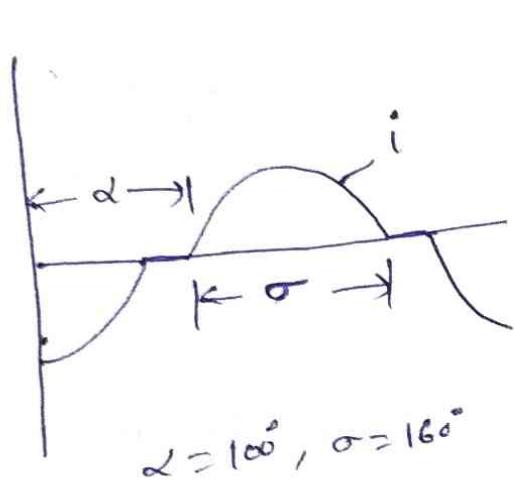
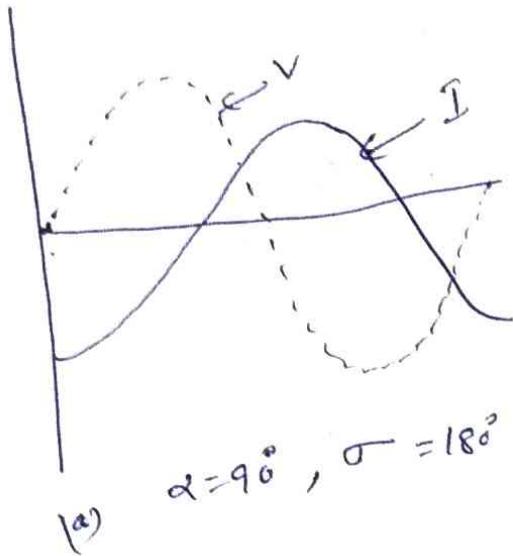
The single phase Thyristor controlled reactor is shown.

By controlling the firing angle of the back-to-back connected thyristors, the current on the reactor can be controlled.



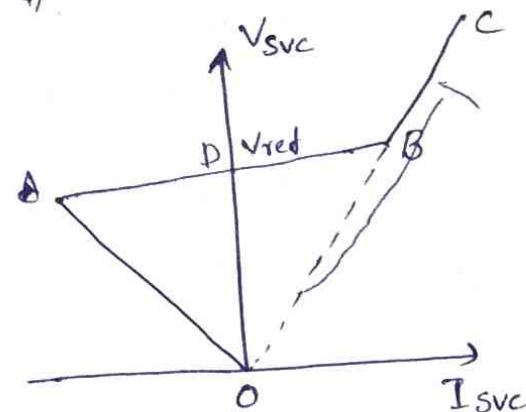
This is shown in below. For $\alpha=90^\circ$, the current is maximum, while for $\alpha=180^\circ$ the current is zero.

here α is the conduction angle related to σ



The steady-state control characteristics of a SVC in the V - I plane is shown below.

The control range is AB which shows a positive slope which can be adjusted from the gain in the current feedback path.



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

Reactive power control during transients :-

The control characteristics of the reactive power sources has a bearing on the system behaviour during transient. In this context, it is to be noted that the converter control characteristics can be modified to control the reactive power demand. This is feasible mainly for back-to-back links. Suitable control of reactive power is required during a transient for the following reasons.

- 1) Control of dynamic overvoltages caused by load rejection.
- 2) speedy recovery of power following a fault in the converter system.
- 3) control of instability.

The dynamic overvoltages are mainly due to the excess of reactive power released by the sudden blocking of the converters. This requires a fast control of the reactive power generation from capacitive to inductive. The SVS can achieve the speed.

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

The voltage instability can also be a problem at low SCR and can be tackled by suitable converter control strategy (a) the provision of SVS at the converter bus. Unit-7 page no:- 26/26