Date 17/7/15

UNIT-II

Converter & HVDC system control

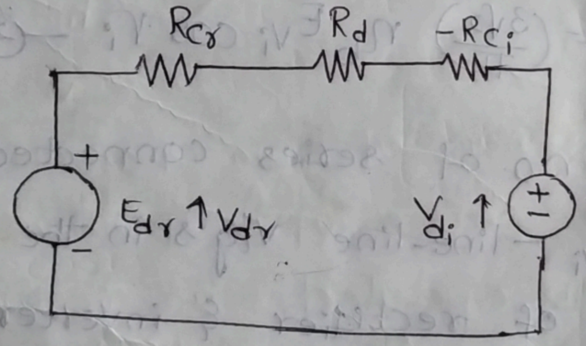
- One of the major advantage of HVDC link is the rapid controllability of transmitted power through the control of the firing angles of the converters.

Modern converter controls are not only fast but also very reliable & they are used for protection against line & converter faults.

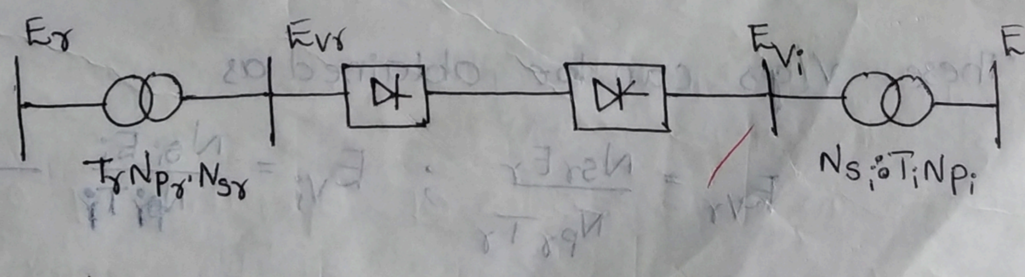
High speed microprocessors are being used for many control functions including monitory & supervisory control.

**** Imp

Principle of DC link control: (or) Expression for steady state current 'I_d' in a dc link:



(steady state Equivalent Ckt. of two terminal Dc link)



Schematic diagram of a Dc link showing Transformer ratios.

- The control of power in a dc link can be achieved through control of current (or) voltage.

- It is important to maintain constant voltage in the link & adjust the current to meet the required power. This strategy is also helpful for voltage regulation.

$P = VI$

- firing angle control (current control) Total Transm.

- The voltage drop along a dc line is small compared to AC line mainly because of absence of reactive v/g drop.

consider steady state equivalent ckt of two terminal dc link. It is based on the assumption that all the series connected bridges in both poles of a converter station or identical and have the same delay angle. also the no. of series connected bridges in both stations are same.

The voltage sources are V_{dr} & V_{di} are defined by

$$E_{dr} = \left(\frac{3\sqrt{2}}{\pi}\right) n_b \, E_{vr} \cos \alpha_r \quad \text{—①}$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

$$V_m = \sqrt{2}V_s$$

$$E_{di} = \left(\frac{3\sqrt{2}}{\pi}\right) n_b \, E_{vi} \cos \gamma_i \quad \text{—②}$$

$$V_0 = \frac{3\sqrt{3}\,\sqrt{2}V_s}{\pi}$$

$$V_L = \sqrt{3}V$$

n_b - no. of series connected bridges. (depends pulse no)

E_{vr}, E_{vi} - line-line v/g's in the valve side windings of rectifier & inverter t/f^r respectively

These v/g's can be obtained as

$$E_{vr} = \frac{N_{sr} E_r}{N_{pr} T_r} \; ; \; E_{vi} = \frac{N_{si} E_i}{N_{pi} T_i} \quad \text{—③}$$

E_r, E_i - ac line to line voltage of converter bus on rectifier and inverter ~~bu~~side.

T_r, T_i - off ~~normal~~ nominal Tap ratios on rectifier and inverter side combining ①, ② ③

$$E_{dr} = \left(\frac{A_r E_r}{T_r}\right) \cos\alpha_r \quad \text{—④} \qquad E_{vr} = \frac{N_{sr}}{N_{pr}} \frac{E_r}{T_r}$$

$$E_{di} = \left(\frac{A_i E_i}{T_i}\right) \cos r_i \quad \text{—⑤}$$

A_r, A_i are constants.

- By steady state current I_d in the dc link is given by

$$I_d = \frac{E_{dr} - E_{di}}{R_{cr} + R_d - R_{ci}} = \frac{\frac{A_r E_r}{T_r}\cos\alpha_r - \frac{A_i E_i}{T_i}\cos r_i}{R_{cr} + R_d - R_{ci}}$$

$$\boxed{I_d = \frac{\frac{A_r E_r}{T_r}\cos\alpha_r - \frac{A_i E_i}{T_i}\cos r_i}{R_{cr} + R_d - R_{ci}}}$$

$R_{c_r} = \left(\frac{3\omega L_c}{\pi}\right)$ (or) $= 6 f L_c$

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

The control variables are T_r, T_i, α, r $\quad V_d + R_{c_r} I_d = \frac{V_{do}\cos\alpha}{R_{cr}}$

- At rectifier there shall be α-control and T/f Tap changing.
- At Inverter there shall be Tap changing and r-control.
- For fast control α (or) r-control is used.
- For low control Tap changing is used.
- Tap changing is also used when also α_{max}.

$\alpha_{min} = 5^\circ \qquad \delta_{min} = 8^\circ$

23/7/15

<u>Constant voltage system</u>:-

All power sources and loads are connected in parallel. v/g's across all is maintained constant.

<u>Merit</u>: I^2R loss will be as per the load. At light loads it will be less.

<u>Demerit</u>:- short circuit [illegible] currents.

Constant current system:-

All power sources and loads are connected in series. current is maintained constant.

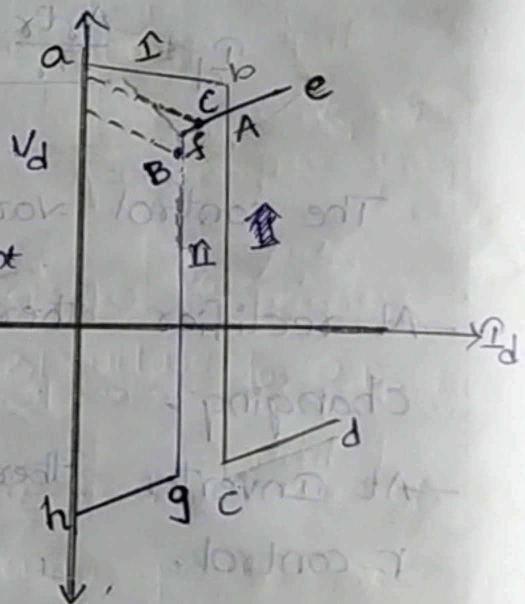
Merit:- For short circuit faults, the current will remain the same.

Demerit:- I^2R loss in the system will remain the same at full load.

Imp.

Converter control characteristics :(or) V_d-I_d characteristics of HVDC converter station:-

Station I	Station II	Type
ab	hg	min α
bc	gf	constant current
cd	fe	min γ



- The intersection of two characteristics (point a) determine mode of operation.
- Station I operated as rectifier with constant (current control) (CCC)
- Station II operating as inverter at constant Extension station angle. (CEA)

There can be 3 modes of operation of a link.

(i) CC (constant current) at the rectifier & (operating at point A) is the normal modes of operation.

(ii) with slight (fall) dip in AC v/g's point of intersection shift which implies

Min α at the rectifier
min γ at the inverter

(iii) with lower AC V/g at rectifier the mode of operation shift to B which implies
Min α at the rectifier.
CCC at the inverter

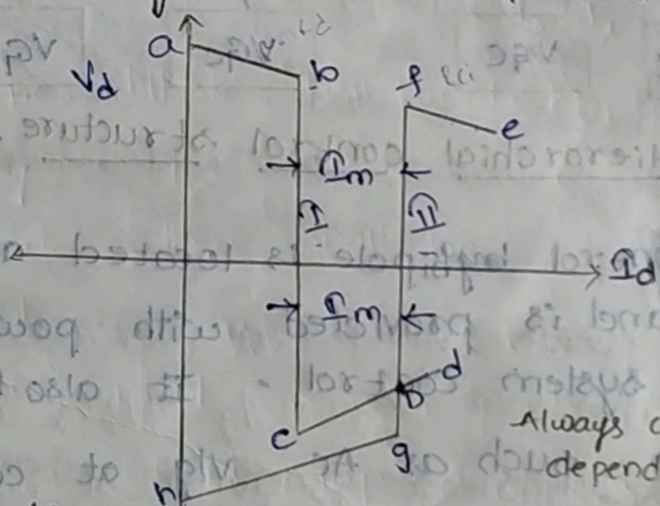
- The operation at minimum extension angle at the inverter & current control at the rectifier. results in better V/g regulation then operation will min. delay angle.

[To overcome commutation failure] - CEA
- CC
Minimise the reactive power

- At the rectifier and cont current control at the inverter.

CEA acts as control reactive power.

Converter control characteristics for negative current margin: (Reversal of power flow)



slope ab ⇒ $R_{cr}+R_d$
slope fe ⇒ R_{ci}

[without firing angle, we can't start the operation]

Always current margin depends on intersection.

The operating point is now shifted to D which implies power reversal.

- Station I operates as inverter with CEA control.
- station II operates as rectifier with CC control.

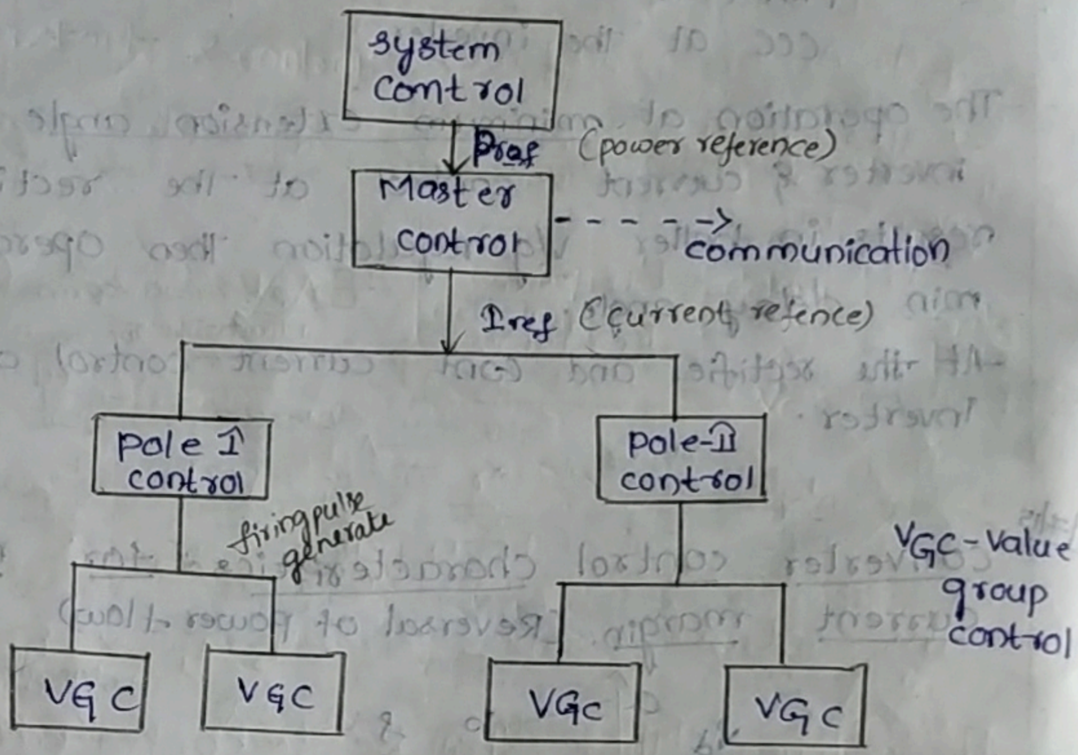
In actual characteristics ab has more -ve slope then characteristic fe. This is because of the fact that slope of ab is combined resistance of R_{cr} & R_d where as slope of fe is R_{ci}.

[why we are preferring CC
① can maintain v/g regulation]

7m

* *** System control Hierarchy:- (or) Block diagram of HVDC control.

The control functions required for HVDC link are explained by using hierarchial structure.



Hierarchial control structure for a DC link

- Master control bybipole is located at one of terminal and is provided with power order (p) from the system control. It also has other information such as AC vlg at converter bus, DC vlg.

- Master control transmits current (order reference I) to the pole control units which intern, provide firing pulse to individual Value group control

- Pole control incorporate, pole protection & DC line protection value group (or) converter control overseas. (looks after). [overseas (Abroad)]

- Value monitory, by pass space selection commutation failure protection and value protection ckts.

Master controller oversees complete bipole includes functions of frequency control, power modulation, AC voltage & reactive power torsional frequency damping control.

27/7/15

Imp ***

Firing angle control (FAC):- FAC [IPC [cons α, Inverse cosine ; EPC [PFC, pulse period, PPC

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

(i) The firing instant for all the values are determined at ground potential & the firing signals sent to individual thyristors by light signals through fibre optic cables. (underground)

(ii) while a single pulse is adequate to turn on a thyristor the gate pulse generator must send a pulse whenever required if the particular value is to be kept in conducting state (overhead)

There are two basic firing schemes namely:

(i) Individual phase control (IPC)

(ii) Equidistant pulse control (EPC)

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

(i) Individual phase control (IPC):-

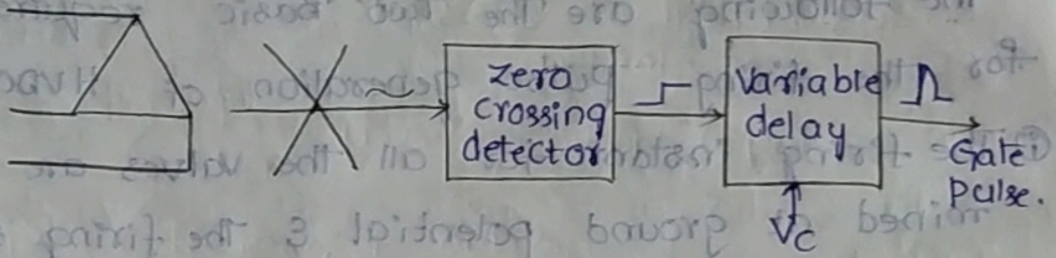
This scheme was used in early HVDC projects. The main feature of this scheme is that firing pulse generation for each phase (or) Valve is independent of each other & firing pulses are rigidly synchronicommutation v/g

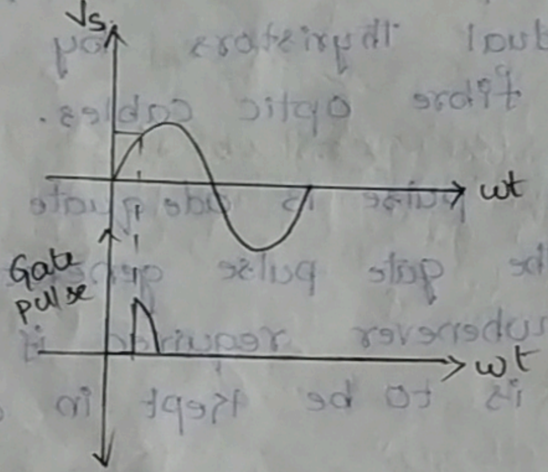
There are two ways in which this can be achieved

(i) constant Alfa (α) control

(ii) Inverse cosine control.

(i) <u>constant</u> <u>α control</u>:-



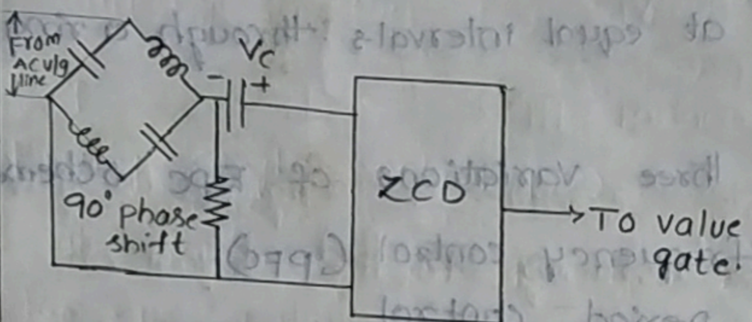


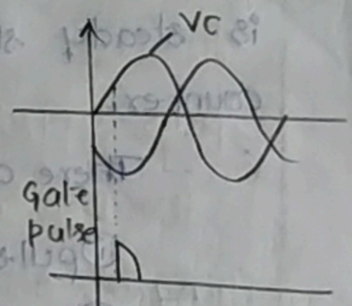
- Six commutation v/g's are derived from converter AC bus via v/g t/f r's and the six gate pulses are generated at nominally identical delay times subsequent to respective v/g zero crossings.

- The instant at zero crossing of a particular commutation v/g corresponds to $\alpha = 0°$ for that value.

- The delays are produced by independent delay ckt's and controlled by a common control v/g V_C derived from current controller.

(ii) Inverse cosine control:-





$$\sqrt{3}V_m \sin(\omega t - 90^\circ) + V_c = 0$$

$$-\sqrt{3}\,V_m \cos\omega t + V_c = 0 \quad ; \ \omega t = \alpha$$

$$\sqrt{3}V_m \cos\alpha = V_c$$

$$\alpha = \cos^{-1}\left(\frac{V_c}{\sqrt{3}V_m}\right)$$

- Six commutation v/g obtained has in constant α control are each shifted by 90° and added separately to a common control voltage V_c.
- The zero crossing of sum of the two v/g's generates firing pulses for the particular value.
- The delay angle α is proportional to inverse cosine of control voltage (V_c). It also depends on ac system v/g amplitude and phase.

Drawbacks:

- Main drawback of IPC is harmonic instability due to non-characteristics harmonics in steady state.
- The following are the measures to overcome harmonic instability.

① use of filter out non characteristic harmonics.

② provision of synchronous condensor. (Improvement pf)

③ using firing angle control zero crossing of AC v/g's.

(ii) Equidistant pulse control:-

In this scheme the firing pulses are generated is steady state at equal intervals through a ring counter.

There are three variations of EPC scheme:

(i) pulse frequency control (PFC).

(ii) pulse period control

(iii) pulse phase control (PPC).

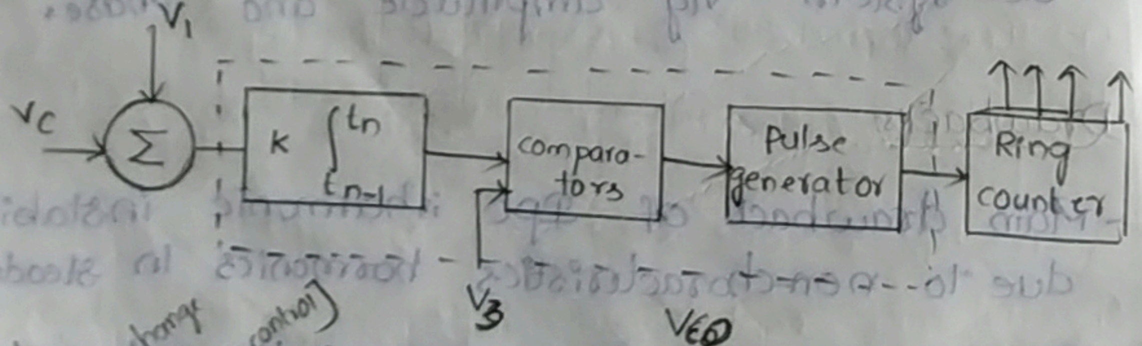
(i) pulse frequency control:-

In this scheme a voltage controlled oscillator (VCO) is used, the frequency of which is determined by the control voltage V_c which is related to the error in the quantity being regulated.

The frequency in steady state is equal to $\frac{1}{P f_0}$.

P - pulse number.

f_0 - Nominal frequency of the ac system.



(Vc & V1 change changes frequency that's why frequency control)

Block diagram of PFC

VCO consists of Integrator, comparator & gate pulse generator.

The o/p pulses of the generator drive the ring counter & also reset the integrator.

The firing instant (t_n) of the firing pulse is determined from the following equations.

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

where $V_1 \rightarrow$ constant voltage

$V_3 \rightarrow$ proportional to the system period

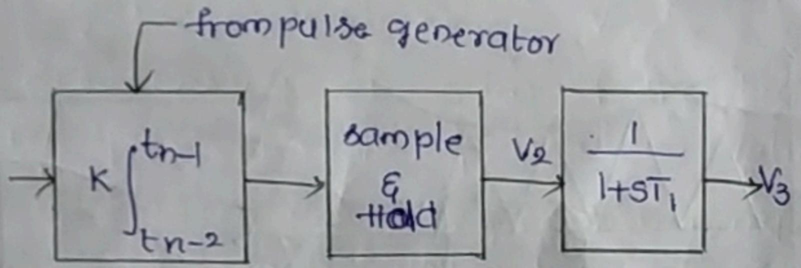
In steady state, $V_c = 0$

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

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

In steady state gain K_1 of the integrator is given by

$$K_1 = \frac{Pf_0 V_3}{V_1}$$



Frequency correction for PFC

$$V_3 = \frac{V_2}{1+sT_1} \quad ; \quad V_2 = K_1 V_1 (t_{n-1} - t_{n-2})$$

30/7/15

(ii) Pulse period control:-

It is similar to PFC, V_c is summed with V_3 instead of V_1 the instant (t_n) of firing pulse generation is given by

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

with $V_c = 0$

$$k_1 V_1 (t_n - t_{n-1}) = V_3$$

$$k_1 = \frac{V_3 P f_0}{V_1}$$

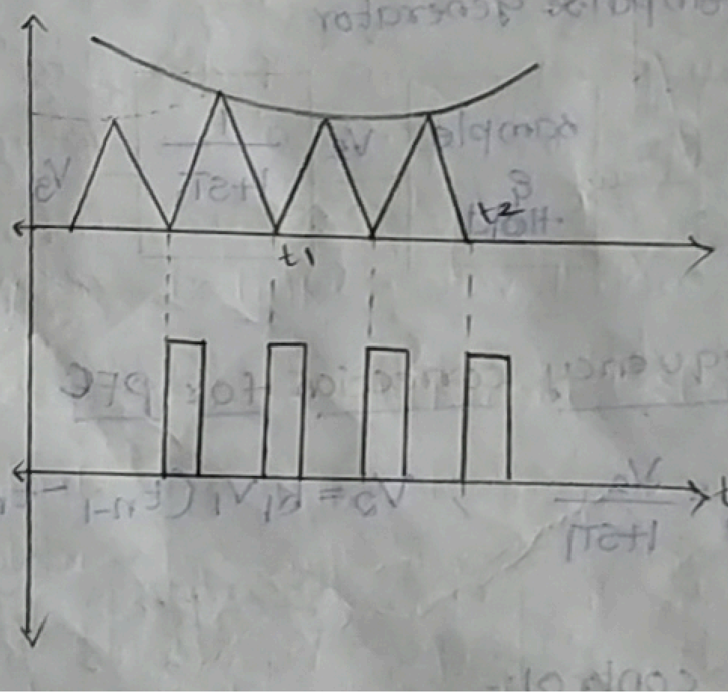
(iii) **Pulse phase control (PPC):-**

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

$$k_1 \int_{t_{n-1}}^{t_n} V_1 \, dt = V_{c_n} - V_{c_{n-1}} + V_3$$

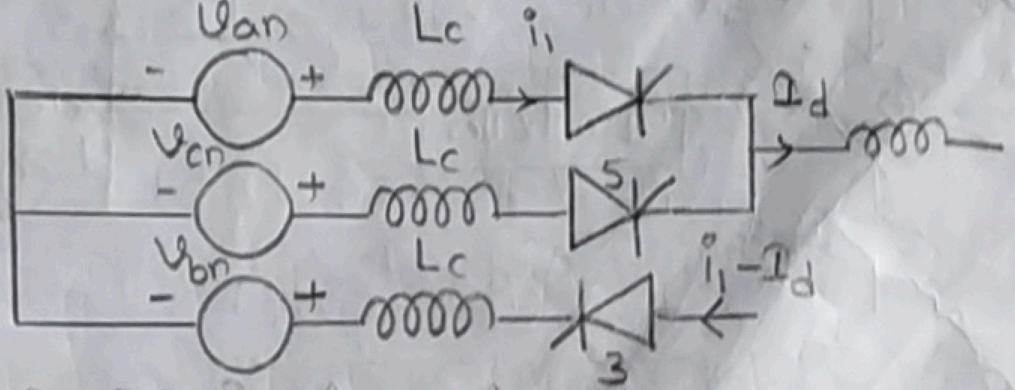
V_{c_n}, $V_{c_{n-1}}$ are the control V/g's at the instant t_n, t_{n-1} respectively.

with $V_C = 0$ in steady state, consecutive pulses will be generated of phase (pulse) intervals of $\frac{1}{Pf_0}$.



Constant Extinction angle control (CEA):-

(Inverter)



when Valve 1 is considered i.e. Commutation from valve 5 to valve 1 is considered. γ_n should have a minimum value to allow turn off time to prevent commutation failure.

If this time is not available before the V/g across the valve becomes positive then commutation failure occurs.

$$L_c D i_1 + L_c D(i_1 - I_d) = v_{an} - v_{cn} = v_{ac}$$

$$2L_c D i_1 = \sqrt{3} V_m \sin\omega t$$

$$2L_c \frac{di_1}{dt} = \sqrt{3} V_m \sin\omega t$$

$$di_1 = \frac{\sqrt{3} V_m}{2\omega L_c} \sin\omega t \, d(\omega t)$$

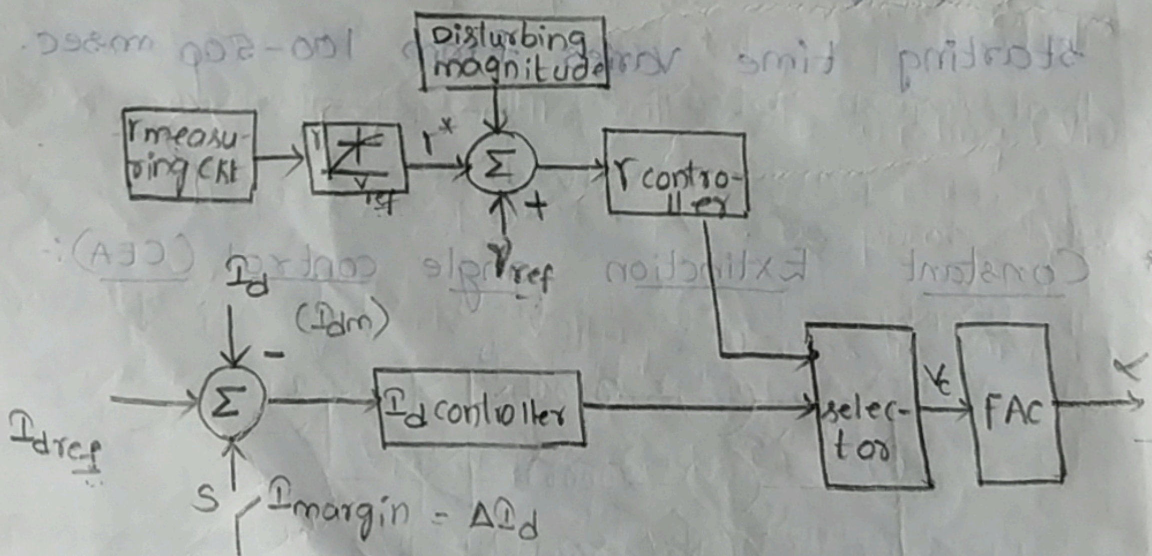
$$\int_0^{I_d} di_1 = \int_{\alpha}^{\pi - \gamma_n} \frac{\sqrt{3} V_m}{2\omega L_c} \sin \omega t \, d(\omega t)$$

$$\frac{2\omega L_c I_d}{\sqrt{3} V_m} = \cos\gamma_n + \cos\alpha$$

$\therefore$ Required value of α to get γ_{min}.

$$\alpha = \cos^{-1}\left[\frac{2\omega L_c I_d}{\sqrt{3} V_m} - \cos\gamma_{min}\right]$$

α depends on I_d & V_m.



Block diagram of CEA & CC controllers.

Switch 'S' is closed for Inverter.

Constant current controller:

For rectifier, $E = I_{ds} - I_{dm}$

Inverter, $E = I_{ds} - I_{dm} - \Delta I_d$

ΔI_d - current margin.

$I_{d's}$ = setting of current regulator.

I_{dm} = measured value.

Current is maintained constant by using constant current regulator.

The current on extinction angle generates control signal V_C which related to the firing angle required.

For FAC generates gate pulses in response to the control signal V_C. selector chooses min. value of α determined by CC & CEA controller.

Q5 Generation of Harmonics:

Harmonics:

They are generated due to unbalance in load (or) vtg (or) current. Harmonics [illegible] creates the following problems.

Scanned By Scanner Go

(i) Telephone Interference
(ii) Over v/g's due to resonance.
(iii) Extra power losses & consequent heating in machines & capacitors connected in the system.
(iv) Instability of converter control.
(v) Interference with ripple control management.

Classification of Harmonics:-

Two types (i) characteristic harmonics
(ii) Non-characteristic harmonics.

Characteristic Harmonics:- (odd / AC)

The harmonics that are present in the Ideal operation i.e, balanced AC v/g's, three phase symmetrical network & Equidistant pulses.

The harmonics in AC are of the order $h = np \pm 1$

Non characteristic harmonics (even) DC

The harmonics in DC are of the order $h = np$

n = any integer
p = pulse number.

Non-characteristic harmonics:-

The harmonics of the order other than characteristics harmonics are termed as non-characteristic harmonics. These are due to imbalances in operation of two bridges forming 12 pulse converter unit.

- Firing angle error
- unbalance & distortion in ac v/g.
- unequal t/f ~~reo~~ leakage reactance.

last 3 causes due to generation of Triplet & (Even) linear harmonics and their analysis is complex.

13/8/15

Triplen, even harmonics comes under non-characteristic harmonics.

The harmonics that are present due to Imbalance in operation of two bridges forming 12 pulse converter unit are Residual Harmonics, unequal leakage impedance of two converter t/f feeding the two bridges also cause Residual Harmonics.

Even Harmonics are considered as both characteristic & non characteristic harmonics.

odd harmonics in balanced condition as called " AC harmonics".

odd harmonics in unbalanced condition are called " Triplen Harmonics".

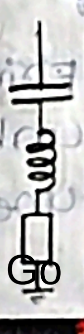
Imp ***

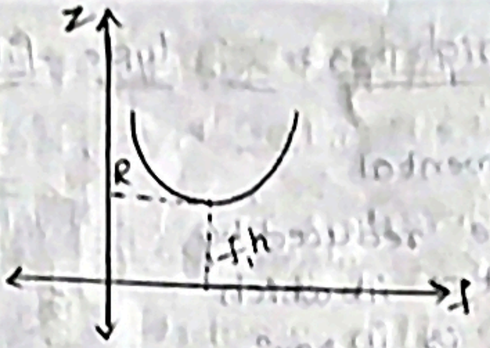
* Ac filters:- eliminate current harmonics. Dc filters :- voltage harmonics

The main objective of design of AC filters is to reduce telephone interference.

Types: single Tuned } lower order harmonics
Double Tuned
second order Hypass – c } higher order

(i) Single Tuned filter: It is used to filter out Harmonics of single frequency.

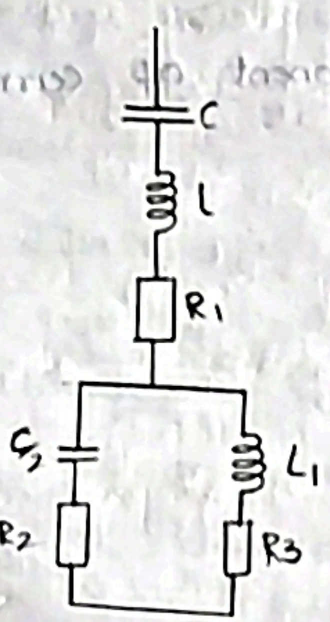




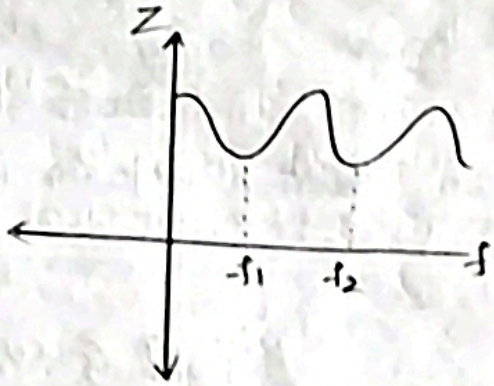
Z Vs f

z = characteristic Impedance.

(ii) Double Tuned filter:-



It is used to filter out two discrete frequencies instead of using two single tuned filters.



Advantages:

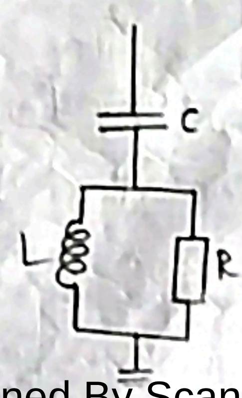
(i) only one Inductor is subjected to full line impedance v/g.

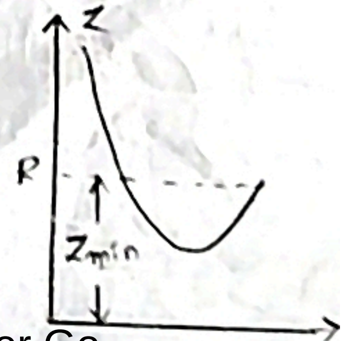
(ii) Reduced power losses of fundamental frequency of harmonic component current

Second Order highpass:-

It is used to filter out higher order harmonics.

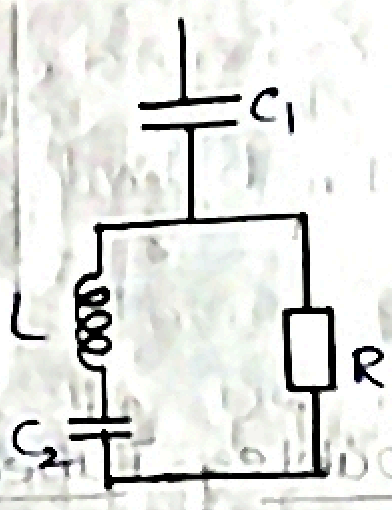
(above 13)





Second order high pass 'c' type filter:

Losses at fundamental frequency can be reduced by a 'c' type filter in which a capacitor 'c' is in series with inductor 'L' provides a low impedance shunt path to harmonic component of current.



filters types
lowpass
Band pass
high pass

Reactive power requirements in steady state :-

Imp.
xxx 7m

Conventional (normal) control strategy :- compensation

A DC link is operated with current control at the rectifier and the minimum Extinction angle control (CEA) at the inverter. This method of control lead to minimum reactive power requirement at both the ends.

The equations for reactive power as a function of active power can be conveniently expressed interms of p.u. quantities.

Basic converter v/g $(V_{db}) = \frac{3\sqrt{2}}{\pi} V_n$

V_n - Rate line - line v/g on the valve side winding

Base dc current (I_{db}) = Rated dc current (I_{dn})

Base dc power $(P_{db}) = \underbrace{n_b}_{\text{No. of series connected bridges.}} V_{db} I_{db}$

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

Base AC power = Base DC power $= \frac{\sqrt{18}}{\pi} V_n I_{db} n_b$

The average dc voltage across the converter is given by

$$\overline{V_d} = \overline{V} \cos\alpha - \overline{R_c} \overline{I_d} \quad \text{--- (1)}$$

$$I_d = \frac{V_{do}(\cos\alpha - \cos\gamma)}{R_{cr} + R_d - R_{ci}}$$

Equation ① can be used for inverter by replacing α by γ.

where $\overline{V_d} = \frac{V_d}{V_{db}}$, $\overline{R_c} = \overline{X_c}$ → p.u leakage reactance of t/f

$\overline{V} = \frac{V}{V_b}$, $\overline{I_d} = \frac{I_d}{I_{db}}$

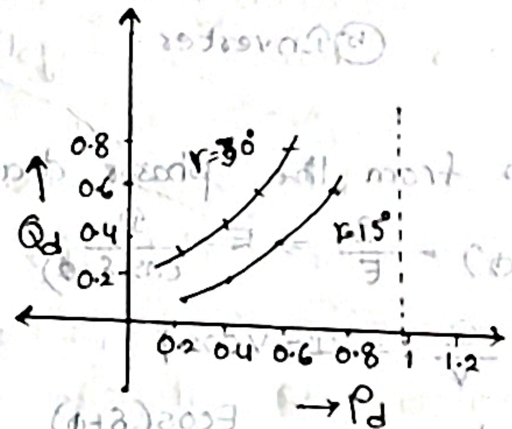
The power factor is given by $\cos\phi = \frac{\overline{V_d}}{\overline{V}}$ $\frac{kW}{kVA}$

$$= \cos\alpha - \left(\frac{\overline{R_c}\,\overline{I_d}}{\overline{V}}\right)$$

The equations for active & reactive power will be given

$$\overline{P_d} = \overline{V}\,\overline{I_d}\cos\phi$$
$$\overline{Q_d} = \overline{V}\,\overline{I_d}\sin\phi$$

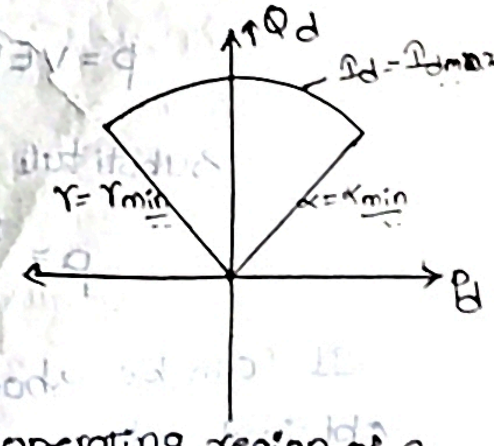
Rated dc power is less than 1 pu as rated Voltage is less than base dc voltage.



Alternate control strategy :-

The operating region of a bridge in $P_d - Q_d$ plane is bounded by

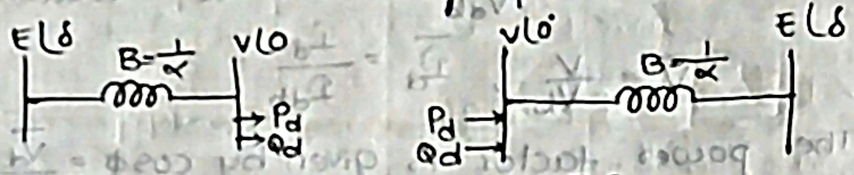
(i) minimum α characteristics
(ii) minimum γ characteristics
(iii) constant rated DC current.



The operation at constant DC v/g implies constant power factor characteristics at the converter bus.

operating region of a bridge in $P_d - Q_d$ plane.

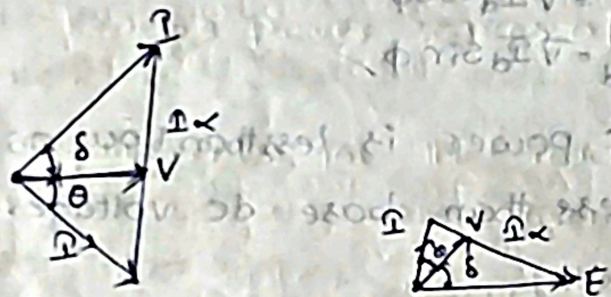
At the rectifier, the characteristics is that of a load with lagging pf while at the inverter, as a generator with leading power factor.



(a) Rectifier (b) Inverter

Simplified system diagram

Phasor diagram:



(a) Rectifier (b) Inverter.

It can be shown from the phasor diagram that

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

$$\cos\phi = \frac{I}{V} \Rightarrow I = V\cos\phi$$

$$E = \frac{V\cos\phi}{\cos(\delta+\phi)} \Rightarrow V = \frac{E\cos(\delta+\phi)}{\cos\phi} \quad \text{—(1)}$$

where ϕ is the powerfactor angle.

The power expression is given by

$$P = VEB\sin\delta \quad \text{—(2)}$$

substitute (1) in (2) we get

$$P = \frac{E^2 B\cos(\delta+\phi)\sin\delta}{\cos\phi} \quad \text{—(3)}$$

It can be shown that max power transfer is obtained when $\delta = 45° - \frac{\phi}{2}$ —(4)

The maximum power for $\phi = 30°$ is given by

$$P_{max} = 0.2887 E^2 B \quad \text{— (5)}$$

This much less than that obtained in the following constants

(i) $\phi = 0°$ $\quad P_{max} = 0.5 E^2 B$

(ii) $\phi = 30°$, $P_{max} = 0.866 E^2 B$

(iii) $V = E$, $P_{max} = E^2 B$

It is to be noted that provision of shunt capacitor at the converter bus results in modification of maximum power expression.

$$P_{max} = \frac{0.2887 E^2 B}{\left(1 - \frac{B_c}{B}\right)}$$

For $B = 3.0$ pu, $B_c = 0.5$ pu

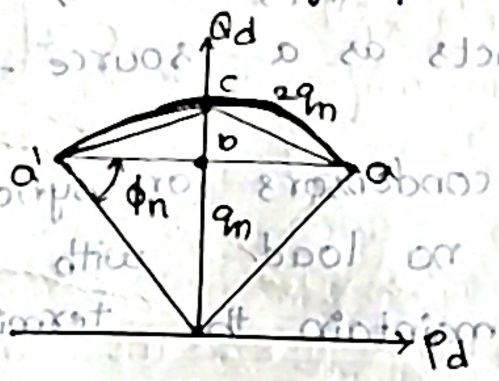
This results in an increase of 20% of max power given by equation (5)

The above analysis shows that there is need to modify reactive power characteristics of the converter power station.

(i) choice of reactive power sources
(or)
(ii) Adjusting the control characteristics

(a) constant reactive power characteristics

(b) constant leading power factor characteristics

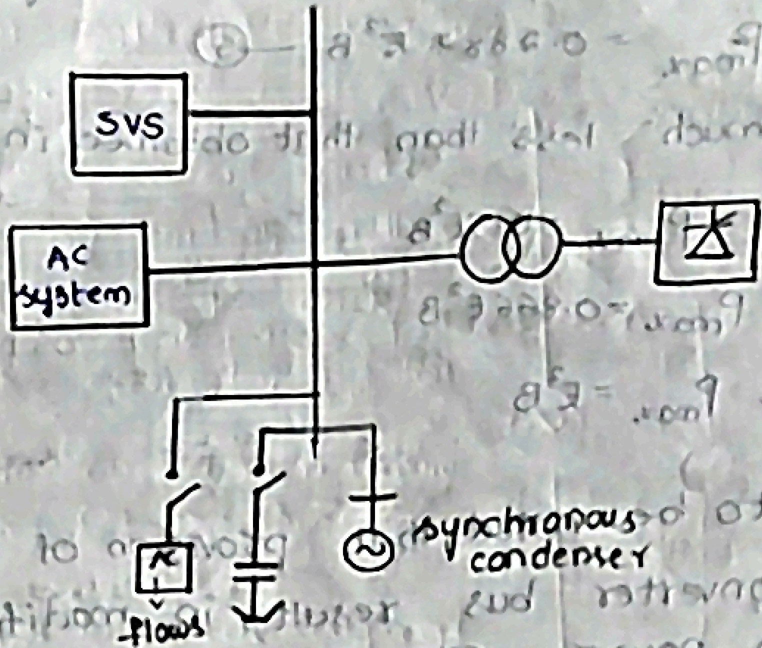


(i) SVS (Static var systems)

(ii) midpoint

4/8/2019

Sources of reactive power (SVS):



Reactive power sources at a converter bus

- The requirements for the reactive power at the converter bus are given by the following sources:- AC system, AC filters, shunt capacitors, synchronous condensors, static var systems (SVS).

- For slow variations, full load switched capacitors are filter can be used to provide control.
- synchronous condensers & SVS provide continuous control and reactive power it can follows fast & load changes.
- All the filter branches are in capacitive in nature they acts as a source for reactive power.
- synchronous condensors or synchronous motors operating at no load with excitation control in maintain the terminal v/g.
- Advantages are availability of v/g source for commutation at the inverter if connection to the ac system is temporary interrupt.

- Better voltage regulation during transient due to the maintainance of flux linkages in rotor windings.

Disadvantage:-

- High maintainance cost.
- possibility of instability due to the machine going out of synchronqusm.

xxxx 14m

Static VAR systems (SVS):-

SVS helps to have fast control of readive power flow there by controlling v/g fluctuations & over comes v/g instability.

SVS provides fast control following a disturbance.

There are three types.

(i) Variable Impedance SVS,

Ex:{ (ii) current source type SVS, } FACTS
STATCom (iii) Voltage source type SVS.

STATCom ↓ static shunt compensator

Voltage

(i) Variable Impedance type SVS

Variable Impedance type SVS is commonly used in power system.

Applications:-

Variable Impedance type SVS devices are
(control thyristor)

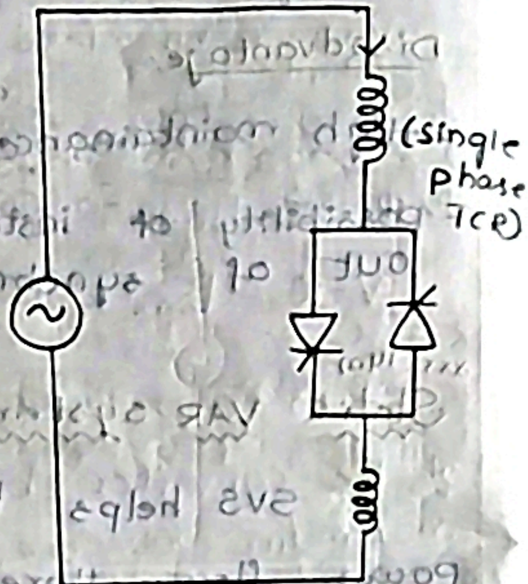
(i) Thyristor controlled reactor (TCR).

(ii) Fixed capacitor thyristor controlled reactor (FC-TCR)

(iii) Thyristor switched capacitors (TSC).

6/8/15 ① **Thyristor controlled Reactor:- (TCR)**

The reactor current can be controlled by controlling the firing angle of the back to back connected thyristors.



For $\alpha = 90°$, current is maximum
For $\alpha = 180°$, current is zero.

The fundamental component of Inductor current is given by,

$$I_1 = \left(\frac{\sigma - \sin\sigma}{\pi X_L}\right) V \quad \text{—①}$$

X_L – fundamental frequency reactance
V = RMS v/g across TCR
σ = conduction angle

$$\sigma = 2(\pi - \alpha) \quad \text{—②}$$

Equation ① can be written as $I_1 = B(\sigma) V$,

where $B(\sigma) = \frac{\sigma - \sin\sigma}{\pi X_L}$

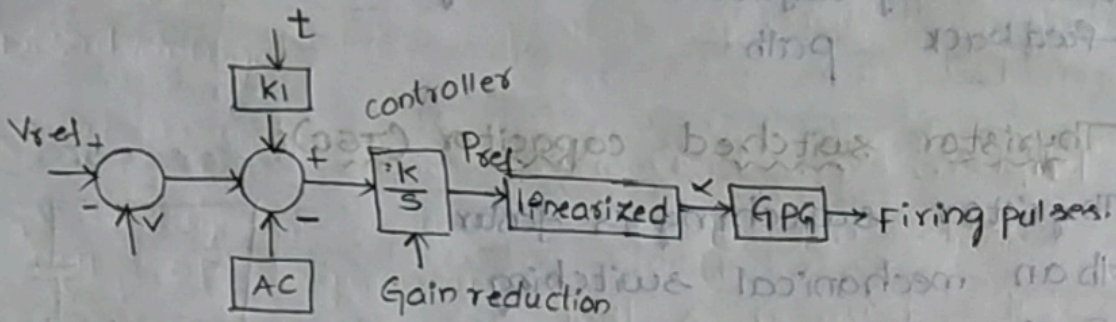
The harmonic component of the current corresponding to harmonic order of 'h' is given by

$$I_h = \left(\frac{4}{\pi}\right)\left(\frac{V}{X_L}\right) \left[\frac{\sin[(h+1)\alpha]}{2(h+1)} + \frac{\sin(h-1)\alpha}{2(h-1)} - \frac{\cos\alpha \sin h\alpha}{h}\right] \quad \text{—③}$$

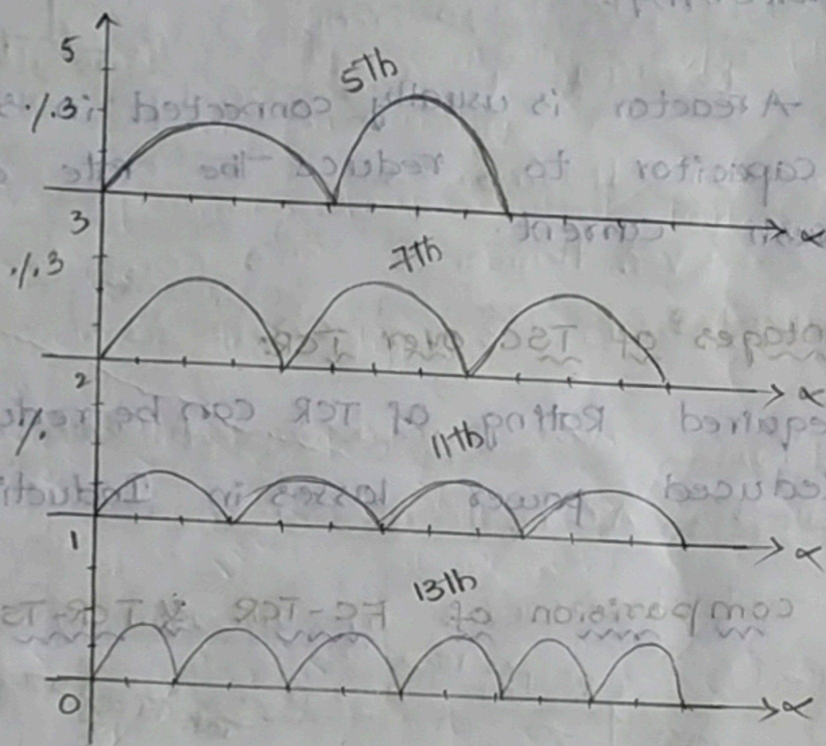
$h = 3, 5, 7$

Triplen harmonics are eliminated by Δ connection of 3 single phase TCR's. The control signals are obtained from the voltage & the reactor current.

The controller is usually an Integral controller with Variable gain to avoid problems of control instability. The auxillary control signal Vs may be derived from the bus frequency.

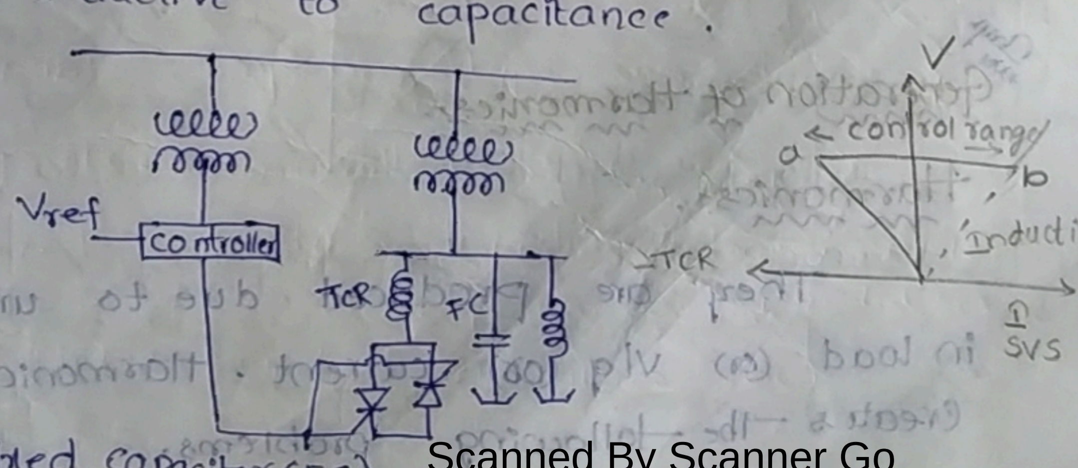


Typical control system of TCR



Harmonic order with respect to conduction

TCR is usually operated with fixed capacitor with provide variation of reactive power consumption from inductive to capacitance.



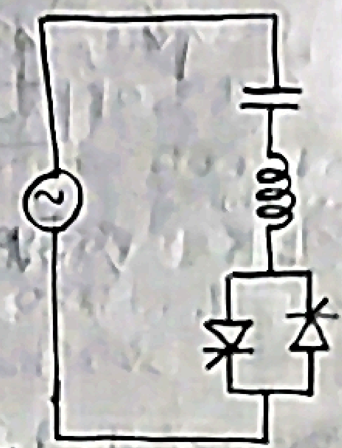
Fixed capacitor (FC)

Scanned By Scanner Go

control range kv which shows +ve slope & which can be adjusted from gain is the current feed back path.

10/8/15 **Thyristor switched capacitor (TSC):**

Thyristor switching is faster than mechanical switching & also it is possible to have transient free operation by controlling the instant of switching.



Single phase (TSC)

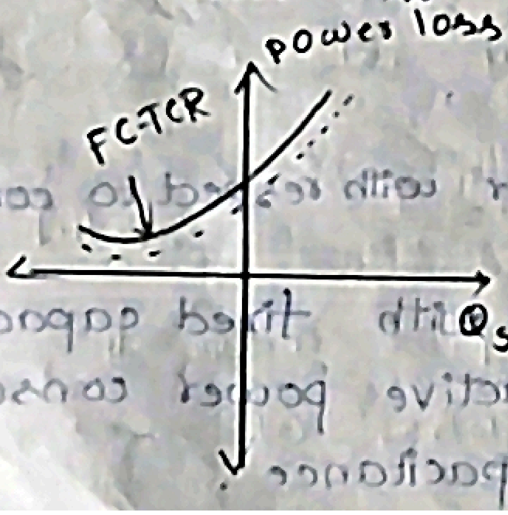
A reactor is usually connected in series with the capacitor to reduce the rate of change of inrush current.

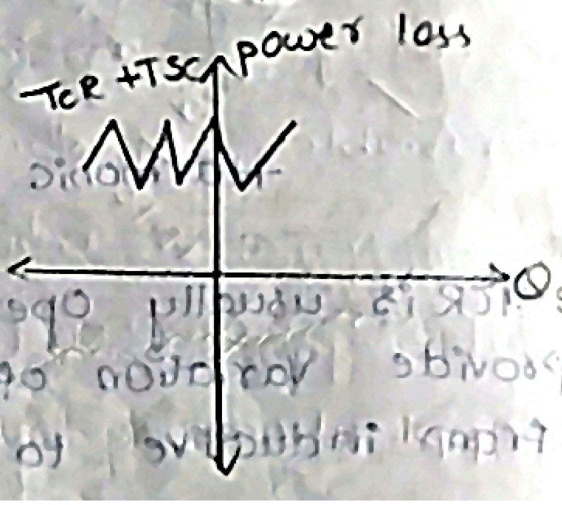
Advantages of TSC over TCR:

(i) Required Rating of TCR can be reduced.

(ii) Reduced power losses in Inductive operation.

Loss comparision of FC-TCR & TCR-TSC:





14m