CBCS SCHEME

USN ☐☐☐☐☐☐☐☐☐☐

15EE751

Seventh Semester B.E. Degree Examination, Dec.2019/Jan.2020
FACTS and HVDC Transmission

Time: 3 hrs.

Max. Marks: 80

Note: ***Answer any FIVE full questions, choosing ONE full question from each module.***

Module-1

1 a. Define "FACTS Controller". **(03 Marks)**

b. Explain the basic types of FACTS controllers, with neat sketch. **(07 Marks)**

c. List the possible benefits from FACTS Technology. **(06 Marks)**

OR

2 a. Explain the limitations on transmission line loading capability. **(06 Marks)**

b. Enumerate the relative importance of controllable parameters. **(06 Marks)**

c. Present in perspective : HVDC or FACTS. **(04 Marks)**

Module-2

3 a. What are the important objectives of shunt compensation? **(04 Marks)**

b. With the help of a two – machine system, explain how shunt compensation can help in improving transient stability. **(07 Marks)**

c. Explain with suitable sketch, the single phase operation of Thyristor Switched Reactor (TSR). **(05 Marks)**

OR

4 a. Explain with suitable, diagram the switching type VAR generator. **(07 Marks)**

b. Why voltage slope is provided in the V – I characteristics of SVC and STATCOM? **(04 Marks)**

c. Compare the V – I characteristics of SVC and STATCOM. Any two points. **(05 Marks)**

Module-3

5 a. What are the important objectives of series compensation? **(04 Marks)**

b. With neat sketch, explain the concept of series capacitive compensation. **(07 Marks)**

c. Write a note on : TSSC. **(05 Marks)**

OR

6 a. Explain with suitable sketch, how voltage stability of a radial system can be improved using static series compensation. **(08 Marks)**

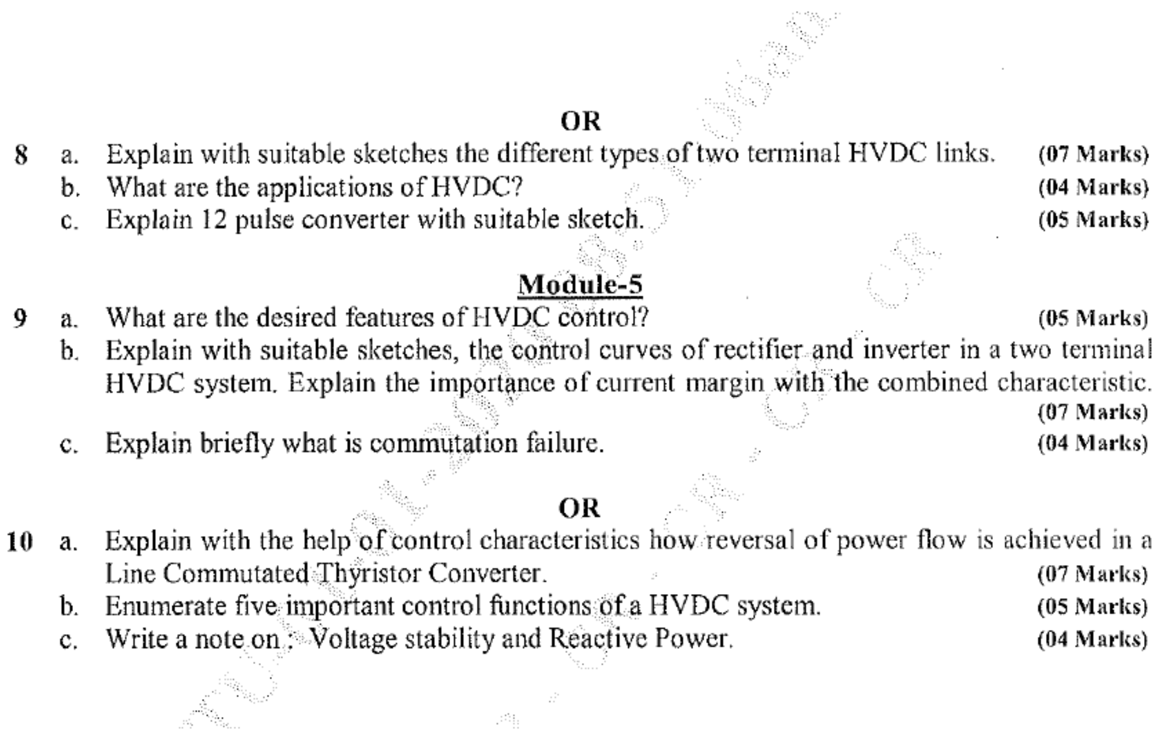
b. Explain the operation of Static Synchronous Series Compensation (SSSC) with the help of suitable sketch. **(08 Marks)**

Module-4

7 a. List five important advantages of HVDC. **(0 Marks)**

b. Explain with neat waveform the operation of the three phase bridge converter with turn – on angle 'α' but no overlap. Derive the expression for the average output , direct voltage V_d. **(07 Marks)**

c. What is multi – terminal HVDC? What are the different types of multi – terminal HVDC? **(04 Marks)**



OR

8 a. Explain with suitable sketches the different types of two terminal HVDC links. **(07 Marks)**
b. What are the applications of HVDC? **(04 Marks)**
c. Explain 12 pulse converter with suitable sketch. **(05 Marks)**

Module-5

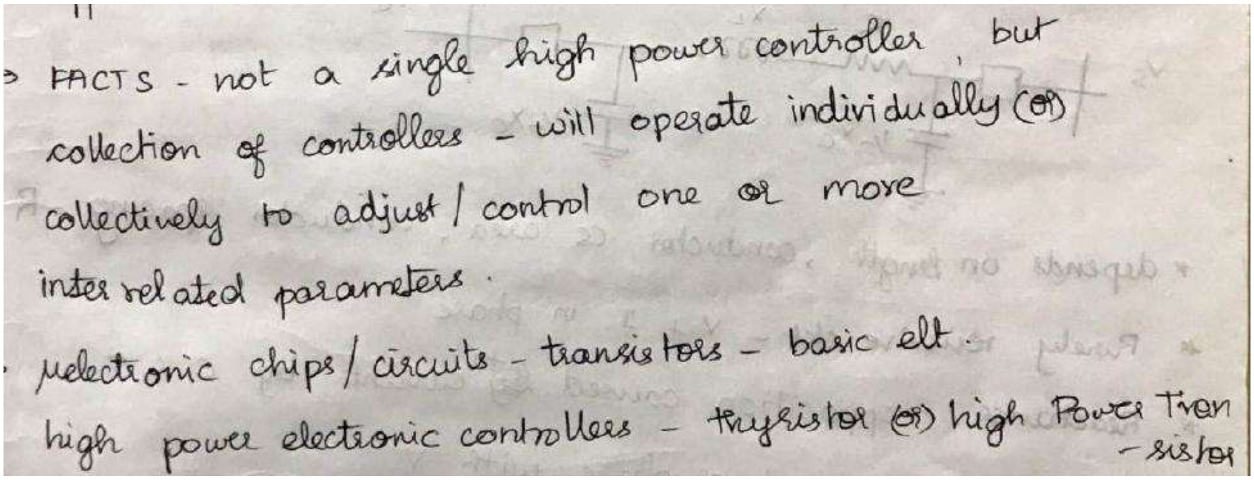
9 a. What are the desired features of HVDC control? **(05 Marks)**
b. Explain with suitable sketches, the control curves of rectifier and inverter in a two terminal HVDC system. Explain the importance of current margin with the combined characteristic. **(07 Marks)**
c. Explain briefly what is commutation failure. **(04 Marks)**

OR

10 a. Explain with the help of control characteristics how reversal of power flow is achieved in a Line Commutated Thyristor Converter. **(07 Marks)**
b. Enumerate five important control functions of a HVDC system. **(05 Marks)**
c. Write a note on : Voltage stability and Reactive Power. **(04 Marks)**

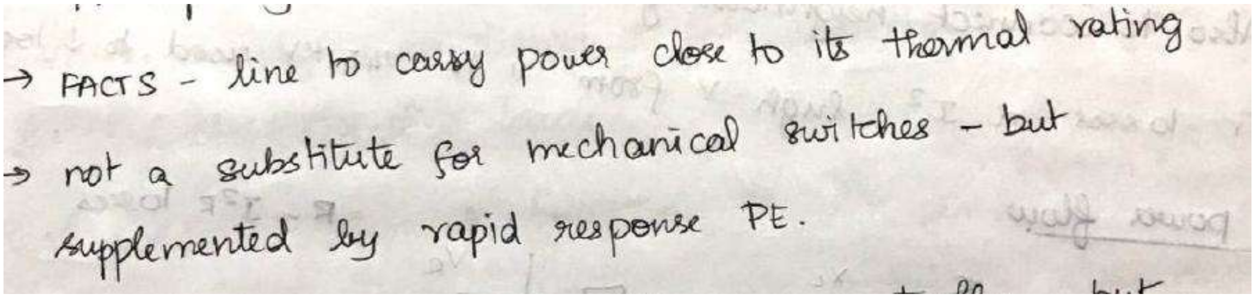
Solution

1a) FACTS Controller



→ FACTS - not a single high power controller, but collection of controllers - will operate individually (or) collectively to adjust / control one or more inter related parameters.

• μelectronic chips / circuits - transistors - basic elt.
high power electronic controllers - thyristor (or) high Power Transistor



→ FACTS - line to carry power close to its thermal rating

→ not a substitute for mechanical switches - but supplemented by rapid response PE.

1b)

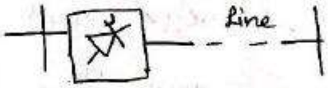
Basic Types of FACTS controller.

* Series controller * Shunt * Combined series - series.

* Combined series - shunt controller.

Series controller.

→ Series controller can be a variable impedance such as C (or) reactor



→ All series controllers inject V in series with the line

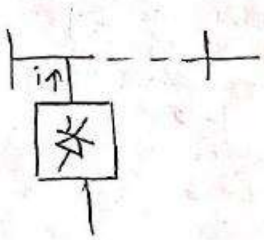
→ variable Z × I through it, also act as injecting a voltage in series

→ Injected V is in phase quadrature with line I, only Q control, some other angle, can control Real power also.

Shunt controllers.

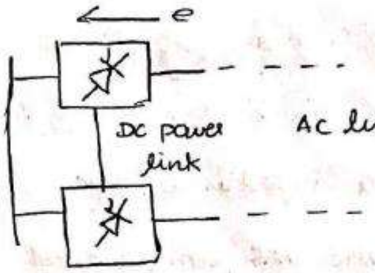
→ it can be a variable Z, variable source etc

→ injects I into the line.



→ injected I quadrature with line v, only Q control some other angle, real power control also

Combined series - series controller.

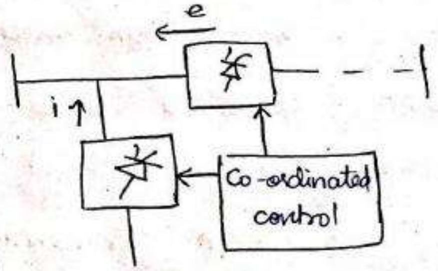


→ combination of separate series controllers - controlled in a coordinated manner in a multiline transmission s/m.

→ Series controllers supply Q for each link & real power P among lines.

→ Real power transfer capability - reffered to as Interline Power flow controller. (balances both P & Q flow)

Combined series - shunt controller



→ combination of series & shunt controller.

→ injects both V & i

FACTS controller with storage

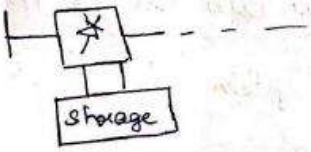
→ DC to AC.

→ Controllers, basically converters that can exchange P & Q.

→ Sometimes, controllers are provided with storage.

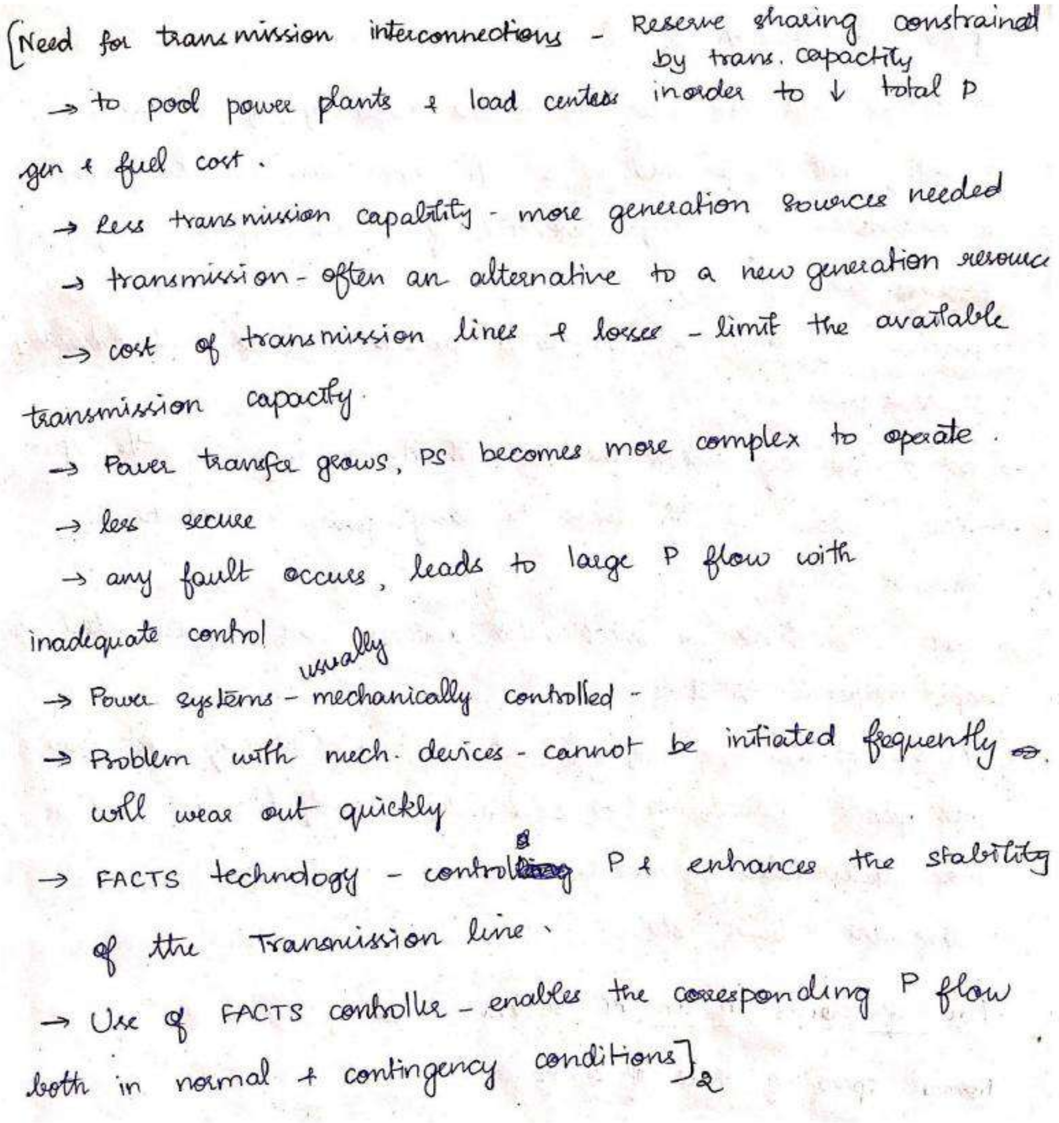
→ This helps in effective control of system dynamics.

→ Energy storage s/m - needed when active power is involved in the power flow.



Series controller
with storage

1c)



[Need for transmission interconnections - Reserve sharing constrained by trans. capacity

→ to pool power plants & load centers inorder to ↓ total P gen & fuel cost.

→ Less transmission capability - more generation sources needed

→ transmission - often an alternative to a new generation resource

→ cost of transmission lines & losses - limit the available transmission capacity.

→ Power transfer grows, PS becomes more complex to operate.

→ less secure

→ any fault occurs, leads to large P flow with inadequate control

→ Power systems - usually mechanically controlled -

→ Problem with mech. devices - cannot be initiated frequently. will wear out quickly

→ FACTS technology - control~~ling~~s P & enhances the stability of the Transmission line.

→ Use of FACTS controller - enables the corresponding P flow both in normal & contingency conditions]$_2$

2a)

Loading capability of a transmission line - Limitations

* Thermal * Dielectric * stability.

Thermal limit

* large I flow - more losses in the form of heat - ↑ conductor temperature - inturns reduces mechanical strength of the conductor.

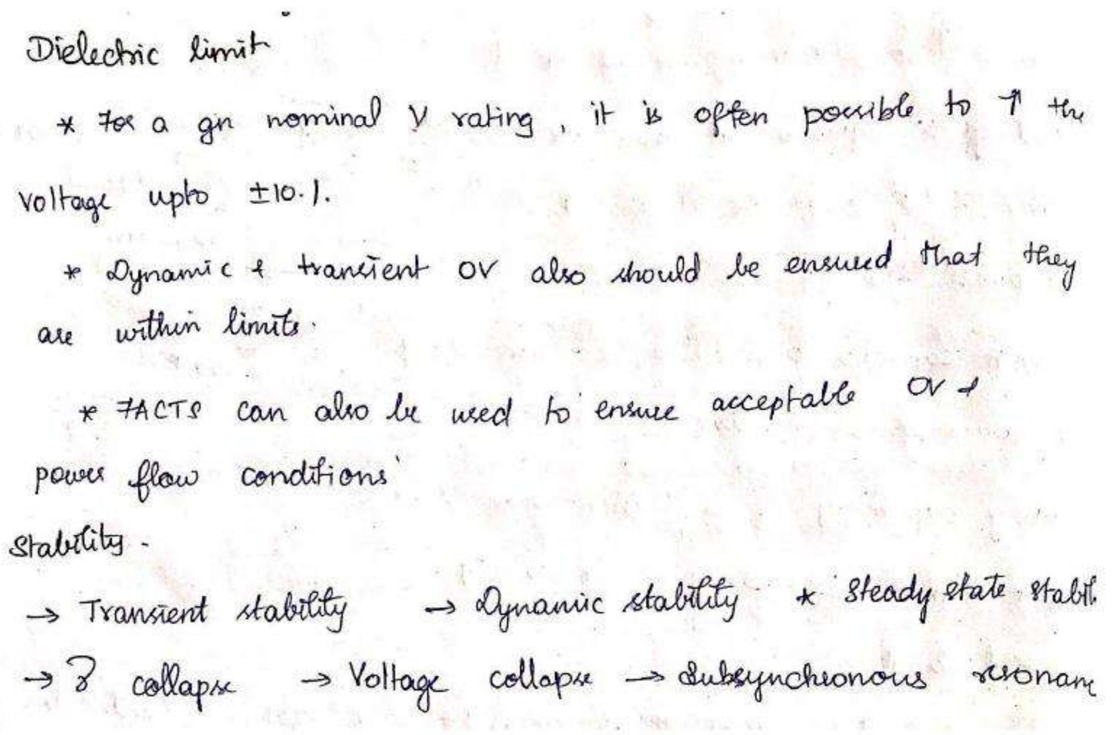
* Thermal limit depends upon ambient temperature, wind condition, condition of the conductor & ground clearance.

* Nominal rating of a line designed for worst environmental case scenario.

* Off-line computer programs that can calculate lines loading capability based on available ambient environmental condns & recent loading history - available.

* On-line monitoring devices are also available to control the power flow.

* FACTS technology can be used to effectively control the power flow.



Dielectric limit

* For a gn nominal V rating, it is often possible to ↑ the voltage upto ±10 %.

* Dynamic & transient OV also should be ensured that they are within limits.

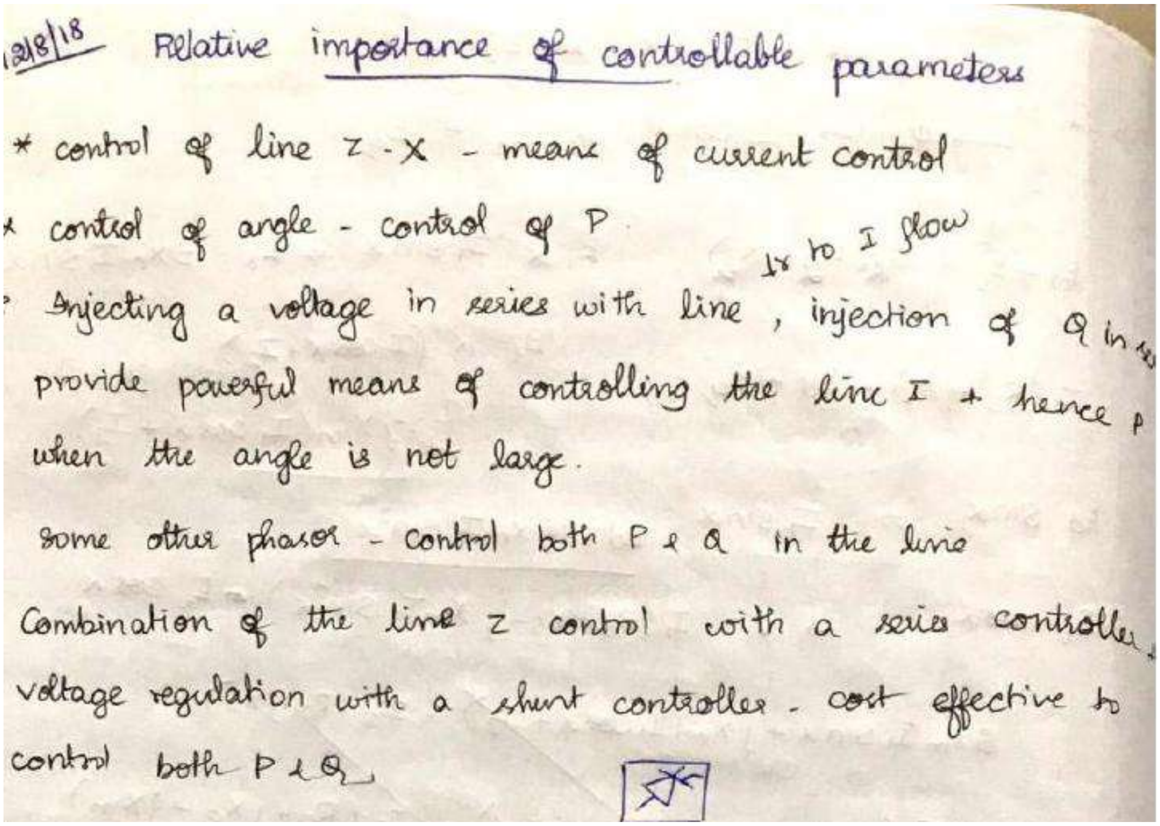
* FACTS can also be used to ensure acceptable OV & power flow conditions

Stability -

→ Transient stability → Dynamic stability * Steady state stabil.

→ δ collapse → Voltage collapse → Subsynchronous resonan

2b)



12/8/18 Relative importance of controllable parameters

* control of line Z - X - means of current control

* control of angle - control of P

* Injecting a voltage in series with line, ⊥r to I flow injection of Q in provide powerful means of controlling the line I + hence P when the angle is not large.

some other phasor - control both P & Q in the line

Combination of the line Z control with a series controller, voltage regulation with a shunt controller - cost effective to control both P & Q

2c)

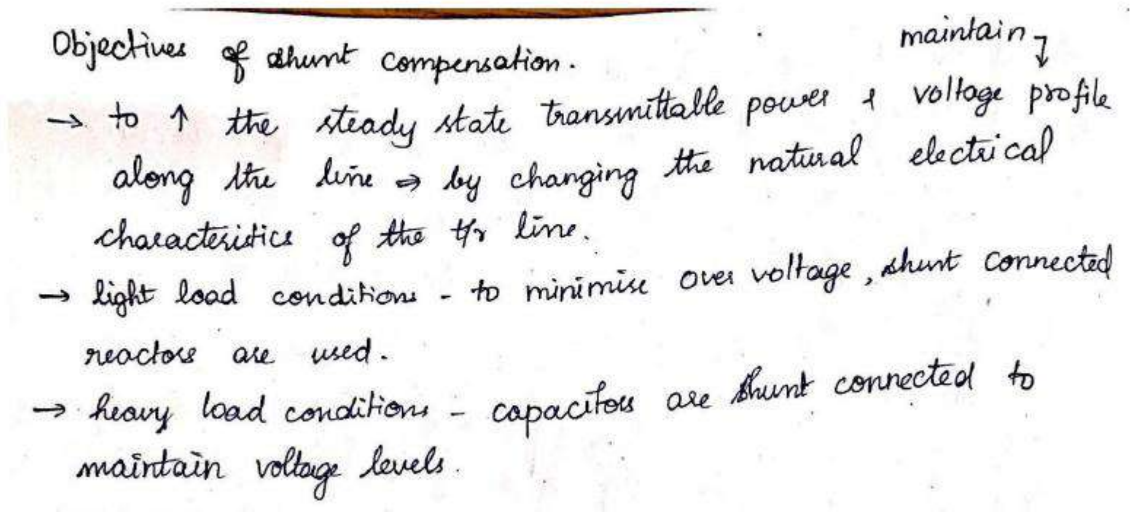
IN PERSPECTIVE: HVDC OR FACTS

It is important to recognize that generally HVDC and FACTS are complementary technologies. HVDC is not a grid network in the way that an ac system is, nor is it expected to be. The role of HVDC, for economic reasons, is to interconnect ac systems where a reliable ac interconnection would be too expensive.

There are now over 50 HVDC projects in the world. These can be divided into four categories:

1. **Submarine cables.** Cables have a large capacitance, and hence ac cables require a large charging current (reactive power) an order of magnitude larger than that of overhead lines. As a result, for over a 30 km or so stretch of ac submarine cable, the charging current supplied from the shore will fully load the cable and leave no room for transmitting real power. The charging current flowing in the cables can only be reduced by connecting shunt inductors to the cable at intervals of 15–20 km, thus requiring appropriate land location. With HVDC cable on the other hand, distance is not a technical barrier. Also, the cost of dc cable transmission is much lower than that of ac which works to HVDC's advantage to cover new markets for long distance submarine transmission. In this area, FACTS technology (e.g., the UPFC) can provide an improvement by controlling the magnitude of one of the end (e.g., the receiving-end) voltages so as to keep it identical to that of the other one. In this way, the effective length of the cable from the standpoint of the charging current can be halved. This approach may provide an economical solution for moderate submarine distances, up to about 100 km, but for long distance transmission HVDC will remain unchallenged.
2. **Long distance overhead transmission.** If the overhead transmission is long enough, say 1000 km, the saving in capital costs and losses with a dc transmission line may be enough to pay for two converters (note that HVDC represents total power electronics rating of 200% of the rated transmission capacity). This distance is known as the break-even distance. This *break-even distance* is very subject to many factors including the cost of the line, right-of-way, any need to tap the line along the way, and often most important, the politics of obtaining permission to build the line. Nevertheless, it is important to recognize that while FACTS can play an important role in an effective use of ac transmission, it probably does not have too much influence on the break-even distance. Thus, the principal role of FACTS is in the vast ac transmission market where HVDC is generally not economically viable.
3. **Underground transmission.** Because of the high cost of underground cables, the break even distance for HVDC is more like 100 km as against 1000 km for overhead lines. Again, FACTS technology probably does not have much influence in this break-even distance. In any case, to date there have been no long distance underground projects, either ac or dc, because, in an open landscape, overhead transmission costs so much less than underground transmission (about 25% of the costs of underground transmission). Cable transmission, on the other hand, has a significant potential of cost reduction, both in the cost of cables and construction cost.
4. **Connecting ac systems of different or incompatible frequencies.** For historical reasons, the oceans in effect separate the globe's electric systems into 50 Hz and 60 Hz groups. The 60 Hz normal frequency pervades all the countries of the Americas, excepting Argentina and Paraguay. Those two countries and all the rest of the world have a 50 Hz frequency except Japan, which is partly 50 Hz and partly 60 Hz. In general, the oceans are too huge and deep to justify interconnections of 50 and 60 Hz systems. Thus there is a limited market for HVDC for connecting 50 and 60 Hz systems.

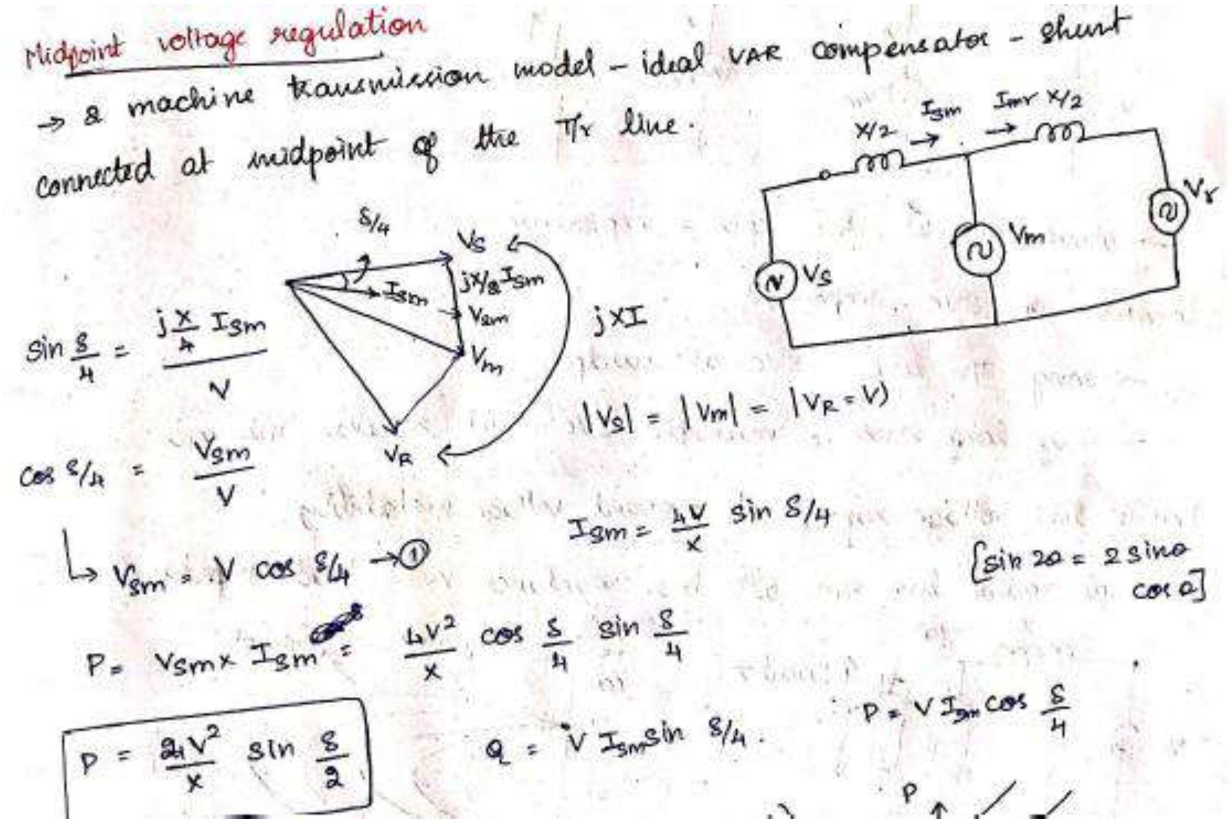
3a)



Objectives of shunt compensation.

- → to ↑ the steady state transmittable power & ~~maintain~~ voltage profile along the line ⇒ by changing the natural electrical characteristics of the T/r line.
- → light load conditions - to minimise over voltage, shunt connected reactors are used.
- → heavy load conditions - capacitors are shunt connected to maintain voltage levels.

3b)



Midpoint voltage regulation

→ 2 machine transmission model - ideal VAR compensator - shunt connected at midpoint of the T/r line.

$$\sin\frac{\delta}{4} = \frac{j\frac{X}{4} I_{sm}}{V}$$

$$|V_S| = |V_m| = |V_R = V)$$

$$\cos\delta/4 = \frac{V_{sm}}{V}$$

$$I_{sm} = \frac{4V}{X} \sin\delta/4$$

$$\hookrightarrow V_{sm} = V\cos\delta/4 \rightarrow ①$$

$$[\sin 2\theta = 2\sin\theta\cos\theta]$$

$$P = V_{sm} \times I_{sm} = \frac{4V^2}{X}\cos\frac{\delta}{4}\sin\frac{\delta}{4}$$

$$P = V I_{sm}\cos\frac{\delta}{4}$$

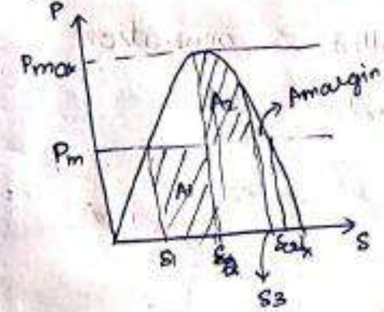
$$\boxed{P = \frac{2V^2}{X}\sin\frac{\delta}{2}}$$

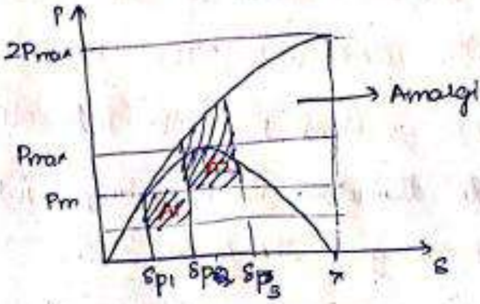
$$Q = V I_{sm}\sin\delta/4.$$

Transient stablity

→ effectiveness can be identified from equal area criterion.

→ uncompensated & compensated s/m - same fault for same period of time





⇒ Normal operating condition,

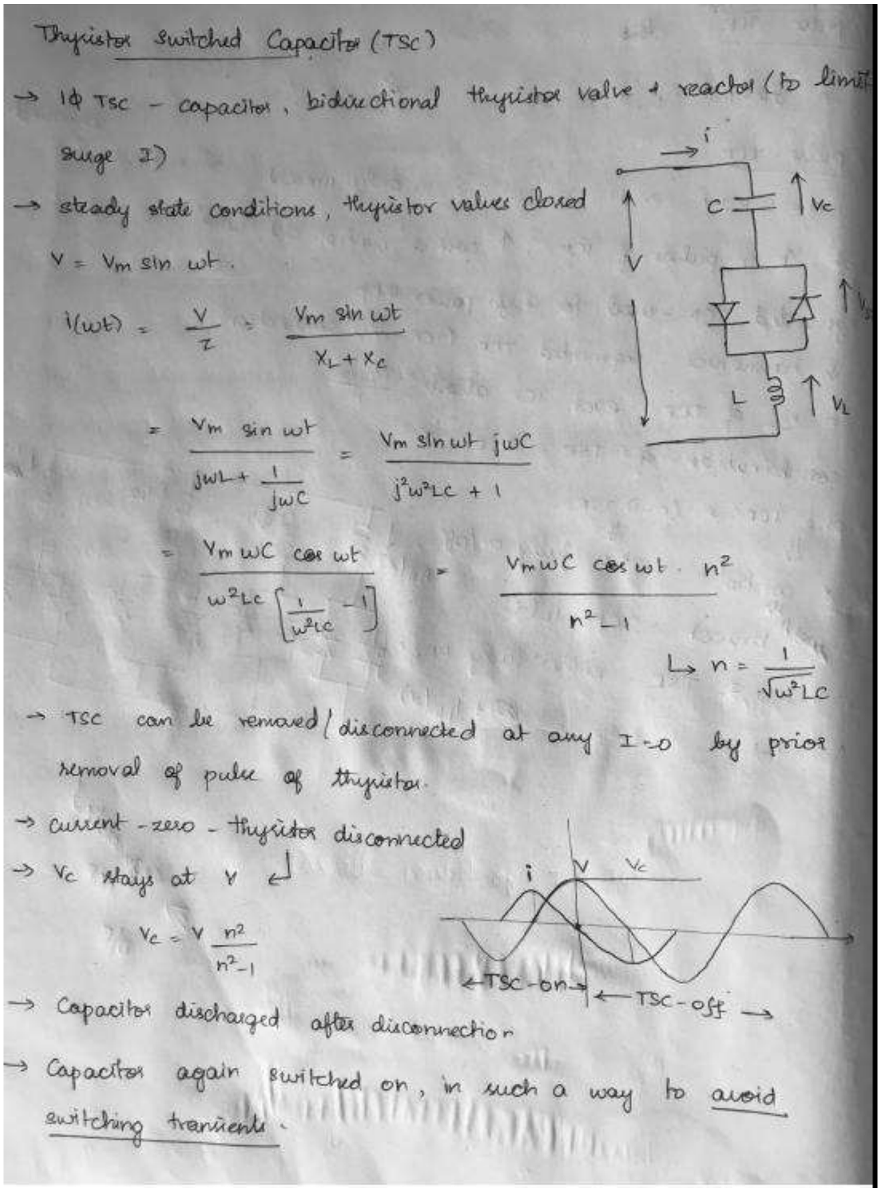
→ P_m - δ_1 & δ_{p1} transmittable power

⇒ fault, transmittable power - zero ⇒ δ changes to δ_2 & δ_{p2}.

⇒ After fault clearing → δ becomes δ_3 & δ_{p3} ∴ Amargin 1 > Amargin

⇒ Tr. stablity improved.

3c)



Thyristor Switched Capacitor (TSC)

- → 1ϕ TSC - capacitor, bidirectional thyristor valve + reactor (to limit surge I)
- → steady state conditions, thyristor values closed

$V = V_m \sin \omega t$.

$$i(\omega t) = \frac{V}{Z} = \frac{V_m \sin \omega t}{X_L + X_C}$$

$$= \frac{V_m \sin \omega t}{j\omega L + \frac{1}{j\omega C}} = \frac{V_m \sin \omega t \; j\omega C}{j^2\omega^2 LC + 1}$$

$$= \frac{V_m \omega C \cos \omega t}{\omega^2 LC \left[\frac{1}{\omega^2 LC} - 1\right]} = \frac{V_m \omega C \cos \omega t \cdot n^2}{n^2 - 1}$$

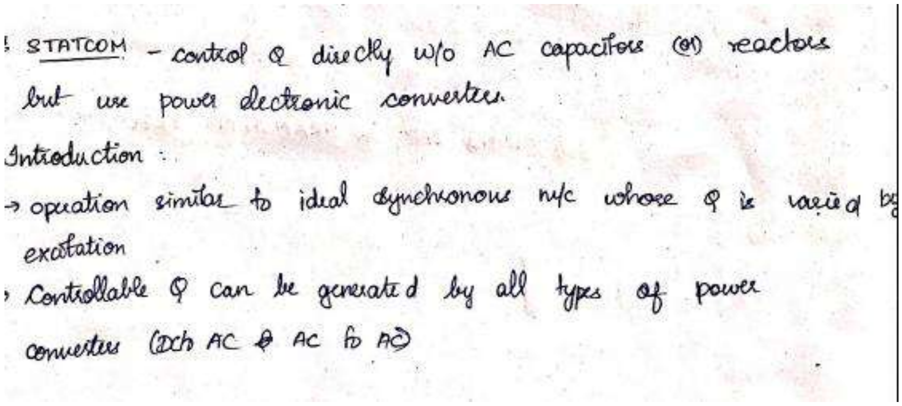
↳ $n = \frac{1}{\sqrt{\omega^2 LC}}$

- → TSC can be removed / disconnected at any $I = 0$ by prior removal of pulse of thyristor.
- → current - zero - thyristor disconnected
- → V_c stays at V ↵

$$V_c = V \frac{n^2}{n^2 - 1}$$

- → Capacitor discharged after disconnection
- → Capacitor again switched on, in such a way to avoid switching transients.

4a)



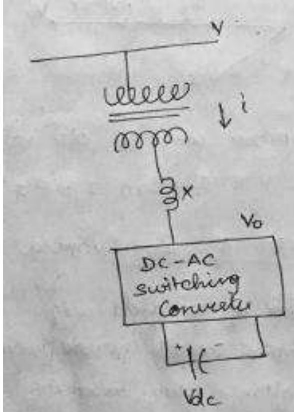
STATCOM - control Q directly w/o AC capacitors (or) reactors but use power electronic converters.

Introduction :

→ operation similar to ideal synchronous m/c whose Q is varied by excitation

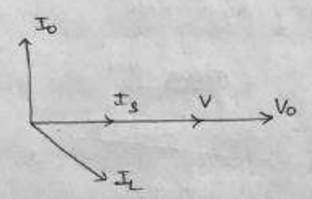
→ Controllable Q can be generated by all types of power converters (DC to AC & AC to AC)

STATCOM VSC

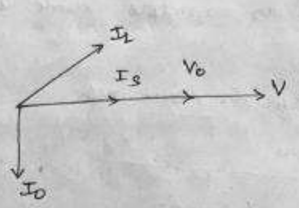


- ⇒ i/p - dc o/p ⇒ controllable 3ϕ o/p.
- ⇒ by varying V_o, can control Q.
- ⇒ $V_o > V$ ⇒ generates Q to the AC s/m
- ⇒ $V_o < V$ ⇒ converter absorbs Q.
- ⇒ $V_o = V$ ⇒ Q exchange = 0
- ⇒ Converters used - 1ϕ, 3ϕ, multipulse converter.

STATCOM in capacitive mode



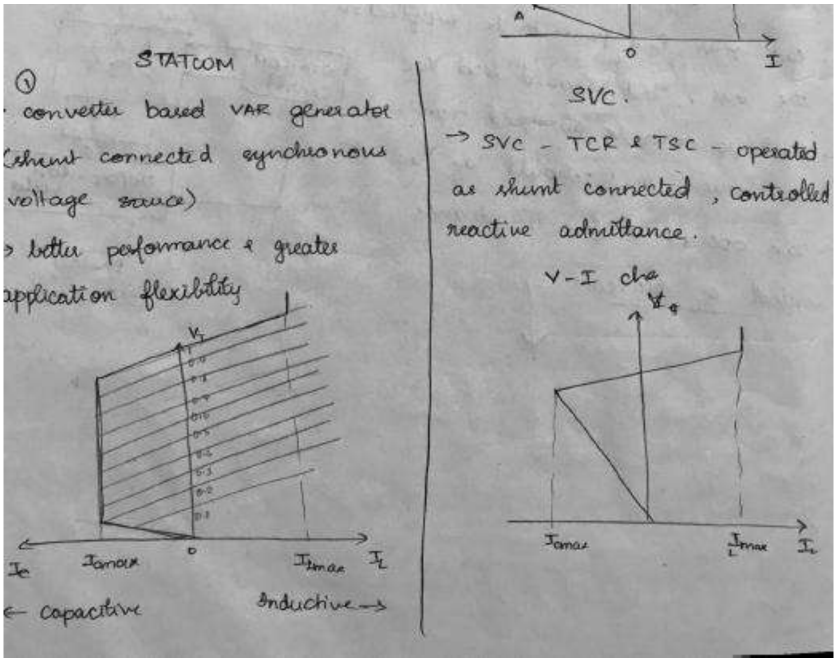
In inductive mode



V_o - STATCOM converter o/p voltage

V - line V I - load I I_o - STATCOM injected I.

4b) and 4c)



STATCOM

①
- converter based VAR generator (shunt connected synchronous voltage source)

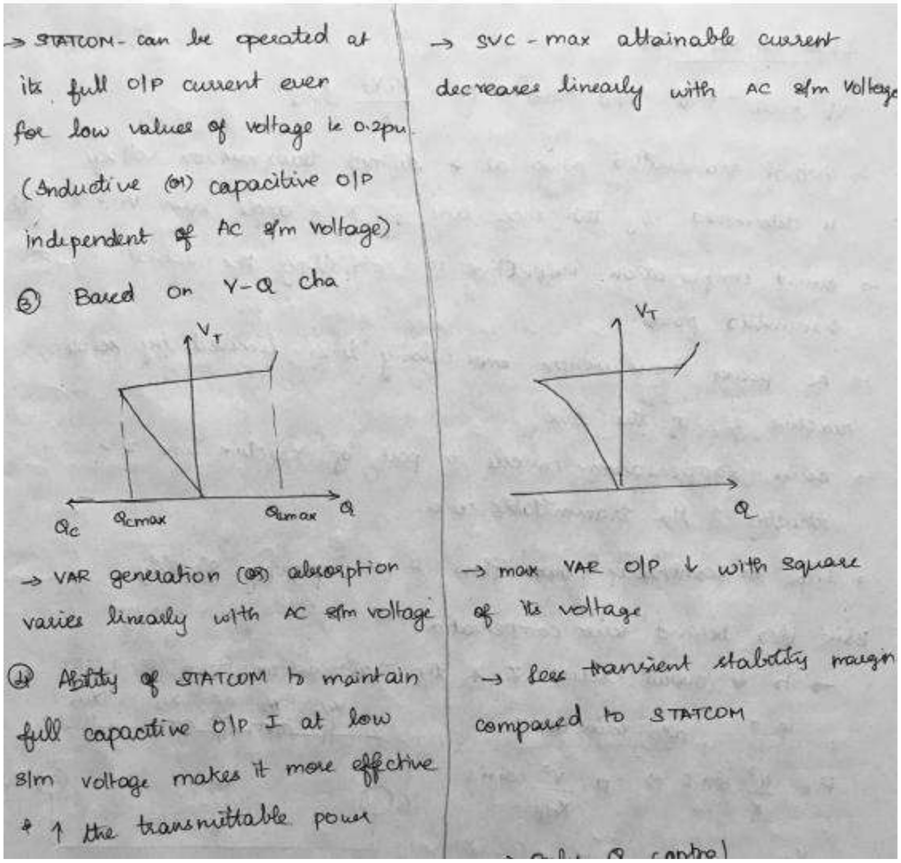
→ better performance & greater application flexibility

← capacitive Inductive →

SVC.

→ SVC - TCR & TSC - operated as shunt connected, controlled reactive admittance.

V-I cha



→ STATCOM - can be operated at its full O/P current even for low values of voltage ie 0.2pu (Inductive (or) capacitive O/P independent of AC s/m voltage)

③ Based on V-Q cha

→ VAR generation (or) absorption varies linearly with AC s/m voltage

④ Ability of STATCOM to maintain full capacitive O/P I at low s/m voltage makes it more effective & ↑ the transmittable power

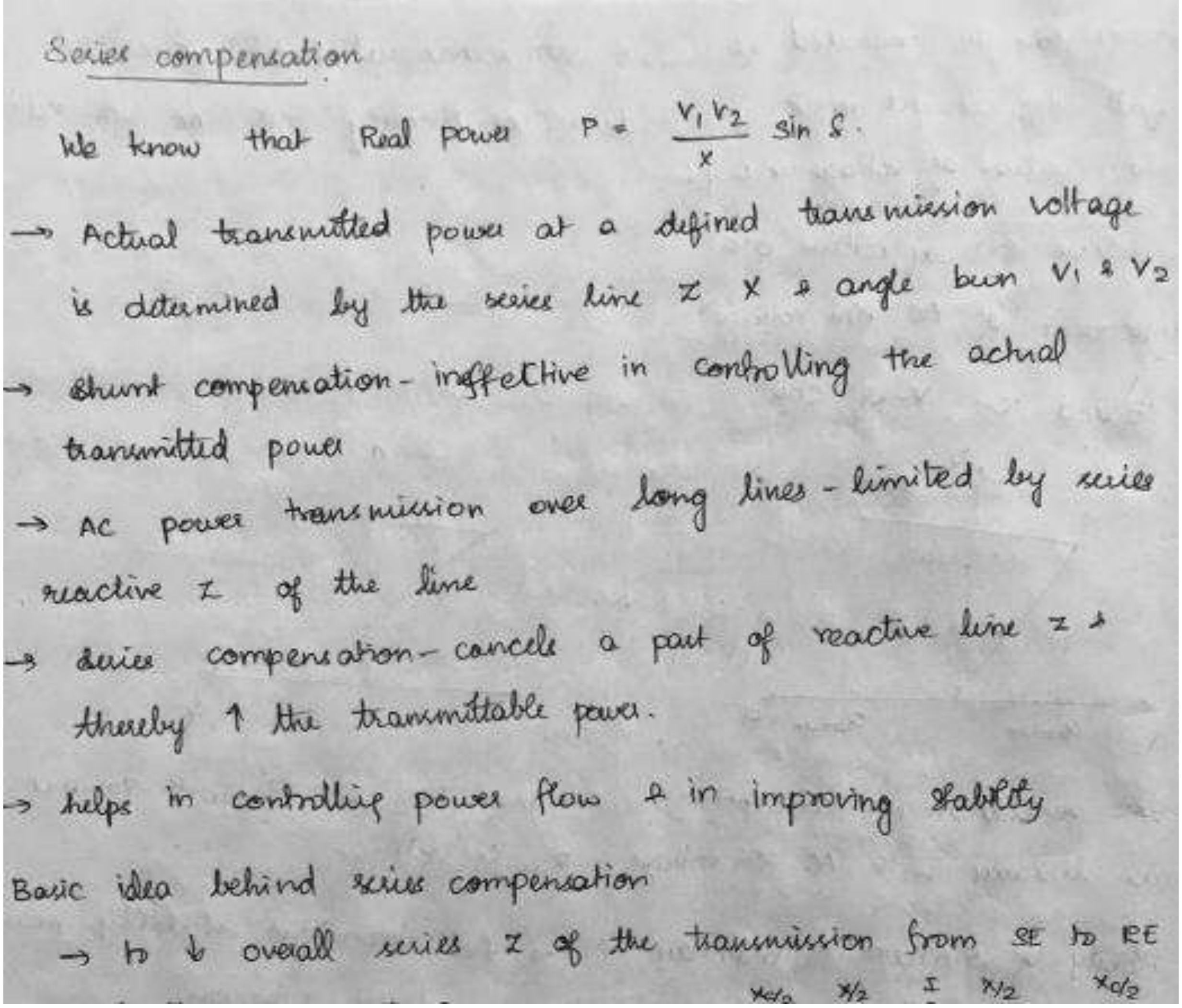
→ SVC - max attainable current decreases linearly with AC s/m voltage

→ max VAR O/P ↓ with square of its voltage

→ less transient stability margin compared to STATCOM

Q control

5a)



Series compensation

We know that Real power $P = \frac{V_1 V_2}{X} \sin \delta$.

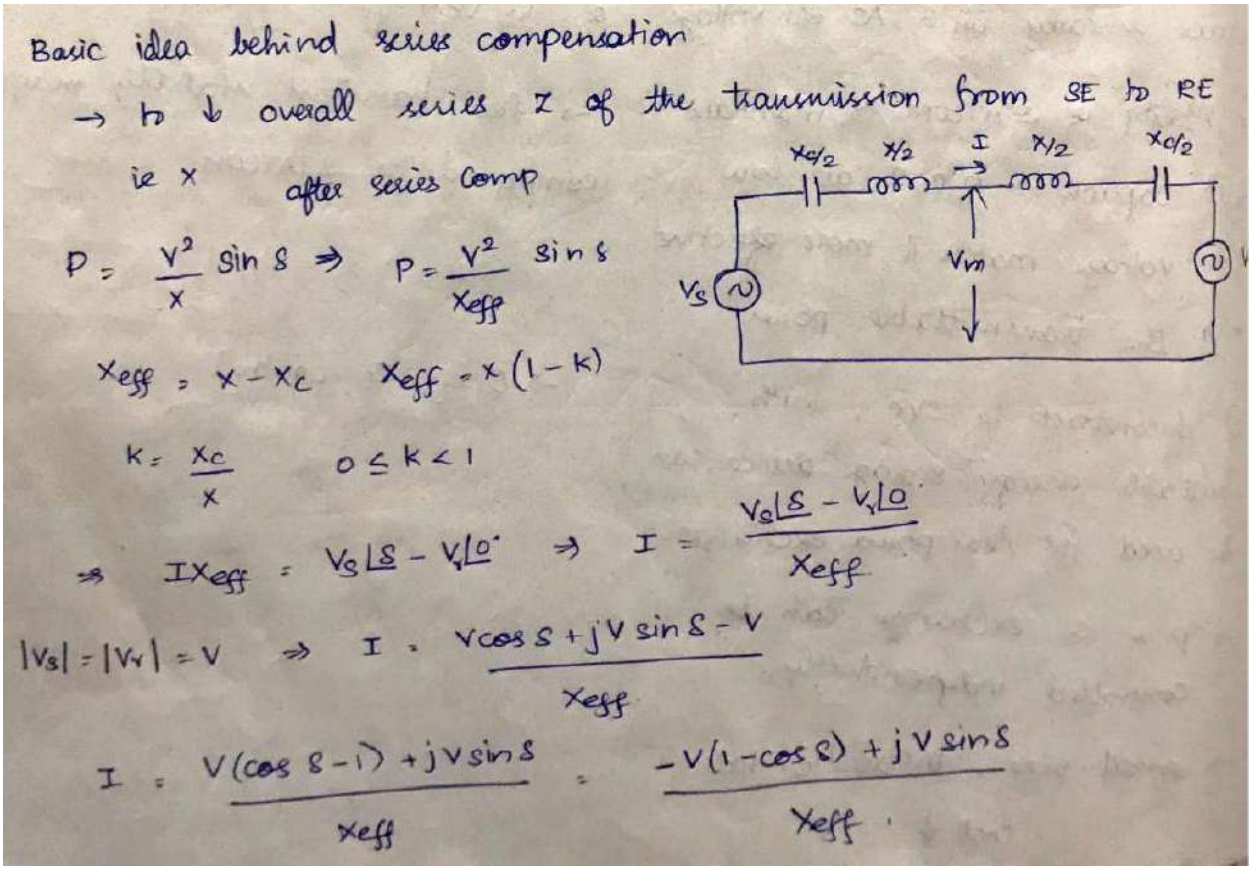
- → Actual transmitted power at a defined transmission voltage is determined by the series line Z X & angle bwn V_1 & V_2
- → Shunt compensation - ineffective in controlling the actual transmitted power
- → AC power transmission over long lines - limited by series reactive Z of the line
- → Series compensation - cancels a part of reactive line Z & thereby ↑ the transmittable power.
- → helps in controlling power flow & in improving stability

Basic idea behind series compensation

→ to ↓ overall series Z of the transmission from SE to RE

$X_c/2$ $X/2$ I $X/2$ $X_c/2$

5b)



Basic idea behind series compensation

→ to ↓ overall series Z of the transmission from SE to RE

ie X after series Comp

$$P = \frac{V^2}{X}\sin\delta \Rightarrow P = \frac{V^2}{X_{eff}}\sin\delta$$

$$X_{eff} = X - X_c \qquad X_{eff} = X(1-k)$$

$$k = \frac{X_c}{X} \qquad 0 \le k < 1$$

$$\Rightarrow I X_{eff} = V_s\angle\delta - V_r\angle 0^\circ \Rightarrow I = \frac{V_s\angle\delta - V_r\angle 0^\circ}{X_{eff}}$$

$$|V_s| = |V_r| = V \Rightarrow I = \frac{V\cos\delta + jV\sin\delta - V}{X_{eff}}$$

$$I = \frac{V(\cos\delta - 1) + jV\sin\delta}{X_{eff}} = \frac{-V(1-\cos\delta) + jV\sin\delta}{X_{eff}}.$$

$$I = \frac{-V \times 2\sin^2 \delta/2 + jV \times 2\sin \delta/2 \cos \delta/2}{x_{eff}}$$

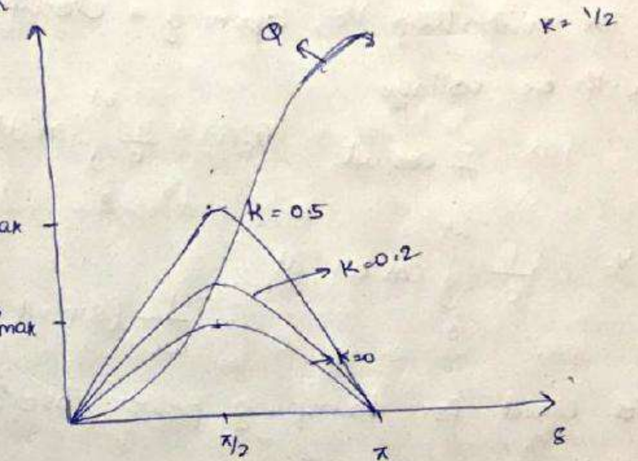
$1 - \cos 2\theta = \sin^2\theta$

$\sin 2\theta = 2\sin\theta\cos\theta$

$$= \frac{2V \sin \delta/2 \left[-\sin \delta/2 + j\cos \delta/2\right]}{x_{eff}}.$$

$$I = \frac{2V \sin \delta/2}{x(1-k)} \qquad Q = I^2 x_c = \frac{4V^2 \sin^2 \delta/2 \times X \times k}{x^2(1-k)^2}$$

$$\therefore \quad Q = \frac{4V^2(1-\cos\delta)}{2x(1-k)^2} \times K = \frac{2V^2(1-\cos\delta)}{x(1-k)^2} \times K.$$



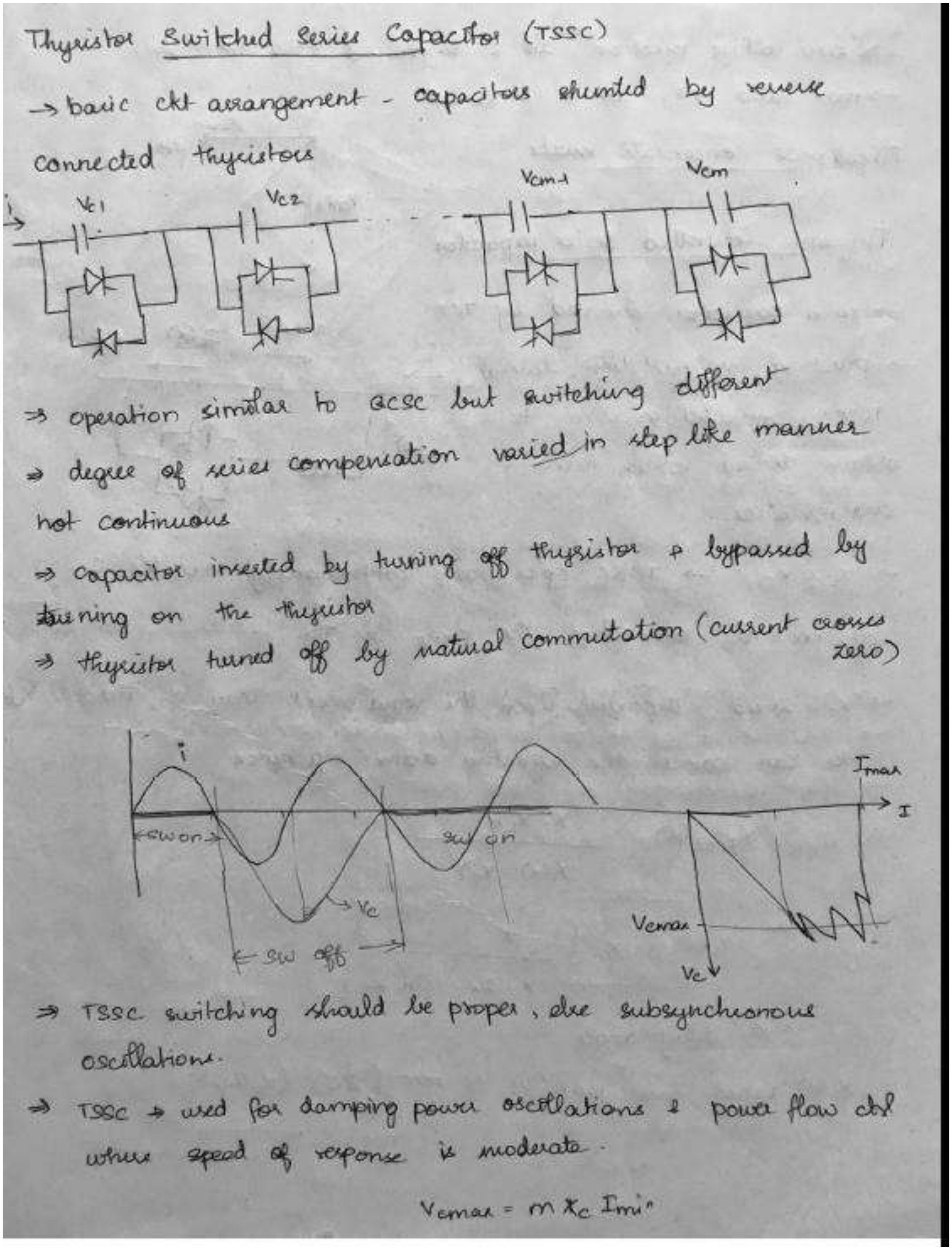
⇒ As expected, transmittable power rapidly ↑ with the degree of series comp (k)

⇒ Q supplied by series apacitor also ↑ sharply with k & varies with δ

Analysis of series comp based on

- Voltage stability
- Improvement of transient stability
- Power oscillation damping.

5c)



Thyristor Switched Series Capacitor (TSSC)

→ basic ckt arrangement - capacitors shunted by reverse connected thyristors

⇒ operation similar to GCSC but switching different

⇒ degree of series compensation varied in step like manner not continuous

⇒ capacitor inserted by turning off thyristor & bypassed by turning on the thyristor

⇒ thyristor turned off by natural commutation (current crosses zero)

⇒ TSSC switching should be proper, else subsynchronous oscillations.

⇒ TSSC → used for damping power oscillations & power flow ctrl where speed of response is moderate.

$$V_{cmax} = m X_c I_{min}$$

6a)

Analysis of series compensation based on

i) voltage stability.

$$P = \frac{V^2}{x_{eff}} \sin \delta \Rightarrow x_{eff} = x - x_c = x(1-k)$$

$$P = \frac{V^2}{x(1-k)} \sin \delta \qquad k = \frac{x_c}{x}$$

$$x_c = 0 \quad k = 0 \quad P = \frac{V^2}{x} \sin \delta$$

$$x = x_c \quad k = 1 \quad P = \frac{V^2}{0} \sin \delta = \infty$$

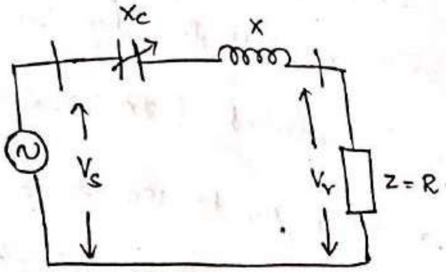
$$x_c = \frac{1}{2} x \quad k = \frac{\frac{1}{2}x}{x} = 0.5$$

$$P = \frac{V^2}{0.5X} \sin \delta = \frac{2V^2}{x} \sin \delta$$

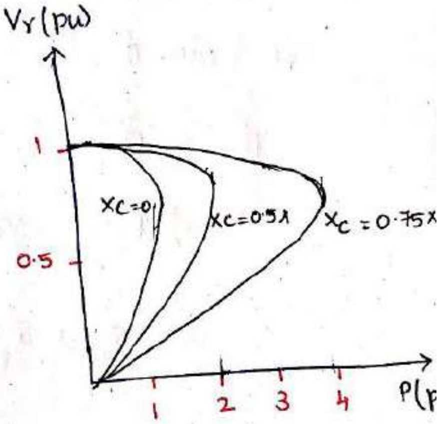
$$x_c = \frac{3}{4} x \Rightarrow k = \frac{\frac{3}{4}x}{x} = 0.75$$

$$P = \frac{V^2}{(1-0.75)x} \sin \delta$$

$$= \frac{V^2}{0.25x} \sin \delta = \frac{4V^2}{x} \sin \delta.$$



→ series capacitive comp. to ↓ series reactive Z to minimise RE voltage variation & possibility of voltage collapse.



⇒ Using both shunt & series capacitive compensation, we can effectively ↑ the voltage stability limit

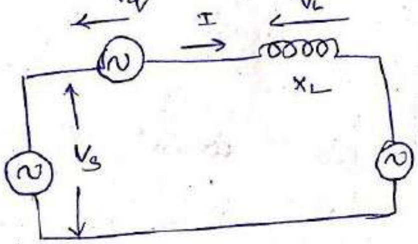
6b)

Static synchronous series capacitor (Converter type series comp)

⇒ An AC voltage source which directly injects the desired comp. voltage in series with the line

⇒ converter - injects directly appropriate voltage at fund. ac 8

$V_q = V_c = -jIX_c = -jkXI$



→ o/p voltage of the synchronous voltage source as a fn. of line I, same compensation as provided by series C is obtained.

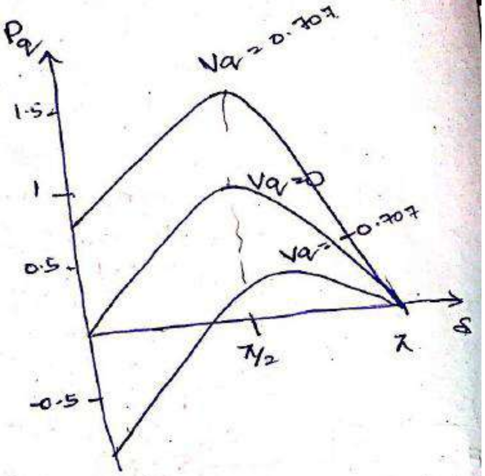
With series C,

$$P = \frac{V^2}{X_{eq}} \sin \delta = \frac{V^2}{X\left(1 - \frac{X_C}{X}\right)} \sin \delta$$

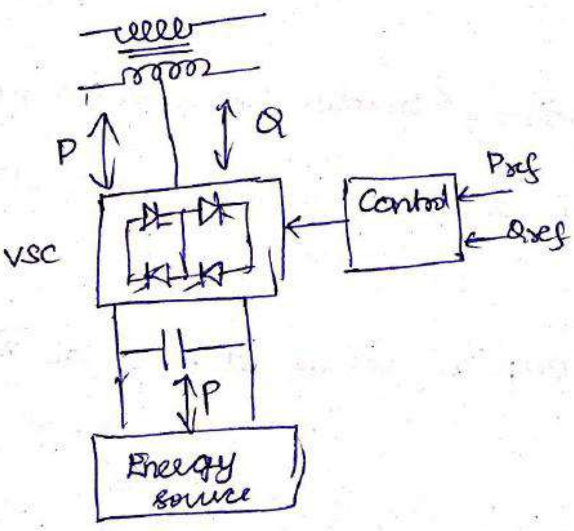
with synchronous voltage src,

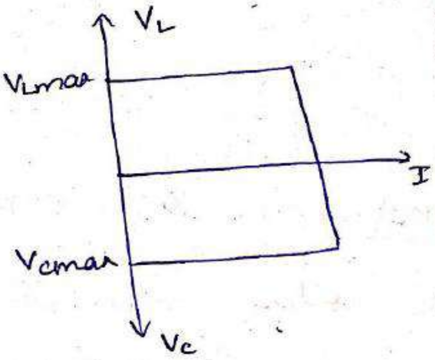
$$P = \frac{V^2}{X\left(1 - \frac{V_q}{I}\right)} \sin \delta$$

$$P_q = \frac{V^2}{X} \sin \delta + \frac{V V_q}{X} \cos(\delta/2)$$



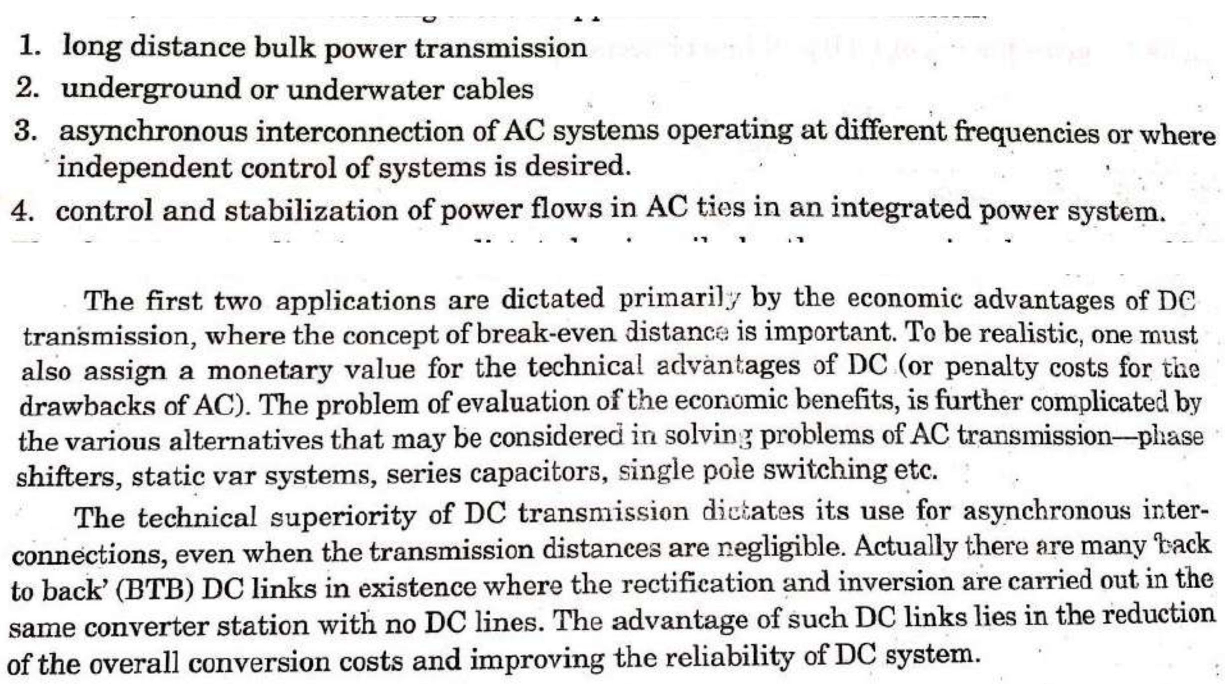
→ It can also exchange Real power with the ac s/m when its dc terminals are connected to a suitable energy source





→ no need P control, $P_{ref} = 0$

7a)

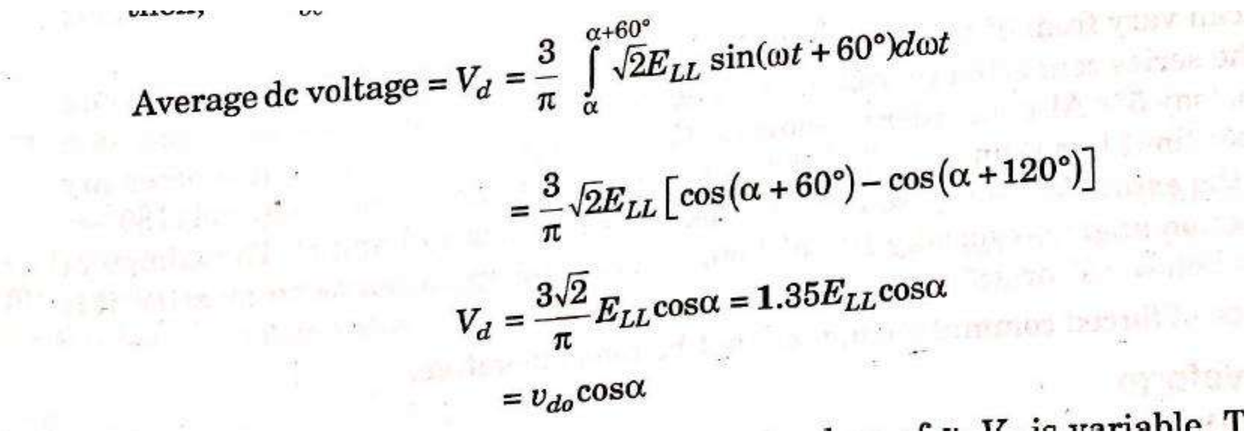


1. long distance bulk power transmission
2. underground or underwater cables
3. asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired.
4. control and stabilization of power flows in AC ties in an integrated power system.

The first two applications are dictated primarily by the economic advantages of DC transmission, where the concept of break-even distance is important. To be realistic, one must also assign a monetary value for the technical advantages of DC (or penalty costs for the drawbacks of AC). The problem of evaluation of the economic benefits, is further complicated by the various alternatives that may be considered in solving problems of AC transmission—phase shifters, static var systems, series capacitors, single pole switching etc.

The technical superiority of DC transmission dictates its use for asynchronous interconnections, even when the transmission distances are negligible. Actually there are many 'back to back' (BTB) DC links in existence where the rectification and inversion are carried out in the same converter station with no DC lines. The advantage of such DC links lies in the reduction of the overall conversion costs and improving the reliability of DC system.

7b)



$$\text{Average dc voltage} = V_d = \frac{3}{\pi}\int_{\alpha}^{\alpha+60^\circ}\sqrt{2}E_{LL}\sin(\omega t+60^\circ)d\omega t$$

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

$$V_d = \frac{3\sqrt{2}}{\pi}E_{LL}\cos\alpha = 1.35E_{LL}\cos\alpha$$

$$= v_{do}\cos\alpha$$

6 pulse converter

⇒ converts ac into dc

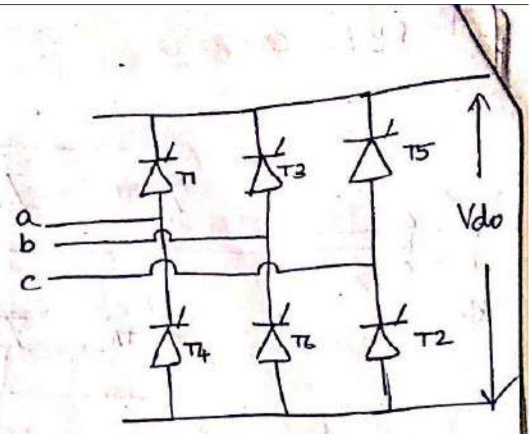
⇒ $V_{an} = V_m \sin \omega t \quad V_{bn} = V_m \sin(\omega t - 120°)$

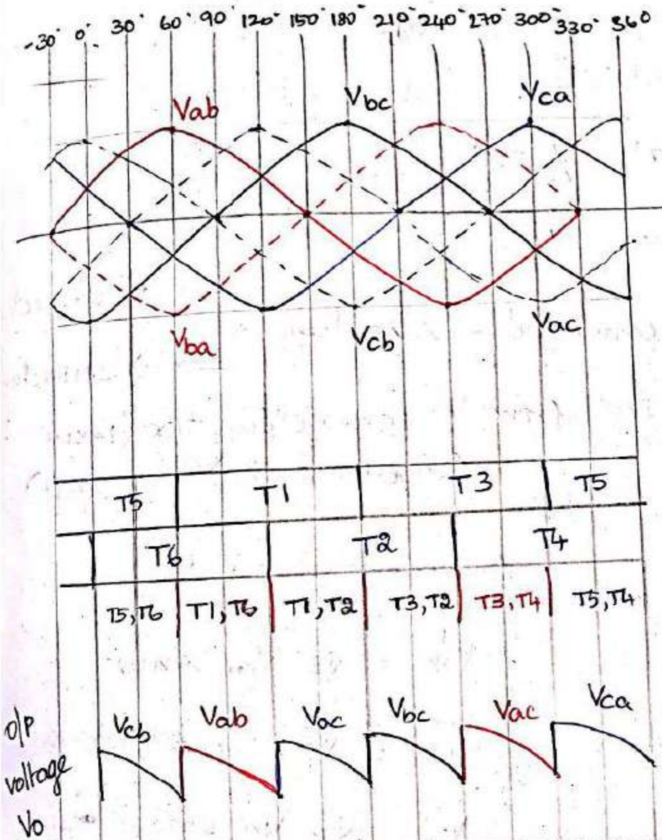
$V_{cn} = V_m \sin(\omega t - 240°)$

$\therefore \quad V_{ab} = \sqrt{3} V_m \sin(\omega t + 30°)$

$V_{bc} = \sqrt{3} V_m \sin(\omega t - 90°)$

$V_{ca} = \sqrt{3} V_m \sin(\omega t + 150°)$





⇒ i/p AC line voltage waveform

ωt $\quad V_{ba} = -V_{ab}$

⇒ each thyristor conducts for 120°

$\alpha = 30°$ ⇒ Thyristors are fired at 60° interval.

⇒ $\omega t = 30° + \alpha$

⇒ when $\alpha = 30°$, T1 starts conducting at 60°, After 60° interval, at 120°, T

starts conducting.

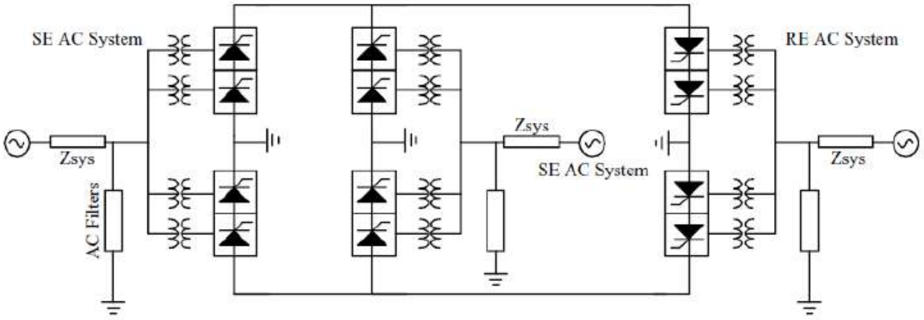
ωt

$$V_o = \frac{6}{2\pi} \int_{\pi/6+\alpha}^{\pi/2+\alpha} \sqrt{3} V_m \sin(\omega t + 30°)$$

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

7c)

HVDC Multi-Terminal. This refers to an HVDC system that consists of three or more transforming stations. Its architecture is more complex compared to that of a two terminal point-to-point system. It requires a significant complexity to facilitate communication and control between each transforming station. However, it is considered to be a relatively new technology and has potential for a wide range of applications in the future. There are two types of multi-terminal links – a parallel or serial type, as shown in Figure 1.18.



(c)

Figure 1.18 HVDC multi-terminal.

8a) Any two HVDC Links with neat diagram

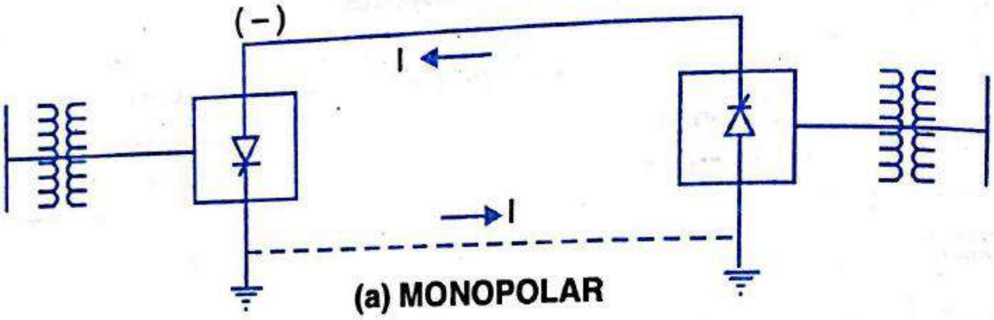
1.4.1 Types of DC Links

The DC links are classified into three types which are defined below:

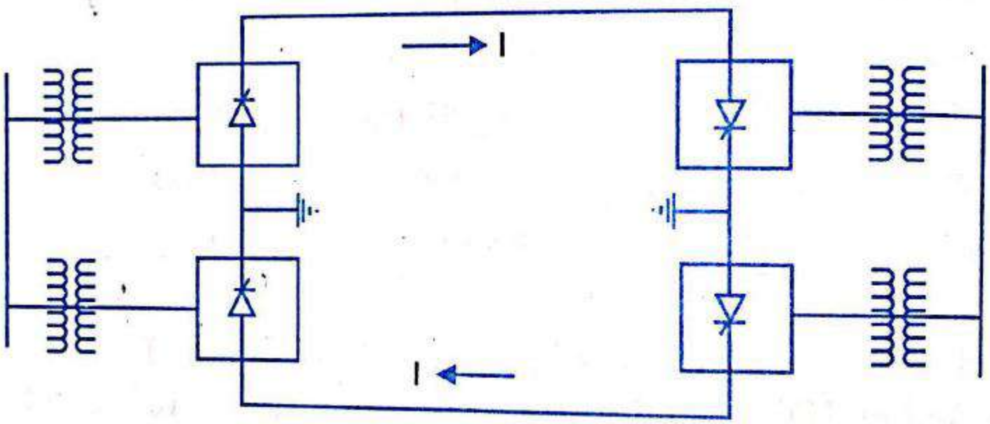
1. Monopolar link (see Fig. 1.4 (a)) has one conductor usually of negative polarity and use ground or sea return. Sometimes metallic return is also used.
2. Bipolar link (see Fig. 1.4 (b)) has two conductors, one positive and the other negative. Each may be a bundled conductor in EHV lines. Each terminal has two sets of converters of identical ratings, connected in series on the DC side. The junction between the two sets of converters is grounded at one or both ends. Normally, both poles operate at equal currents and hence there is zero ground current flowing under these conditions.
3. Homopolar Link (see Fig. 1.4(c)) has two or more conductors all having the same polarity (usually negative) and always operated with ground or metallic return.

Because of the desirability of operating a DC link without ground return, bipolar links are most commonly used. Homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages. Incidentally, the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity.

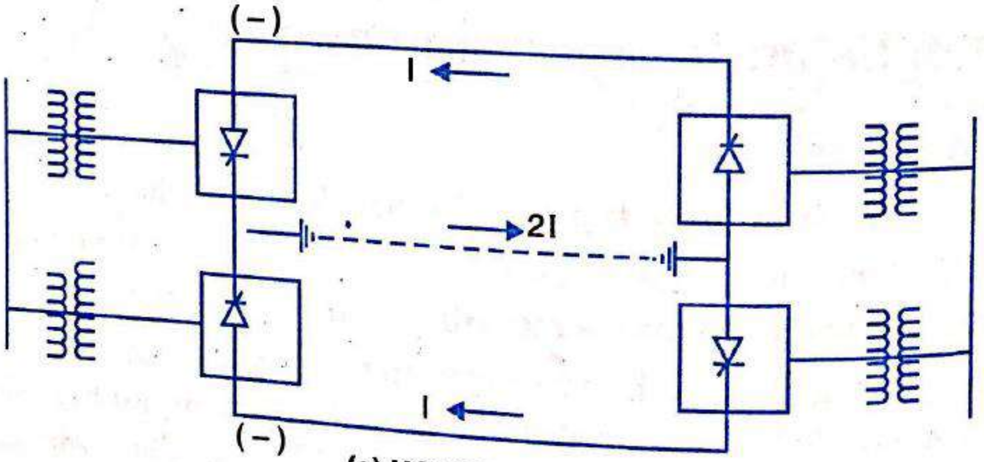
The monopolar operation is used in the first stage of the development of a bipolar line, as the investments on converters can be deferred until the growth of load which requires bipolar operation at double the capacity of a monopolar link.



(a) MONOPOLAR



(b) BIPOLAR



(c) HOMOPOLAR

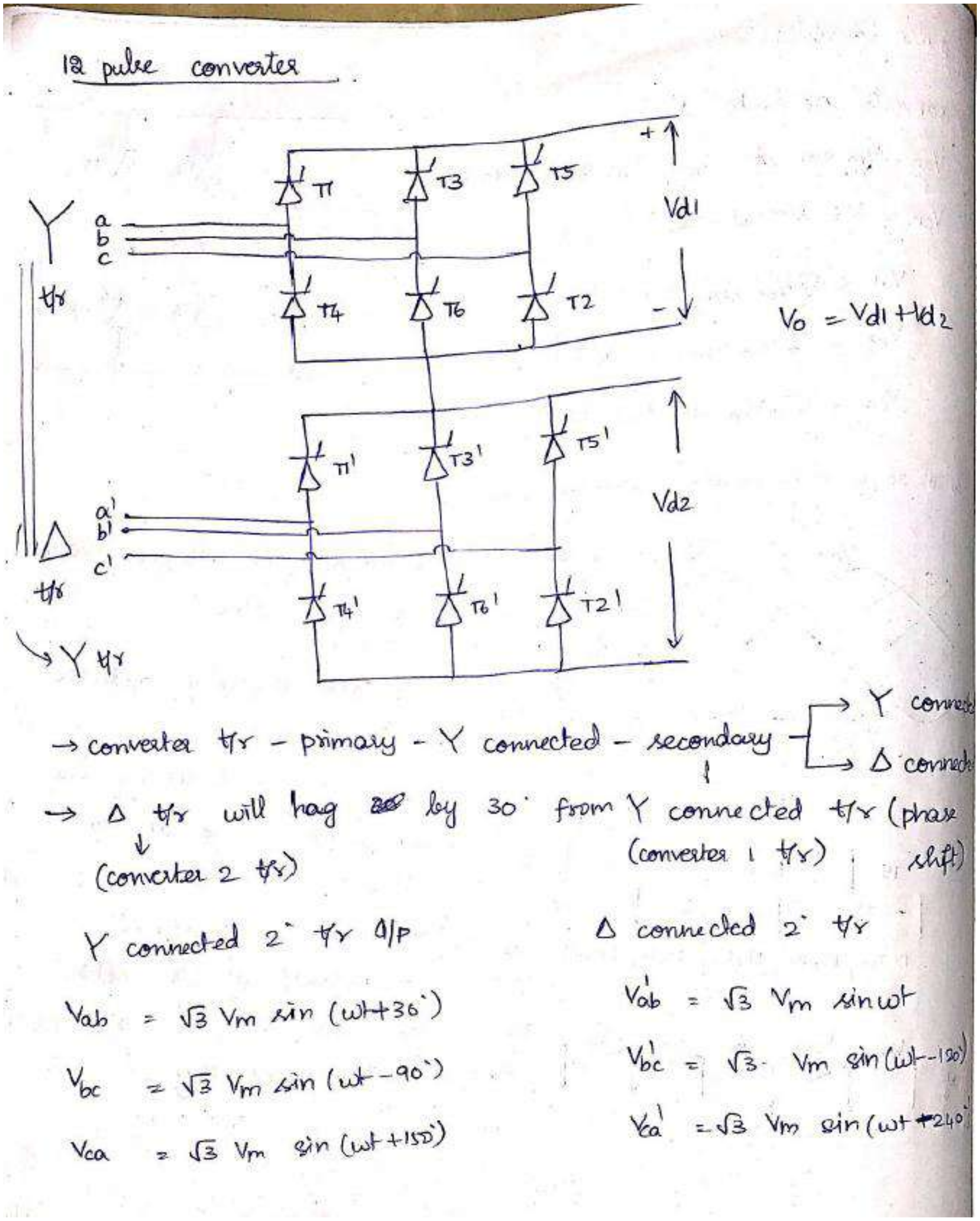
8b)

1.3 APPLICATION OF DC TRANSMISSION

The detailed comparison of AC and DC transmission in terms of economics and technical performance, leads to the following areas of application for DC transmission:

1. long distance bulk power transmission
2. underground or underwater cables
3. asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired.
4. control and stabilization of power flows in AC ties in an integrated power system.

8c)



12 pulse converter

$V_o = V_{d1} + V_{d2}$

→ converter t/r - primary - Y connected - secondary → Y connected / → Δ connected

→ Δ t/r will lag by 30° from Y connected t/r (phase shift)
(converter 2 t/r) (converter 1 t/r)

Y connected 2° t/r O/P

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

$V_{bc} = \sqrt{3} V_m \sin(\omega t - 90°)$

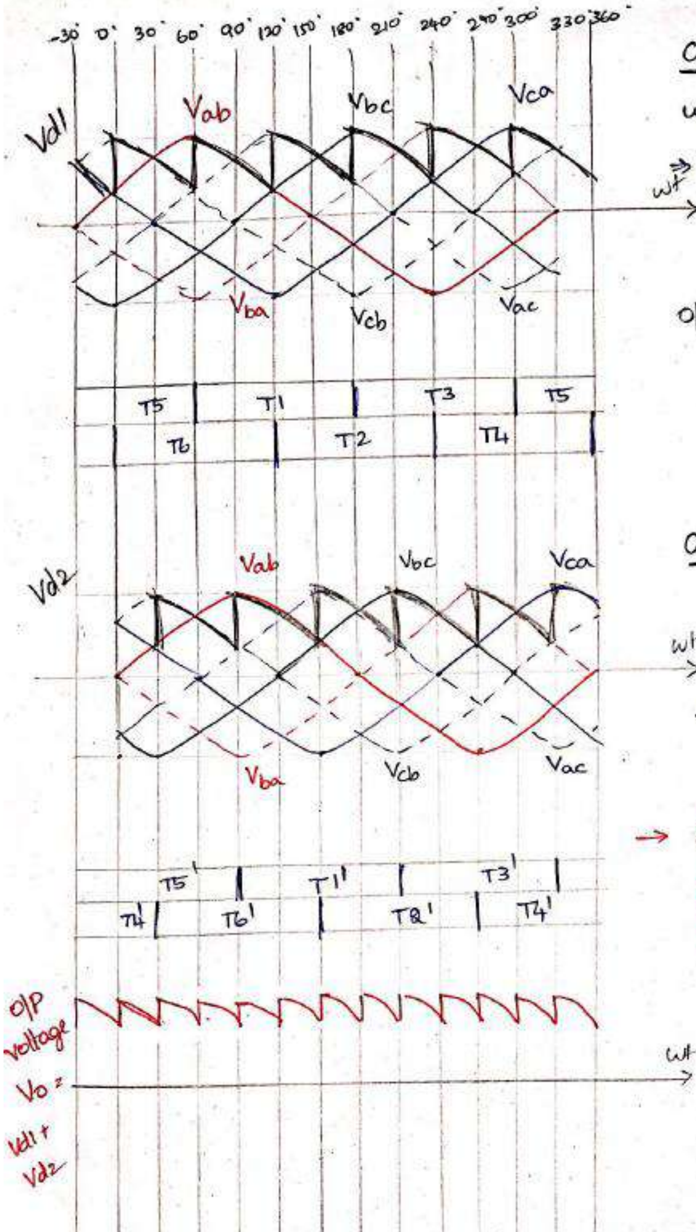
$V_{ca} = \sqrt{3} V_m \sin(\omega t + 150°)$

Δ connected 2° t/r

$V'_{ab} = \sqrt{3} V_m \sin \omega t$

$V'_{bc} = \sqrt{3} V_m \sin(\omega t - 120°)$

$V'_{ca} = \sqrt{3} V_m \sin(\omega t + 240°)$



Converter 1. $\alpha = 30°$

$\omega t = 30° + \alpha$

⇒ T1 starts conducting at 60°

⇒ each Thyristor conducts for 120°

O/P voltage drawn in pencil

Converter 2. (phase shift = 30°)

$\omega t = 30° + ps + \alpha$

$= 60° + \alpha$

→ T1' starts at 90°

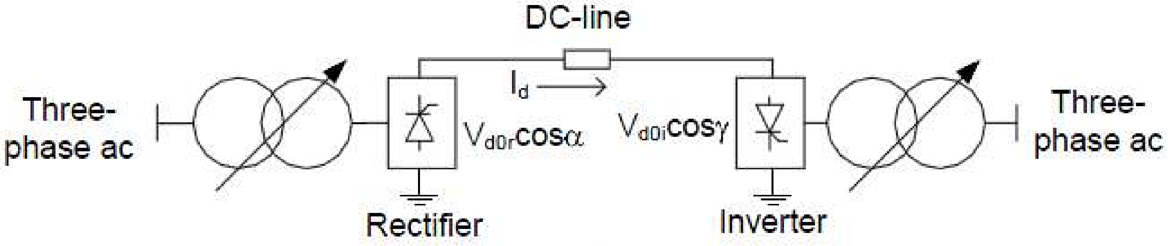
→ At any instant, 2 thyristors from converter 1 & 2 from converter 2 will operate.

→ In o/p voltage, 5th & 7th harmonics are removed

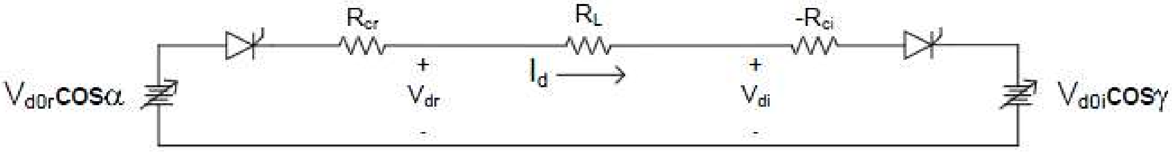
9a)

(a) Symmetry of valve turn-on angles during steady state operation.
(b) Ability to determine the turn-on angle using the commutation voltage and margin minimum reactive power consumption by the converter without incurring commutation failure.
(c) Insensitivity to the variations in voltage and frequency of the AC transmission system.
(d) Ability to predict the optimal turn-on time based on the actual system voltage and the DC current without causing commutation failure.
(e) Current control scheme with a sufficient margin of speed and stability to handle either a change in the reference value or a disturbance.

9b)



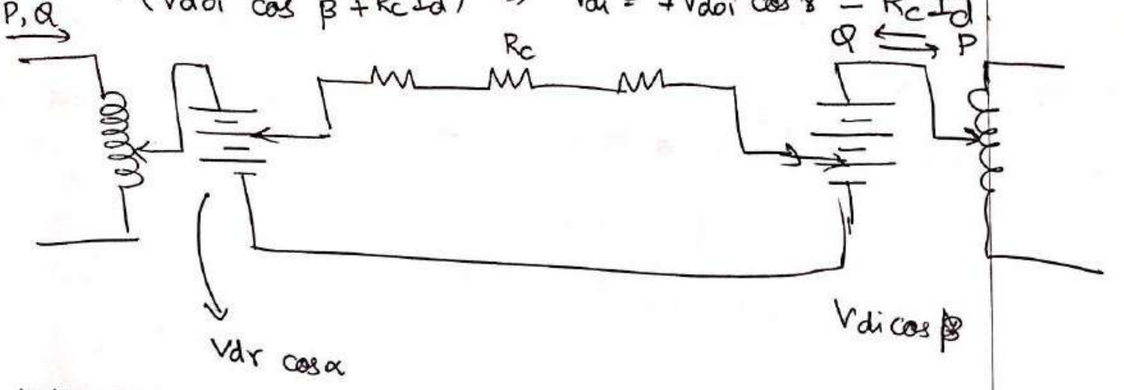
(a)



(b)

$V_{dr} = V_{dor} \cos\alpha + R_c I_d$. $\beta = \pi - \alpha$

$V_{di} = +(V_{doi} \cos\beta + R_c I_d) \Rightarrow V_{di} = +V_{doi} \cos\gamma - R_c I_d$



Extinction angle (γ) → angle b/wn the end of the connection & reversal of voltage.

→ Power reversal ⇒ no Δ in $\rightleftharpoons$ of I but only V.

Constant current control

→ during abnormal condn, I should not exceed too much.

$P_d\uparrow = V_d\uparrow I_d$ ⇒ fault ⇒ no DC ckt breaker ⇒ so adjust α, bring V to 0, thereby I ⇒ 0.

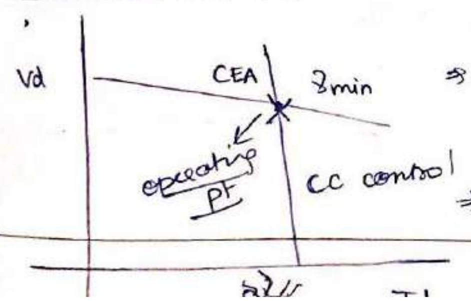
→ const V ⇒ fault ⇒ more fault I

$$I_d = \frac{V_{dr} \cos\alpha - V_{do} \cos\gamma}{R_{cr} + R_c - R_{ci}}$$

AC s/m ⇒ const V control

DC s/m ⇒ const I control.

Constant EA control ⇒ Rectifier side voltage varied by α (or) tap changing t/r (TCR)



⇒ α too much cannot vary so go for TCR

⇒ γ min ⇒ too much vary Pf will worsen then go for Vdoi

9c)

4.2 Commutation Failure

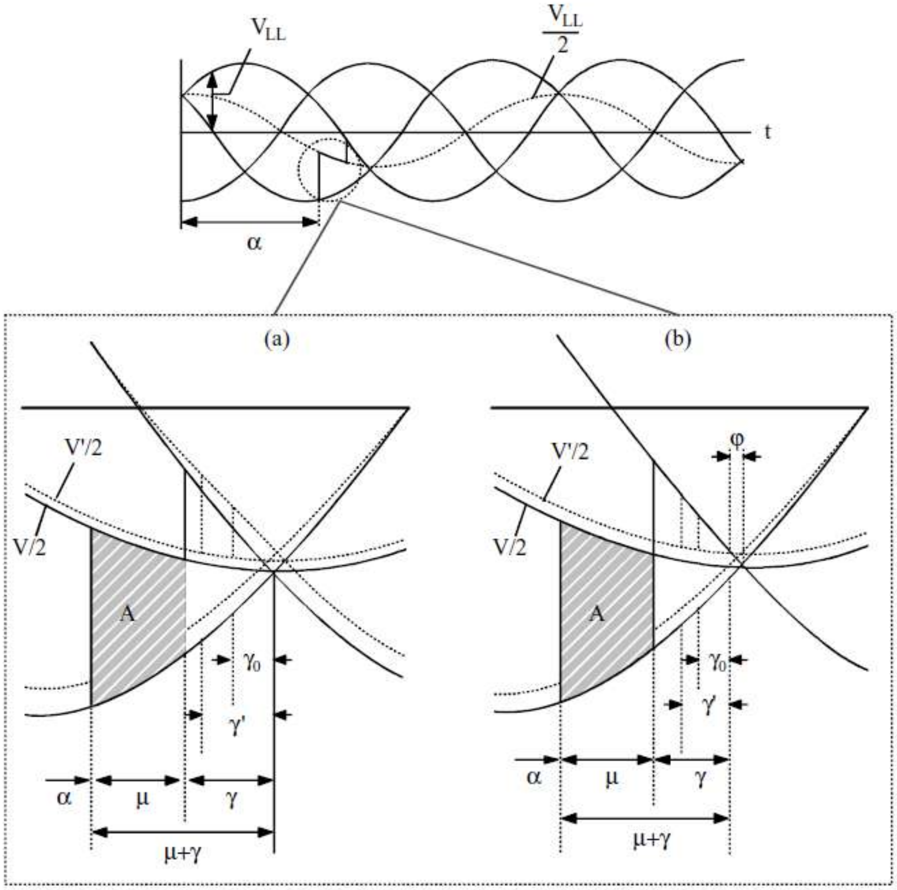
Commutation failure is an unavoidable problem in any type of DC power transmission system using thyristors. The commutation failure causes many problems to the valves, the reactive power of HVDC systems as well as the operation of the protective relays and so on. So, it should be investigated thoroughly before the system is designed. A thyristor is a device that has turn-on capability, but no turn-off capability. The only way to turn it off is to apply a reverse voltage to it.

Commutation Failure in 3-Phase Ground Fault. Figure 4.15 shows the inverter commutation process and the effect of a sudden commutation voltage reduction. The voltage-time domain, ‘A’ shown in Figure 4.15 is given as follows ($\alpha + \mu = 180° - \gamma$):

$$A = \int_{\alpha}^{\alpha+\mu} \frac{\sqrt{2}E}{2} \sin(\omega t) d\omega t \quad = \frac{\sqrt{2}E}{2} \left[-\cos(\omega t)_{\alpha}^{\alpha=\mu} \right.$$

$$= \frac{\sqrt{2}E}{2} [\cos(\alpha) - \cos(\alpha+\mu)] \quad = \frac{E}{\sqrt{2}} (\cos\alpha + \cos\gamma) \tag{4.12}$$

If the 3-phase commutation voltages were suddenly and symmetrically to decrease, the voltage–time area for the commutation margin which is fixed, cannot be fulfilled. It means



(a) (b)

Figure 4.15 Change in turn-off angle of a thyristor due to the decreased commutation voltage of the inverter: (a) 3-phase fault; (b) single-phase fault.

that the end of commutation will extend into the time period of the normal commutation margin:

$$\frac{E}{\sqrt{2}}(\cos\alpha+\cos\gamma)=\frac{E'}{\sqrt{2}}(\cos\alpha+\cos\gamma'),\quad \frac{E'}{E}=\frac{\cos\alpha+\cos\gamma}{\cos\alpha+\cos\gamma'} \tag{4.13}$$

where E' is the new commutation voltage after the commutation voltage reduction and γ' is the new turn-off angle after the commutation voltage reduction

Basically, Equation 4.13 determines the critical turn-off time and the reduced commutation voltage (E'/E) when a commutation failure occurs. If the current increases and the firing angle remains constant when commutation failure occurs, the basic equations for the current can be derived as follows:

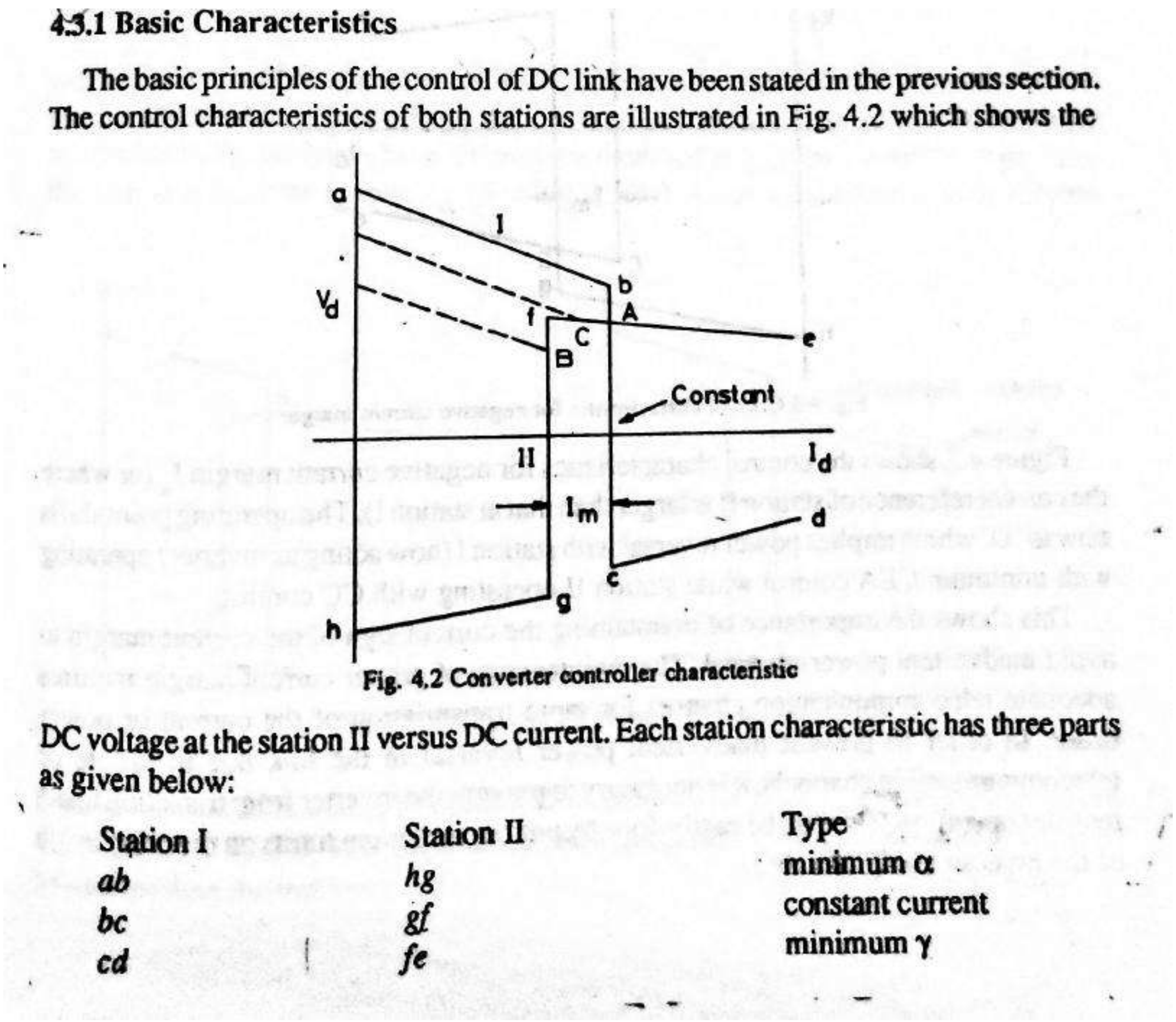
$$\begin{aligned} I_d &= \frac{E}{\sqrt{2}X_c}[\cos\alpha-\cos(\alpha+\mu)] \\ I_d &= \frac{E}{\sqrt{2}X_c}[\cos\alpha+\cos\gamma] \end{aligned} \tag{4.14}$$

where $X_C =$ commutation inductance and $\alpha+\mu=\pi-\gamma$.

If the DC current remains the same while the voltage decreases, then Equation 4.14 can be rewritten as follows:

$$I_d=\frac{E'}{\sqrt{2}X_c}(\cos\alpha+\cos\gamma') \tag{4.15}$$

10a)



4.3.1 Basic Characteristics

The basic principles of the control of DC link have been stated in the previous section. The control characteristics of both stations are illustrated in Fig. 4.2 which shows the

Fig. 4.2 Converter controller characteristic

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

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

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

There can be three modes of operation of the link (for the same direction of power flow) depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics. These are defined below :

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

The characteristic *ab* has, generally, more negative slope than characteristic *fe* for similar values of R_{cr} and R_{ci}. This is because of the fact that the slope of *ab* is due to the combined resistance $(R_d + R_{cr})$ while the slope of *fe* is due to R_{ci}. However, for low SCR at the inverter, the slope of *fe* could be more negative than that of *ab*.

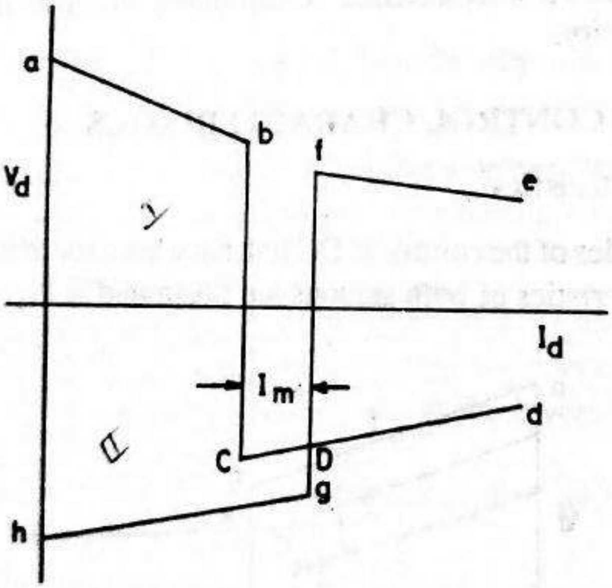


Fig. 4.3 Control characteristic for negative current margin

Figure 4.3 shows the control characteristics for negative current margin I_m (or where the current reference of station II is larger than that at station I). The operating point shifts now to 'D' which implies power reversal with station I (now acting as inverter) operating with minimum CEA control while station II operating with CC control.

This shows the importance of maintaining the correct sign of the current margin to avoid inadvertent power reversal. The maintenance of proper current margin requires adequate telecommunication channel for rapid transmission of the current or power order. In order to prevent inadvertent power reversal in the link 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 minimum limits on the delay angle of the inverter (100° to 110°).

10b)

4.4 HVDC Control Functions

Figure 4.32 shows the control system block diagram of a conventional HVDC system and Figure 4.33 shows the major components of an HVDC terminal and their allocation to converter group, terminal pole and HVDC terminal. According to this organization, it is possible to arrange the various control functions according to the actuator elements used.

Therefore, an HVDC system consists of a master control, pole control and phase control. Control functions which use the major variables of the HVDC system – DC current or DC voltage – as control variables can also be assigned to a higher system level. Their hardware implementation is, however, always assigned to the control devices used in the terminal. For example, current control of an HVDC terminal with two converter groups per pole connected in series is hierarchically assigned to the pole level (upper half of Figure 4.33) but to the group level in an HVDC station with two parallel converter groups per pole (lower half of Figure 4.33).

Hierarchically, the master control is the uppermost control in the HVDC system, and it determines the filter switching mode for reactive control, the frequency control and the dynamic control of an AC network (Figure 4.34).

The pole control receives the signal for the control mode and power transfer direction from the master control, which sends the corresponding control signal to the phase control. The pole control includes the current control, voltage control and power control.

The phase control, which controls the converter of the HVDC, generates the control angle α. The function of the trigger device is to convert the control angle into the twelve trigger pulses for a 12-pulse converter group.

10c)

4.5 Reactive Power and Voltage Stability

Voltage Stability and PowerTransferLimits of AC Lines. Figure 4.37 is a simplified representation of a long AC line system having substantial effective series reactance from remote generation to the load point; the line shunt capacitance effects are taken into account simply by the equivalent reactance shown. Normal operation of the system, without any outages, does not usually produce major problems with control, or maintenance of a rated voltage of 1.0 pu with varying loads because of the availability of var supply from local generation and also lead power factor correction capacitors. The transmission system is then designed to have adequate steady-state and transient stability margins to maintain synchronism between the remote and local generation, using series capacitor compensation and power system stabilizers if necessary.

Normal design practices for security of supply require consideration of outage conditions, for example, on one of the lines under maintenance (meaning the so-called (*n*–1) condition). If during such an outage, a severe fault condition arises which resulted in loss of all, or a large part of, local generation, the maintenance of voltage stability at the loads becomes a major design and operational consideration since the remaining transmission circuit may be incapable of carrying the full load requirements.

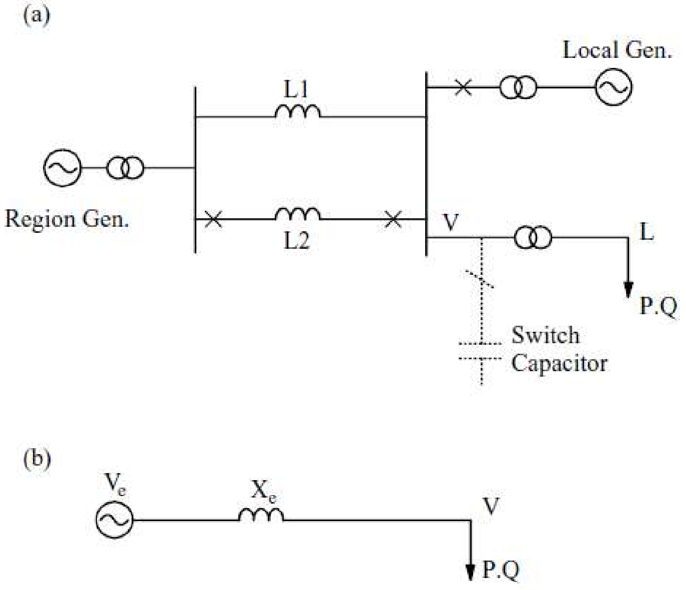


Figure 4.37 (a) Simplified AC transmission system and (b) its Thevenin equivalent circuit.

Reactive Compensator. The reactive power compensating device in an HVDC system adopts a capacitor bank to achieve an economical efficiency and a prompt response time. However, as the load increases, turning on/off the capacitor with a hysteresis switch causes the instantaneous AC voltage to be irregular and it performs reactive power compensation with discrete values rather than with continuous values. Such an operation has no significant impact to a high-SCR system but in a smaller system, it forces the AC voltage to be significantly unbalanced. Thus, instantaneous reactive power compensation devices are indispensable for such a low-SCR system.

Secondly, when a disturbance such as HVDC power interruption or line-ground fault occurs in the AC side of an HVDC system being operated normally, the problem of overvoltages is created. Since the HVDC system may not be able to function, the overall AC active power will be decreased compared to the normal condition. However, the operating sequence of the capacitor is larger than the time required for the above mentioned disturbance to occur. In general, the AC voltage increases by a factor of 1.5–2 pu. At this time, the reactive power compensation device should absorb the reactive power at a much higher rate in order to decrease the overvoltage in the AC system.