ANNAMACHARYA UNIVERSITY

(ESTD UNDER AP PRIVATE UNIVERSITIES (ESTABLISHMENT AND REGULATION) ACT, 2016

New Boyanapalli, Rajampet,
Annamayya (Dist), Andhra Pradesh – 516 126

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Course: HVDC & FACTS

Course Code: 20A27BT

Branch: Electrical & Electronics Engineering

Prepared by: Dr.O.Hemakesavulu

Designation: Professor

Department: Electrical & Electronics Engineering

ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES RAJAMPET
(An Autonomous Institution)
Department of Electrical and Electronics Engineering

Title of the Course	HVDC & FACTS
Category	PEC
Couse Code	20A27BT
Year	IV
Semester	I
Branch	EEE

Lecture Hours	Tutorial Hours	Practice Hours	Credits
3	-	-	3

Course Objectives:

- To introduce the concept of HVDC Transmission system and FACTS.
- To familiarize with operation of HVDC converters and their control.
- To distinguish series & shunt compensation.

Unit 1 Introduction 10

Comparison of AC and DC Transmission systems, Applications of D.C. Transmission, Types of DC links, Typical layout of a HVDC converter station. HVDC converters, Analysis of 3-phase Bridge circuit with and without overlap.

Learning Outcomes: At the end of the unit, the student will be able to:

- Compare HVDC & AC Transmission(L4)
- List the applications of D.C Transmission.(L1)

Unit 2 Converter and HVDC Control 10

Principle of DC link control, Converter control characteristics, System control Hierarchy, Firing angle control, Current and Extinction Angle control.

Harmonics, Filters and Sources of Reactive Power:

Introduction of Harmonics, Generation of Harmonics, AC and DC Filters, Sources of Reactive power.

Modeling of DC/AC converters, Converter controller equations, Solutions of AC/DC load flow- Simultaneous approach and Sequential approach

Learning Outcomes: At the end of the unit, the student will be able to:

- Explain the Principle of DC Link control(L2)
- Identify the various filters for elimination of Harmonics.(L2)

Unit 3 Introduction to FACTS Concepts 08

FACTS concepts, Flow of power in AC parallel paths and meshed systems, Basic types of FACTS controllers, Brief description and Definitions of FACTS controllers.

Learning Outcomes: At the end of the unit, the student will be able to:

- Analyze the flow of power in AC parallel paths(L4)
- Explain about the basic types of FACTS controllers(L2)

Unit 4 Static Shunt & Series Compensators 10

Objectives of shunt compensation, Methods of controllable VAR generation, Static VAR compensators, SVC and STATCOM comparison. Objectives of series compensation, Variable impedance type- Thyristor Switched Series Capacitors (TSSC), and Switching Converter type Series Compensators – Static Series Synchronous Compensator (SSSC)

Learning Outcomes: At the end of the unit, the student will be able to:

- Explain the objectives of series & shunt compensation (L2)
- Distinguish series & shunt compensators (L2)

Unit 5 Combined Compensators 10

Unified power flow controller (UPFC), Basic operating principle, Independent real and reactive power flow controller.

Learning Outcomes: At the end of the unit, the student will be able to:

- Explain the operation and principle of UPFC.(L2)
- Analyze the concept of independent real and reactive power flow control in UPFC.(L4)

Prescribed Text Books:

1. Padiyar, K.R., ‘HVDC transmission systems’, Wiley Eastern Ltd., 2010.
2. Hingorani ,L.Gyugyi, ‘Concepts and Technology of Flexible AC Transmission System’, IEEE Press New York, 2000 ISBN –078033 4588.

Reference Books:

1. Padiyar K.R., ‘FACTS controllers for Transmission and Distribution systems’ New Age International Publishers, 1st Edition, 2007.
2. Mohan Mathur R. and Rajiv K.Varma , ‘Thyristor – based FACTS controllers for Electrical Transmission systems’, IEEE press, Wiley Inter science , 2002.

Web Resources:

1. http://www.nptelvideos.in/2012/11/high-voltage-dc-transmission.html
2. http://nptel.ac.in/courses/108104013/
3. https://nptel.ac.in/courses/108/107/108107114/

Course Outcomes: Blooms Level of Learning

At the end of the course, the student will be able to

1.	Analyze the Economical & Technical aspects of AC & DC Transmission	L4
2.	Analyze the Converter control characteristics & Filters for harmonics elimination.	L4
3.	Identify the basic types of FACTS controllers	L4
4.	Distinguish series and shunt compensation	L1
5.	Analyze the operation of Unified Power Flow Controller (UPFC) with independent real and reactive power flow control	L4

CO-PO Mapping:

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2
20A27BT.1	3	3	-	-	-	-	-	-	-	-	-	-	3	-
20A27BT.2	3	3	-	3	-	-	-	-	-	-	-	-	3	-
20A27BT.3	3	3	3	3	3	-	-	-	-	-	-	-	-	3
20A27BT.4	3	3	3	3	3	-	-	-	-	-	-	-	-	3
20A27BT.5	3	2	3	1	1	-	-	-	-	-	-	-	-	1

HVDC → High voltage Direct current tr
FACTS → Flexible AC Tr. systems
AC → Generation → Tr → Distribution → AC (AC tr)
(or)
utilization

$\underbrace{AC - DC}_{R} - \underbrace{AC}_{I}$ → HVDC tr.

Why HVDC ?
For long distance bulk power tr we use HVDC.

Unit 1 : Introduction

Comparision of AC & DC tr :-

1. Economic of tr.
2. Technical performance
3. Reliability

1. **Economics of tr:-**

⇒ Economics of tr is cost of tr.
→ cost of tr is of 2 types.

Investment of cost
↓
It is the cost of conductors, insulators, terminal equipment.

Operational cost
↓
It is the losses

*) No.of conductors req. for AC is 3 while DC requires 2 conductors. so DC requires less conductors
*) No. of insulators requires for AC is 3 and DC requires 2. so, no.of insulators in DC are less.
*) A Two conductor DC line can carry as much power as three conductor AC line when provided with same conductor size and insulation level.

$\boxed{I_d = I_a}$, I_d = DC current
I_a = AC current

Losses in DC = $2 I_d^2 R$

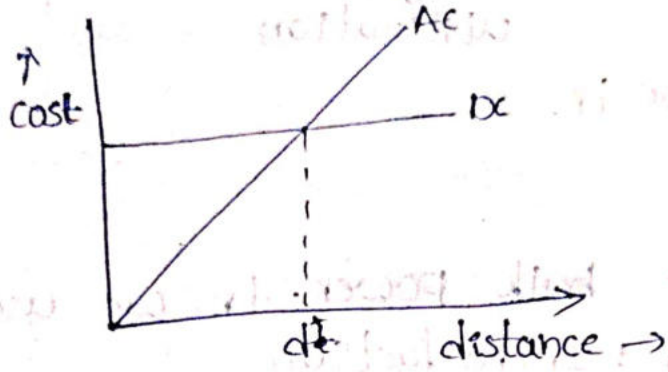
losses in AC = $3 I_a^2 R$

$$3 I_a^2 R > 2 I_d^2 R$$

Hence losses in DC are less compared with AC

*) Skin effect & corona are present in AC tr. Line and are absent in DC Line.

Cost Vs Distance graph:-



d^* → Break even distance

*) In the above graph, DC is

*) AC is economical upto break even distances (d^*)

*) AC is costlier for Long distance while DC Cost is less for long distance.

*) Hence DC is more feasible as it remains same for short /Long distances.

*) d^* → 500 ~ 800 kms for overhead Lines
48 ~ 96 kms for underground cables
24 ~ 48 kms → submarine

*) Beyond these distances (or beyond d^*) DC is economical. upto d^*. AC is economical. So, HVDC is used for long distance bulk power tr.

Terminal Equipment :-

AC	DC
*) Terminal equipment req. in AC is transformers.	*) Terminal equipment is req. in DC Line are: → Converters { Rectifiers (AC-DC), Inverters (DC-AC) → Filters
* Less cost	* costlier (as it requires filters to remove harmonics)

{ Comparision
Types of DC Links
Applications } or { Typesical Layput
3-ø bridge }

** 2) <u>Technical Performance</u> :-

DC tr. has the following advantages over AC tr

1) full control over the power transmitter.
2) The stability to enhance Dynamic & transient state stability in associated AC networks.
3) fast control to limit fault currents in DC lines.

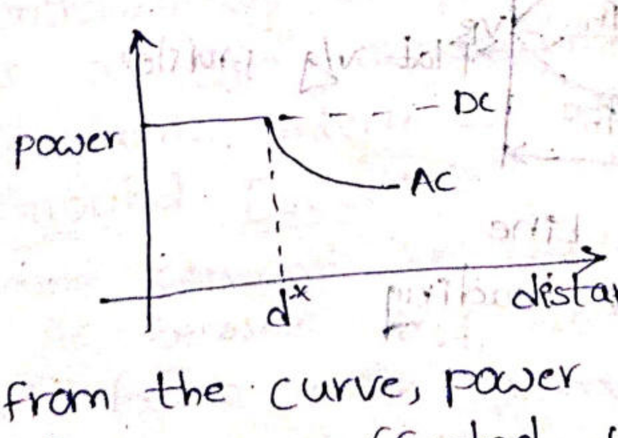
In addition to this DC tr. over-comes some of the problems in AC tr.

<u>They are as follows</u>:-

1) <u>Stability Limit</u>:

* Also known as power transfer
* power transfer in AC line is dependent on the angle difference between the Vlg phasors at the two ends.
* for a given power level this angle increases with distance.

$$P = \frac{V_1 V_2}{X} \sin\delta$$



<u>power Vs Distance</u>

* from the curve, power vs Distance power transfer is unaffected with distance in DC line

I_d = current in each DC conductor.
I_a = current in each AC conductor.
V_d = voltage ~~of~~ in each DC conductor.
V_a = voltage of AC conductor.
$\cos\phi$ = power factor of AC line
$I_d = I_a$ (∵ conductors of same size & insulation level)

* consider 2 conductors of a DC line and 3 conductors of AC line insulation line. then

power in a DC line, $P_d = 2V_d I_d$

power in a AC line, $P_a = 3V_a I_a \cos\phi$

$$2V_d I_d \quad \frac{P_d}{P_a} = \frac{2V_d I_d}{3V_a I_a \cos\phi}$$

$$\frac{P_d}{P_a} = \frac{2V_d}{3V_a \cos\phi} \quad (\because I_d = I_a)$$

$$\frac{P_d}{P_a} = \frac{2\sqrt{2}V_a}{3V_a\cos\phi} \Rightarrow \frac{2\sqrt{2}}{3\cos\phi} = \frac{0.945}{\cos\phi}$$

$\cos\phi < 0.945$

$(V_d = \sqrt{2}V_s)$

$(V_s = V_a)$

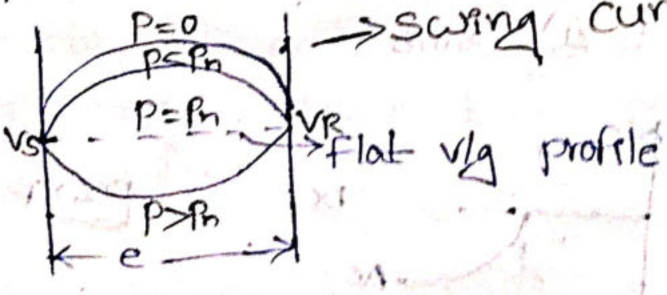
If $\cos\phi = 0.945$ then $P_d = P_a$

A 2 conductor DC line can carry more power when compared with 3 conductors AC line for power factors less than 0.945.

ii.) Voltage control :-

Voltage control is not needed in case of DC lines since v/g drop is due to only resistance.

$\Rightarrow$ In case of AC lines, voltage control as load varies is required.



l - length of the line

Pn - surge impedance loading

$$= \frac{|V|^2}{Z_0}$$

P = Actual (Loading)

n → Distance from the sending end

$\Rightarrow P < P_n \rightarrow$ Reactive power Absorbtion.

$\Rightarrow P > P_n \rightarrow$ Reactive power injection

$\Rightarrow$ more no. of ~~reactors~~ Inductor is there then it is reactive power Absorbtion.

$\Rightarrow$ more no. of capacitors is there the it is reacti power injection.

-> In DC curve is flat curve in AC is swing curve.

iii) Compensation :-

-> AC line required shunt and series compensation. no such compensation is required in case of DC line.

iv) problems of AC Interconnection :-

[AC]—[AC] ~ AC

Synchronous Interconnection

[AC]—[DC]—[AC] ~ HVDC

Asynchronous Interconnection.

when two power systems are connected by AC lines it is called as synchronous Interconnection.

The problems are :

1) The presence of large power oscillations which can lead to frequent tripping
2) Increase in fault level.
3) Transmission of distribution from one system to other coordinated control of interconnected systems is needed
4) controlability of power flow in DC lines eliminates all the above problems.

-> Telephonic Interfaces affcted the AC Lines.

v) Ground Return :-

=> Ground can not be used as return path in case of AC because impedance offered by is high.

=> Interference with communication lines.

=> Ground can be used as return path in case of DC line because of following advantages.

1) In a two conductor dc line if there is a fault on one conductor power can be transferred from other healthy conductor & Ground.

vi) Relaiability :-

(probability of success/failure)

→ Reliability of DC transmission is quite good & comparable to that of AC system.

→ performance of thyristor values is much more reliable than mercury Arc values.

There are two measures for overall system reliability.

i) Energy Availability.

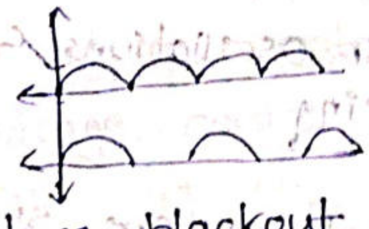
ii) Transient Reliability.

i) Energy Availability:-

$$E.A = 100\left[1 - \frac{\text{Equivalent outage Time}}{\text{Total time}}\right] \%$$

Equivalent time is the product of actual outage of time & fraction of system capacity lost due to outage.

ii) Transient Reliability:-



outage = blackout

Transient Reliability:-

$$T.R = 100 \times \frac{\text{No. of times HVDC system performed as Designed}}{\text{No. of Recordable AC faults}}$$

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

Both energy availability & transient reliability of DC systems with thyristor values is 95%.

* Applications of DC transmissions:-

i) Long distance bulk power Transmission.

ii) underground/water cables

iii) synchronous interconnection of AC system operating at different frequencies.

iv) Control & stabilization of powerflow in AC tie lines.

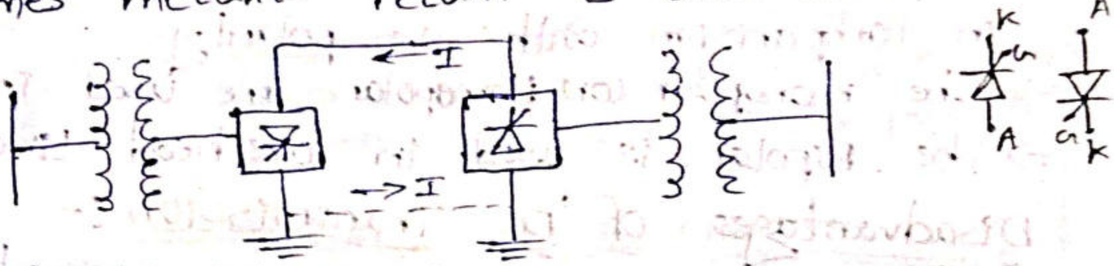
v.) simple line construction.
vi) Greater power per conductor.
vii) cables can be worked at high v/g gradients.

v.) **Types of DC Links :-**

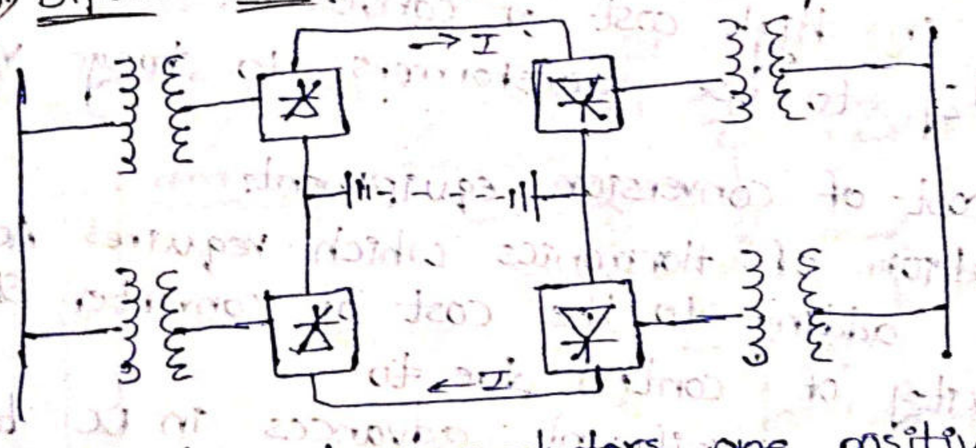
There are three types of DC Links
i) Monopolar Link
ii) Bipolar Link
iii.) Homopolar Link.

i) **Monopolar Link :-**

It has only one conductor usually of negative polarity and uses ground (or) sea as return path sometimes metallic return is also used.



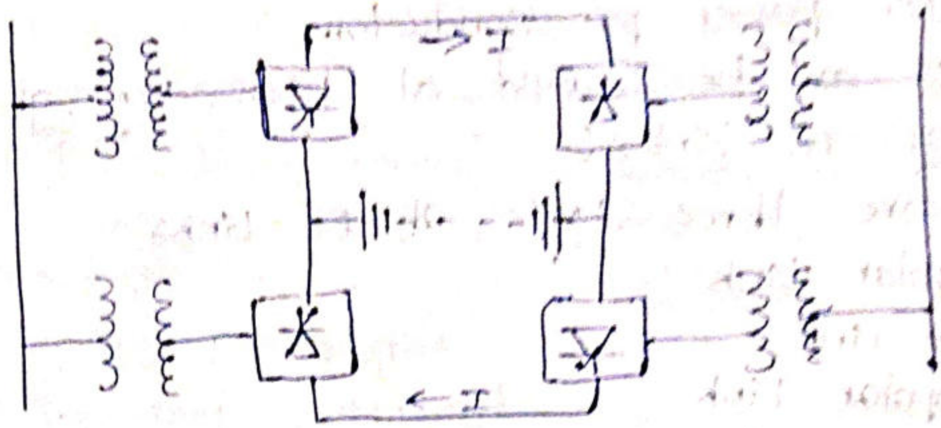
ii.) **Bipolar Link :-**



=> It has two conductors one positive and other negative. Each may be double conductor in EHV Lines.
=> Each terminal has two sets of converters of identical ratings in series on DC side
=> The junction between two sets of converters is grounded at one end (or) both the ends.
=> Both poles operate at equal currents and hence there is zero ground current flowing.

iii.) **Homopolar Link :-**

It has two (or) more conductors usually all having the same polarity i.e negative. It is always operated with ground (or) metallic return.



⇒ In 3 links the most preferable is Bipolar link

⇒ Homopolar link is having the advantages of reduced insulation cost.

⇒ corona effect is less in -ve polarity conductor in comparision with +ve polarity.

⇒ The monopolar (or) Homopolar are used in underground sea

⇒ The Bipolar is used in overhead lines and HVDC.

Disadvantages of DC Transmission :-

1) The difficulty of breaking DC currents which results in high cost of converters.

2.) Inability to use transformers to change voltage levels.

3) High cost of conversion equipment.

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

5) complexity of control due to

Due to the significant advances in DC technology all the disadvantages mentioned above have tried to overcome except (ii)

a) Development of DC breakers

b.) modular construction of thyristor value.

c) Increase in the ratings of cells that make up a value.

d.) Twelve pulse operation of converters

e) use of metal oxide gaplen surge arresters

f) Application of Digital electronics & fibre operato optics in control of converters.

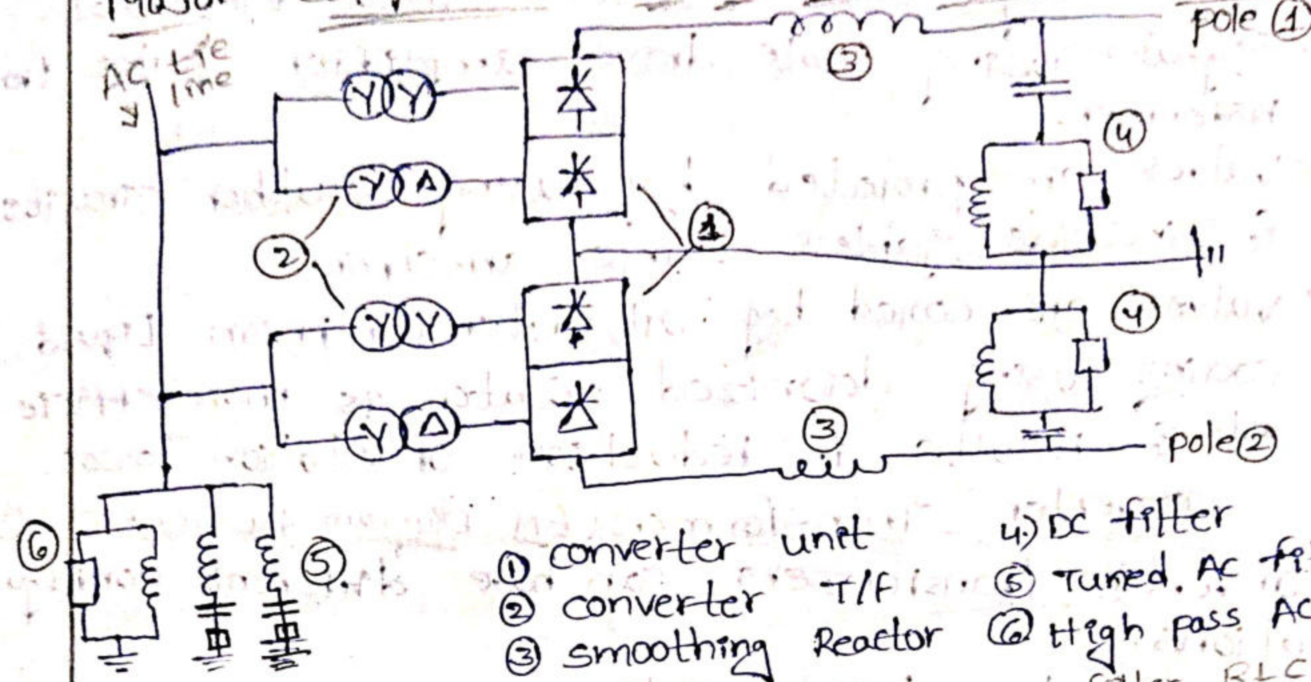
Some of these advances has improved the relaibility and reduced the cost of conversion equipment.

V.I 6M

Typical Layout of a HVDC converter station :-

(or)

Major components of a HVDC converter station :-

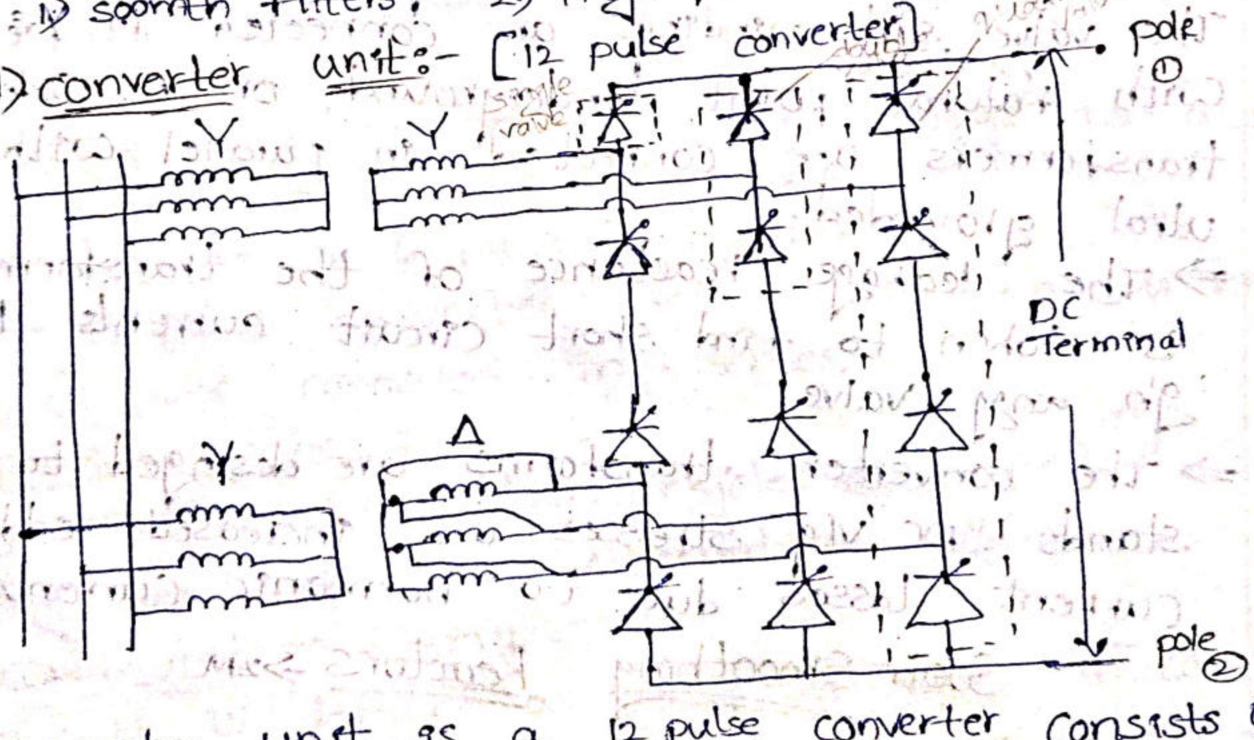


(1) converter unit
(2) converter T/F
(3) smoothing Reactor
4.) DC filter
(5) Tuned AC filter
(6) High pass AC filter
filter, RLC

* Remove LLL in AC side. in Y & Δ

-> Tuned filters are two
1) soomth filters, 2.) High pass filters.

1) converter unit:- [12 pulse converter]



* converter unit is a 12 pulse converter consists of
* 2 6 pulse converter connected in series * It is fed by converter transformer connected in Y-Y & Y-Δ arrangment.

* The valves in converter are packed as single wall, double valve wall & quadratic valve arrangment.

* Each valve is used to switching a segment of AC vlg waveform.

⇒ Valve firing signals are generated at ground potential & are transmitted to each thyristor in the valve through filter fiber optic light signal.

⇒ Light signal is converted into electrical signal using gate drive amplifier pulse transformer.

⇒ Valves are protected by using snubber circuits & zinconide gapless surge arrestrers.

⇒ Valves are cooled by oil, water (or) freon liquid cooling using deionized water is more efficient & results in reduction of station losses.

Converter Transformers (6M Diagram for converter unit)

Converter transformers can have different configurations:

i.) Three phase two winding.

ii.) Single phase two winding

iii.) Single phase three winding

The valve side windings are connected in Y & Δ with neutral point underground on AC side the transformers are connected in parallel with neutral grounded.

⇒ The leakage reactance of the transformer is taken to find short circuit currents through any valve.

⇒ The converter transforms are desinged to withstands DC V/g stresses and increased eddy current losses due to harmonic currents.

~~Soom~~ Smoothing Reactors → 2M

* It is connected between DC line & DC filter.
* It is used to smoothear DC current & provide protection by limiting short circuit currents.

Filters → 2M

There are two types of filters:

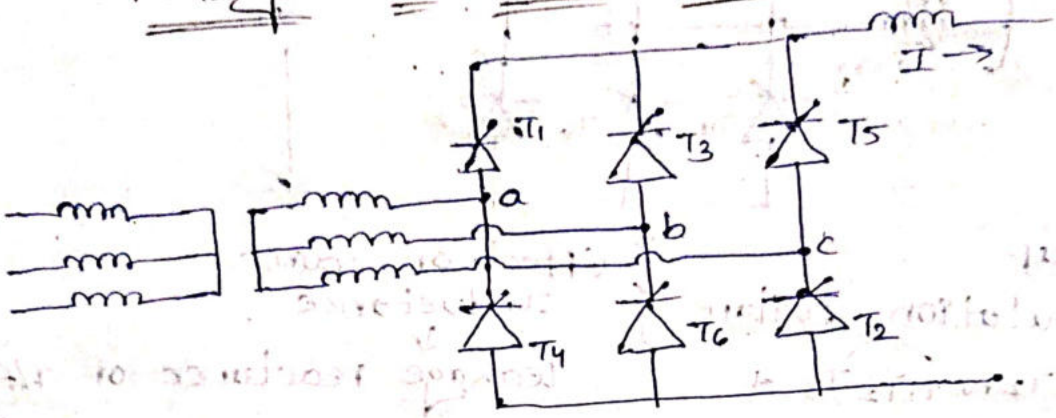
1.) AC filters: They are used to filterout AC harmonics.

2) DC filters : They are used to filterout DC harmonics.

⇒ High frequency filters are used ~~to~~ to suppress high frequency surges.

⇒ AC harmonics are easily to remove & compare to DC even harmonics.

Analysis of HVDC converters



⇒ Six pulse converter is also known as Graetz ckt.

⇒ The (conversion) of from AC to DC & DC to AC in done in HVDC converter station by using 3-ϕ bridge converter.

⇒ The configuration of the bridge is also known as Graetz circuit.

⇒ It is a 6 pulse converter.

⇒ 12 pulse converter consists of two 3-ϕ bridges (6 pulse connected in series)

pulse number :-

No. of pulse station (cycles of ripple) of direct vlg per cycle of Alternating vlg.

Commutation Group :-

It is defined as group of values in which only one thyristor conducts at a time. If there are 'q' values in a commutation group & all 'r' of them are connected in parallel & 's' of them are connected in series.

$$p = qrs.$$

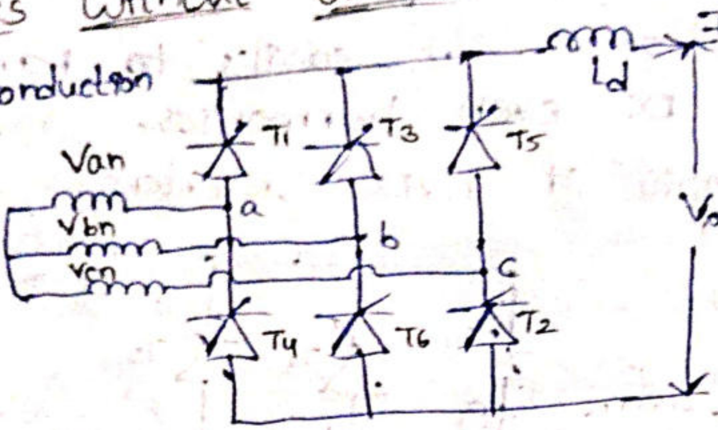
Note :- 3 thyristors are there in commutation group i.e. either from +ve (or) -ve group & 2 of them are connected in series & only one parallel.

$\therefore P = 3 \times 2 \times 1 = 6 = 6$ pulse converter.

Ist 3 phase (6 pulse converter) full bridge HVDC converter

Analysis without overlap :-

Two valve conduction mode



⇒ overlap ↓ commutation failure ↓ $T_1 T_2 \sim T_1 T_2 T_3$ + $T_2 T_3 T_4$ − } Effect of source Inductance ↓ leakage reactance of T/f

⇒ All the higher converters are from by using 6 pulse converter.

⇒ Total no. of thyristor in this converter is 6.

⇒ Those thyristors are divided into two types/groups i.e +ve group & −ve group.

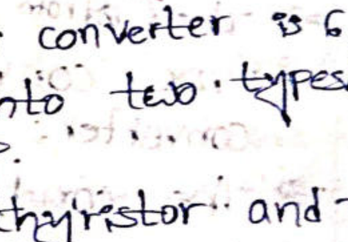
⇒ T_1, T_3, T_5 are +ve type of thyristor and T_4, T_6, T_2 are −ve type of thyristor.

⇒ Each thyristor can trigger at $60°$.

⇒ period of each thyristor is $120°$.

⇒ Thyristor are trigger in sequence according to there numbering ($T_1, T_2, T_3, T_4, T_5, T_6$.)

Thyristors in conduction	o/p v/g	Two valve conduction Duration Mode
T_1 T_6	Vab	$60°$
T_1 T_2	Vac	$60°$
T_3 T_2	Vbc	$60°$
T_3 T_4	Vba	$60°$
T_5 T_4	Vca	$60°$
T_5 T_6	Vcb	$60°$



Vac = −Vca

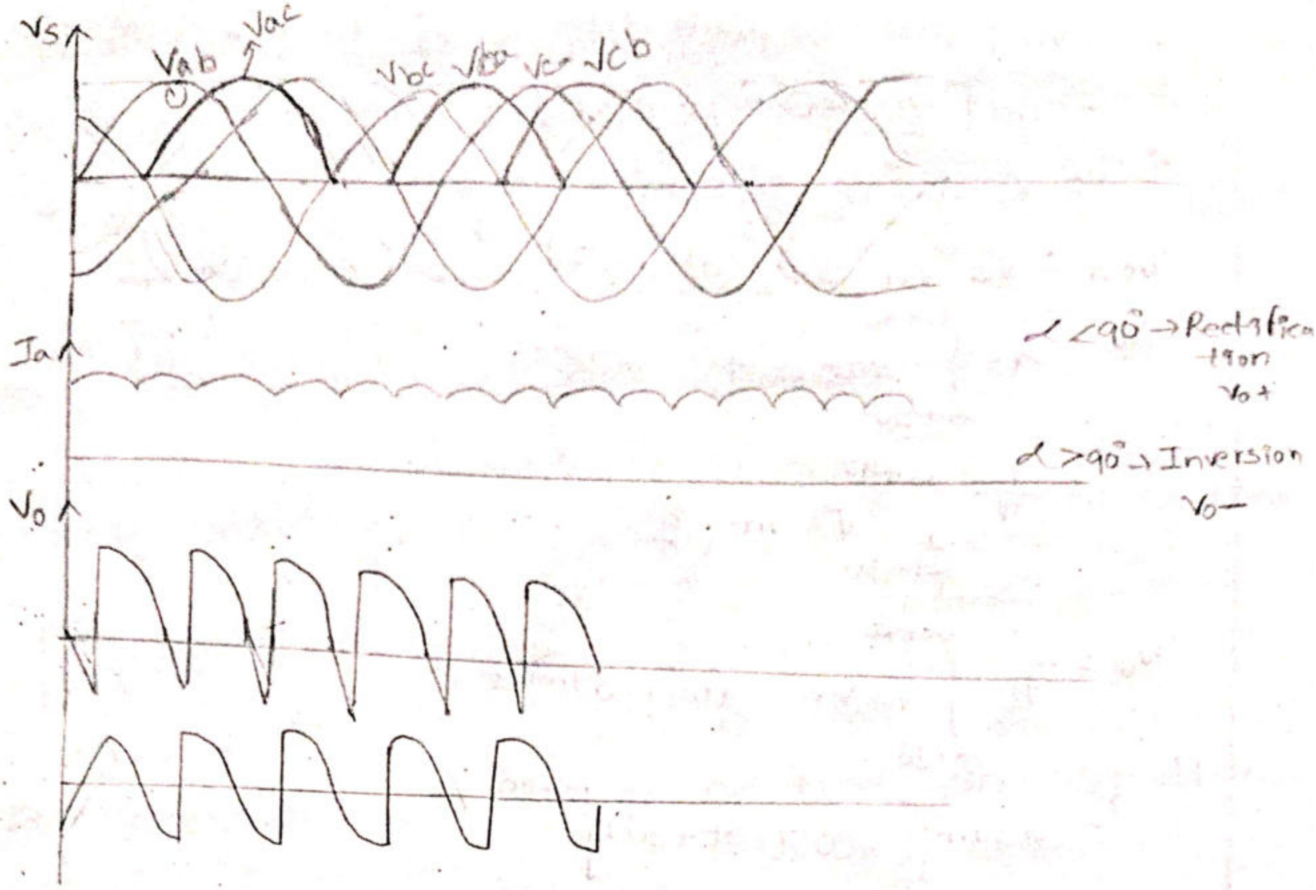
Vbc = −Va

⇒ $\alpha + 30°$

$\alpha + 150°$

$\alpha + 270°$

$\alpha + 90°$



Operation:-

⇒ The thyristor T_5, T_6 are already in conduction.

⇒ T_1 is trigger at an angle of $\alpha+30$.

⇒ The thyristor T_5 stops conduction due to natural commutation. At this incidance T_1, T_6 are in conduction. therefore $V_0 = V_{ab}$.

⇒ The thyristor T_2 is trigger at an angle of $\alpha+90°$. then T_6 stops conduction due to natural commutation. At this incidance T_1, T_2 are in conduction. therefore $V_0 = V_{ac}$. In this manner thyristor get ⇒ triggering according to their ~~m~~number of to obtain 6-pulse converter.

Average output voltage:-

$V_{an} = V_m \sin\omega t$

$V_{bn} = V_m \sin(\omega t - 120°)$

$V_{cn} = V_m \sin(\omega t - 240°)$

$1, 6 \rightarrow V_0 = V_{ab}$

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

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

$= V_m (\sin\theta - \{\sin\theta \cos 120° - \cos\theta \sin 120°\})$

$= V_m [\sin\theta - \{\sin(-\frac{1}{2}) - \cos\theta \frac{\sqrt{3}}{2}\}]$

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

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

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

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

$$\boxed{V_0 = \frac{1}{T}\int_{\alpha+30}^{\alpha+90} V_{ab}\, d\omega t = \frac{1}{T}\int_{\alpha+30}^{\alpha+90} \sqrt{3}\,V_m\left(\frac{\sqrt{3}}{2}\right.}$$

$$V_0 = \frac{1}{\frac{\pi}{3}}\int_{\alpha+30^\circ}^{\alpha+90^\circ} \sqrt{3}\,V_m \sin(\omega t + 30^\circ)\, d(\omega t)$$

$$= 3\sqrt{3}V_m\Big[\big(-\cos(\omega t + 30^\circ)\big]_{\alpha+30^\circ}^{\alpha+90^\circ}$$

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

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

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

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

$$= \frac{3\sqrt{3}V_m}{\pi}\left[2\cos\alpha \cdot \cos 60\right]$$

$$\boxed{(\cos(A+B) + \cos(A-B) = 2\cos A \cos B}$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\cancel{2}\cos\alpha \cdot \frac{1}{\cancel{2}}\right]$$

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

where $V_m = \sqrt{2}V_s$, $V_s = \frac{V_L}{\sqrt{3}}$

Unit - I

Economics of Transmission
Technical performance
Reliability

Typical layout of HVDC converter station
Graetz ckt
Analysis without overlap

Comparison of Ac & DC Transmission
Applications of DC Transmission → 2M
Types of DC links

Unit-2

Converter and HVDC control

V.Imp Principle of DC link control (or) Expression for steady state DC current (I_d) in DC link :

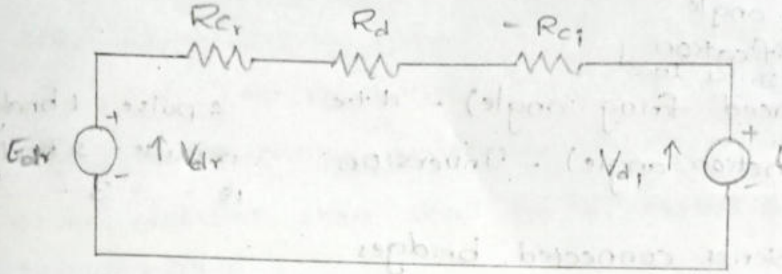


fig: steady state equivalent ckt of two terminal DC link

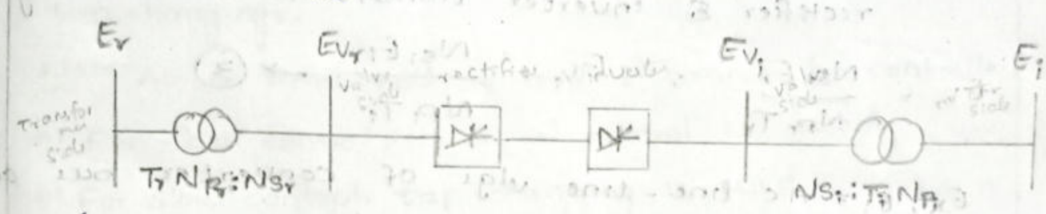


fig: Schematic Diagram of DC link showing transformer ratios.

r = rectifier T = Tap changing

d = dc link vlg

i = inverter

*) The control of power in DC link can be achieved through control of voltage /current

*) It is important to maintain constant voltage in the link and adjust the current to meet the required power. This strategy is also helpful for vlg regulation.

*) The vlg drop along a DC line is small compared to AC line mainly because of absence of reactive vlg 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 are identical in ratings and have the same delay angle.

*) Also the no. of series connected bridges in

both the stations are same.

*) The v/g sources are given by:

$$E_{dr} = \left(\frac{3\sqrt{2}}{\pi}\right) n_b E_{v_r} \cos\alpha_r \rightarrow (1)$$

$$E_{di} = \left(\frac{3\sqrt{2}}{\pi}\right) n_b E_{v_i} \cos\gamma_i \rightarrow (2)$$

firing angle
α - Rectification
used in RL load
β (Advanced firing angle) - $\pi + \alpha$
γ (Extinction angle) - Inversion

6 pulse - 1 bridge
12 pulse - 2 bridge
18 " - 3 "

n_b = No. of series connected bridges

E_{v_r}, E_{v_i} = line to line v/g's in the value side wdg's of rectifier & inverter transformer respectively.

$$E_{v_r} = \frac{N_{sr} E_r}{N_{pr} T_r} \quad ; \quad E_{v_i} = \frac{N_{si} E_i}{N_{pi} T_i} \rightarrow (3)$$

E_r, E_i = AC line-line v/gs of converter bus on rectifier & inverter side

T_r, T_i = off nominal tap ratios on rectifier & inverter side

combining eqns (1), (2) & (3)

$$E_{dr} = \left(\frac{A_r E_r}{T_r}\right) \cos\alpha_r \rightarrow (4)$$

$$E_{di} = \left(\frac{A_i E_i}{T_i}\right) \cos\gamma_i \rightarrow (5)$$

where A_r & A_i are constants;

$$A_r = \left(\frac{3\sqrt{2}}{\pi}\right) n_b \frac{N_{sr}}{N_{pr}}$$

$$A_i = \left(\frac{3\sqrt{2}}{\pi}\right) n_b \frac{N_{si}}{N_{pi}}$$

therefore, steady state DC current I_d in the DC link is given by:

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

$$= \frac{\left(\frac{A_r E_r}{T_r}\right)\cos\alpha_r - \left(\frac{A_i E_i}{T_i}\right)\cos\gamma_i}{R_{cr} + R_d - R_{ci}}$$

The control variables are T_r, T_i, α & γ

R_{cr} = Commutation resistance of rectifier

R_d = DC link resistance.

R_{ci} = Commutation resistance of inverter

*) At rectifier, there shall be 'α' control & transformer tap changing.

*) At inverter, there shall be 'γ' control & transformer tap changings.

Note: At a time both α and γ cannot be controlled

*) For fast control, α or γ control is used

*) For slow control, tap changing is used

Constant voltage System (CVS):

All power sources and loads are connected in parallel. Voltages across all is maintained constant.

Merit:

*) I^2R loss will be as per the load.

*) At light loads, it will be less.

Demerit: short circuits produce larger currents.

Constant Current System: (CCS)

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

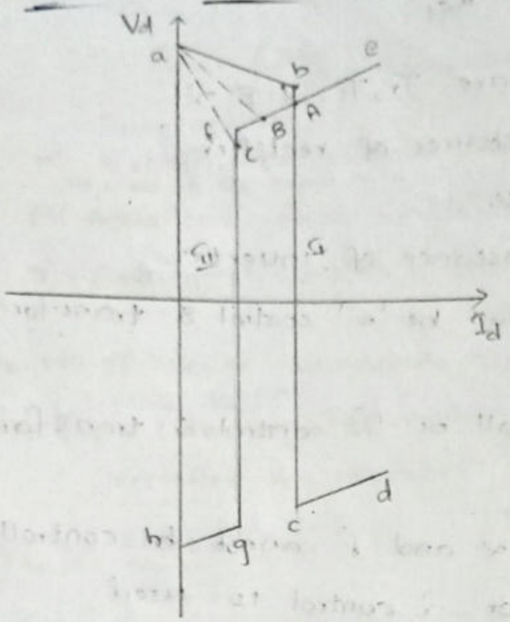
Merit: For short ckt faults, the current will remain the same.

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

Note: When α is controlled then it carries variable current & at inverter side, γ will & current will be constant. When γ is controlled then variable current. α and current are controlled.

CEA - Constant Extinction Angle

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

Note: R

*) Rectifier acts as rectifier, α control, constant current and opp. operation or side i.e inverter

$R \begin{cases} R+ \\ I- \end{cases}$ $I \begin{cases} I+ \\ R- \end{cases}$

*) At any converter station, there will be 3 controls (α, γ, constant current control).

γ control is also known as CEA control

*) the intersection of two characteristics (point 'A' determines normal mode of operation i.e station-I operates as rectifier with constant current control (ccc) and station-II operating as inverter with constant Extinction Angle control (CEA)

*) there are three modes for operation of a DC link

i) Constant Current Control (ccc) at the rectifier and constant Extinction Angle (CEA) at the inverter is the normal mode of operation with intersection point 'A'

ii) With slight fall in Ac vlg point of intersection shifts to 'c' which implies min α at the rectifier and min γ at the inverter

iii) With lower AC v/g at rectifier the point of intersection shifts to 'B', which implies min. α at rectifier and ccc at the inverter.

The operation at min. extinction angle at the inverter and current control at the rectifier results in better v/g regulation than operation with min. delay angle at the rectifier and current control at the inverter.

Note: 1) When CC is operated then another with CEA. (At normal mode)

2) When station-1 operates at min α then station 2 is operated at CC.

FAC - Firing Angle Control

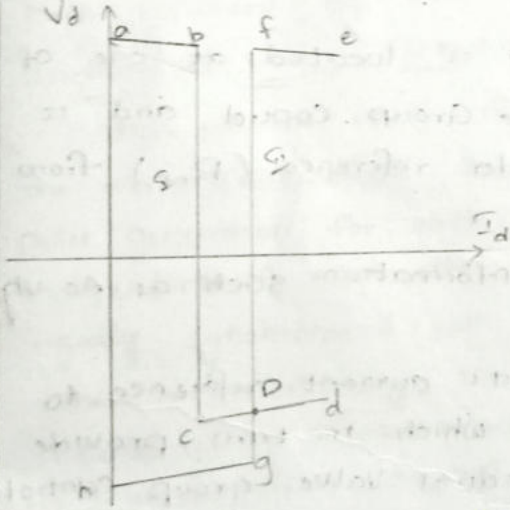
α -> Rectifier -> I: R, II

β -> Inverter -> I: α, CC; II: CC, γ

FAC, CEA

	1st	2nd	3rd
R	CC	min α	min α
I	CEA	min γ	CC
	Normal	Fault	

Reversal of Power flow characteristics:



Station I -> Inverter - CEA

Station II -> Rectifier - CC

Station II config will be started again, interchanged only controls are changed, not converter.

1) Station-I operates as inverter with CEA control

2) Station-II operates as rectifier with CC control

3) Point of intersection is 'D'. Resulting in reversal of power flow.

$$I_d = \frac{\overbrace{\left(\frac{A_r E_r}{T_r}\right)\cos\alpha}^{\text{Rectifier}} - \overbrace{\left(\frac{A_i E_i}{T_i}\right)\cos\gamma_i}^{\text{Inverter}}}{R_{cr} + R_d - R_{ci}}$$

I_d ↓ Current control

commutation inductance

$$R_{cr} = R_{ci} = \left(\frac{3\omega L_c}{\pi}\right) = 6fL_c$$

$\omega = 2\pi f$

Rectifier → min α CC

Inverter → min γ CC

System Control Hierarchy (or) Block diagram of HVDC control

VGC = Valve Group Control

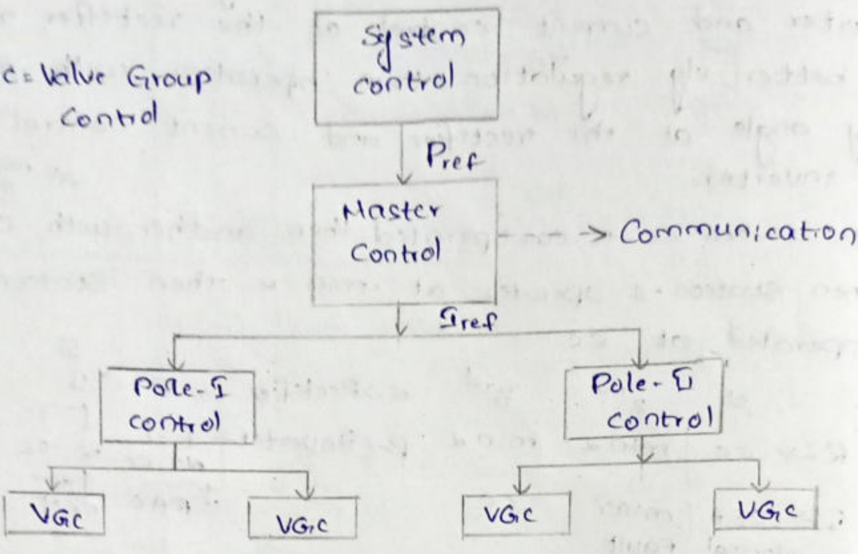


fig: Hierarchial control structure of HVDC Link

Master control for bipole is located at one of the terminals VGC - Valve Group control and is provided with power order reference (Pref) from the System Control.

*) It also have other information such as Ac vlg at converter bus, Dc vlg

*) Master control transmits current reference to the pole control units which in turn provide firing pulses to individual Valve group control

*) Pole control incorporates pole protection and Dc line protection.

*) Valve control provides valve monitoring and commutation failure protection.

*) Master control includes functions of power modulation, frequency control, Ac vlg & reactive power & damping control and takes care of complete bipole

V.Imp **Firing angle Control:**

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

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

ii) While single pulse is adequate to turn ON a thyristor. The Gate pulse generator must send a pulse whenever required if a particular value is to be kept in conducting state

There are two basic firing schemes

a) Individual phase Control (IPC)

b) Equidistant Pulse Control (EPC)

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

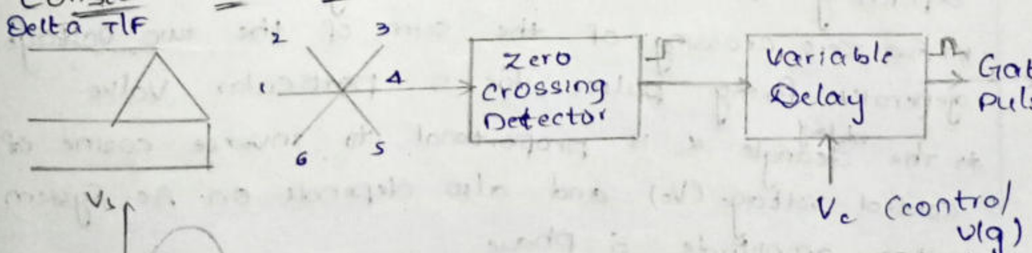
Individual Phase Control (IPC):

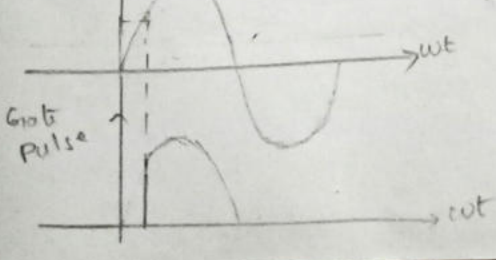
This scheme was used in early HVDC projects. The main feature of this scheme is that firing pulse generation for each phase (or) valve is independent of each other and firing pulses are rigidly synchronized with commutation v/g. There are two ways in which this can be achieved

i) Constant α (Alpha) control

ii) Inverse cosine control

Constant α Control:



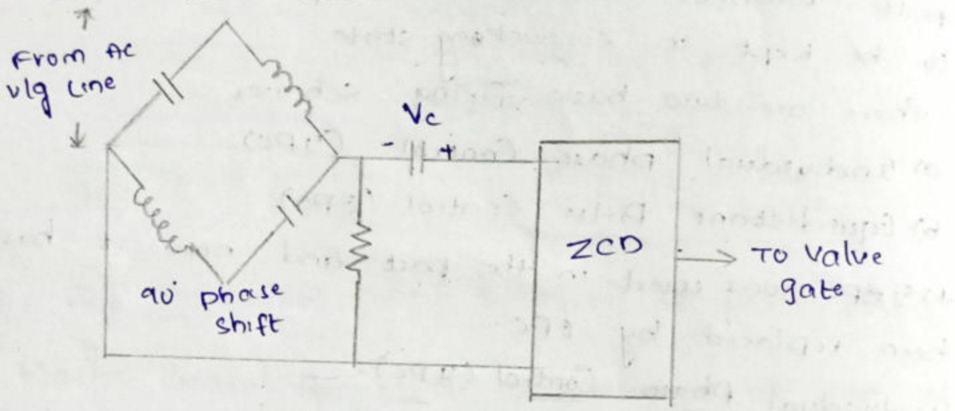


Six Commutation vlg's are derived from converter Ac bus via vlg T/F's and the six gate pulses are generated at nominally identical delay times subsequent to respective vlg zero crossings.

The instant of zero crossing of a particular commutating vlg corresponds to $\alpha=0^\circ$ for that value.

* The delays are produced by independent delay circuits and controlled by a common control vlg (V_c) derived from current controller.

Inverse Cosine Control:



ZCD: Zero Crossing Detector

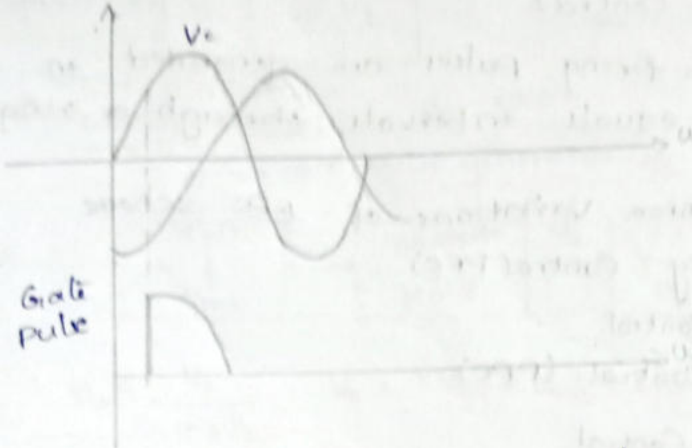
$$\sqrt{3}V_m \sin(\omega t-90^\circ)+V_c=0$$

$$-\sqrt{3}V_m \cos\omega t+V_c=0$$

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

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

* Six Commutation voltages obtained just like constant α control are each phase shifted by 90° and added seperately to common control Voltage, V_c.
* In zero crossing of the sum of the two voltages generates firing pulses for a particular valve.
* The delay angle α is proportional to inverse cosine of control voltage (V_c) and also depends on Ac System voltage amplitude & phase.



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

i) Usage of filters to filter out non-characteristic harmonics

ii) Provision of synchronous condensor (Improvement of p.f)

No Pending

Equidistant Pulse Control:

In this scheme, firing pulses are generated in steady state at equals 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)

Pulse Frequency Control

In this scheme, a voltage controlled Oscillator (VCO) is used. the frequency of which is determined by the control v/g 'V_c' which is related to the error in the quantity being required.

the frequency is steady state is ~~called~~ equal to $\frac{1}{Pf_0}$

where

P - Pulse number

f_0 - nominal frequency of AC System.

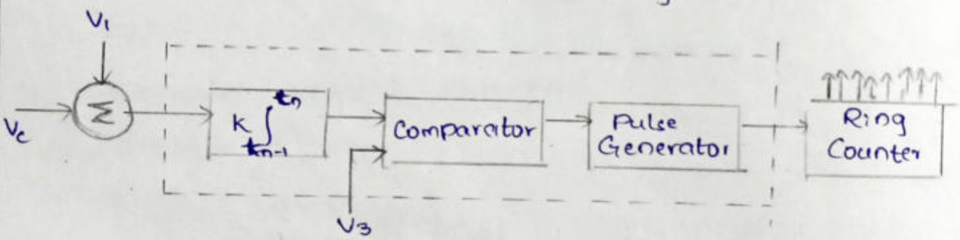


fig: VCO block diagram of PFC

VCO consists of integrator, Comparator and Gate pulse generator. the o/p pulses of the Gate pulse Generator drive the ring counter.

the firing instant (t_n) of the gate pulse is determined from the following equation.

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

where, V_1 - Constant V/g

V_3 - proportional to the System Period

V_c - Control v/g

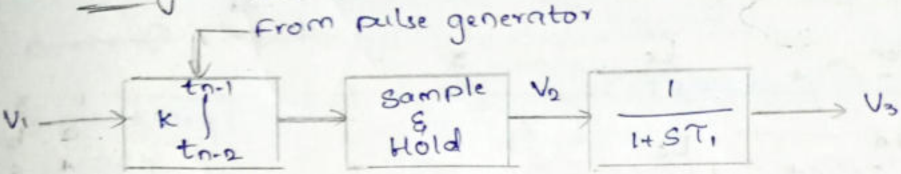
In steady state, $V_c = 0$

$$K_1V_1(t_n - t_{n-1}) = V_3$$

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

In steady state, gain K_1 of the integrator is given by : $\boxed{\dfrac{Pf_o V_3}{V_1}}$

Frequency Correction for PFC:



$$V_3 = \frac{V_2}{1+ST_1} \; ; \; V_2 = KV_1(t_{n-1} - t_{n-2})$$

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 $V_c = 0$

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

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

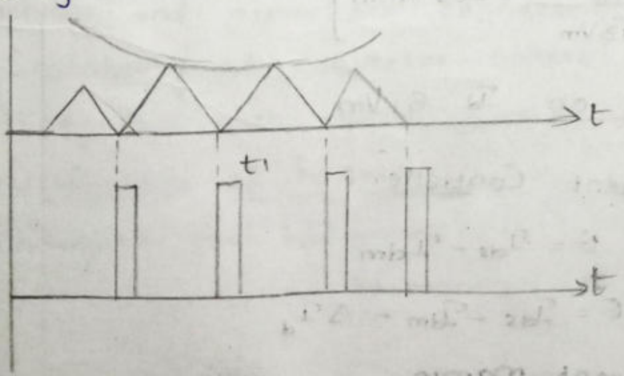
iii) Pulse Phase Control (PPC):

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

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

where V_{cn}, V_{cn-1} are the control v/g's at the instants t_n, t_{n-1} respectively.

With $V_c = 0$ in steady state consequtive pulses will be generated at phase intervals of $\frac{1}{Pf_o}$.

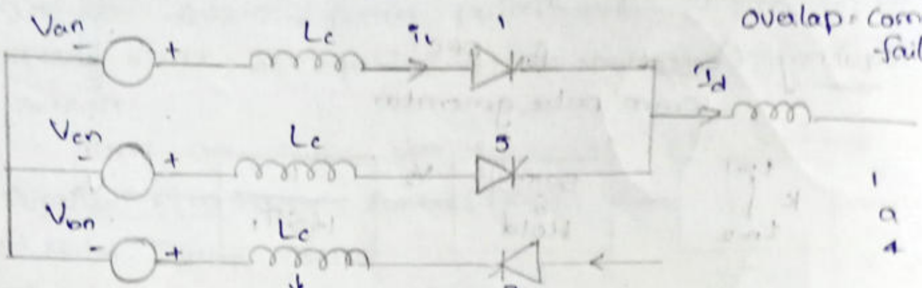


R	I
Fixed	Variable
CC	γ
α	CC

Best control CC must be at rectifier

Constant Extinction Angle Control (CEA): L_c = Commutating inductance

Overlap - Commutation failure



↓ Leakage reactance of t/f

Commutation problem is there in inverter / equation

When valve 1 is considered i.e commutation from valve 5 to valve 1 γ_n should have a min. value to allow turn off time to prevent commutation failure.

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

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

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

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

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

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

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

Required value 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

Constant Current Controller:

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

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

ΔI_d - current margin

I_{ds} = Setting of current regulator
I_{dm} = Measured value

Current is maintained constant by using constant current regulator.

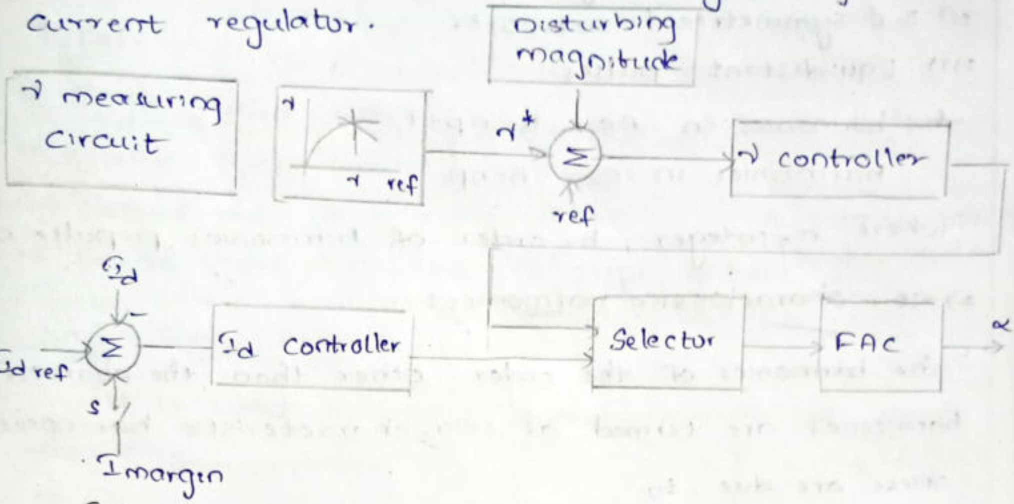


fig: Block diagram of CC & CEA Controllers

*) Firing angle control generates gate pulse in responds to the control signal (V_c).

*) Selector chooses min. value of α determined by CC & CEA Controller

*) The current controller generates control signal; V_c related to the firing angle required.

4m

Generation of harmonics:

Harmonics are generated to disturbances in voltage or current and unbalance in load.

Problems associated with harmonic generation:

1) Telephone interface
2) Extra power losses and consequent heating in machines and capacitors connected in the system.
3) Instability of converter control
4) Interface with ripple control management.

Classifications of harmonics:

1) characteristic harmonics
2) Non-characteristic harmonics

1) Characteristics harmonics:

The harmonic that are present in ideal operation i.e.

i) Balanced AC voltages

ii) 3-Ø symmetrical networks

iii) Equidistant pulses

The harmonics in AC : $h = np \pm 1$

harmonics in DC : $h = np$

where n - integer, h - order of harmonics, p - pulse no.

2) Non-characteristic harmonics:

The harmonics of the order other than the characteristic harmonics are termed as non-characteristic harmonics. These are due to

i) firing angle errors

ii) Unbalance and distortion in AC voltage

iii) Unequal transformer leakage reactance

iv) Imbalance in operation of 12-pulse converter unit.

*) Triplen, even harmonics comes under non-characteristic harmonics.

Residual harmonics:

The harmonics that are present due to imbalance in operation of two bridge firing 12-pulse converters unit are known as residual harmonics.

*) Even harmonics are considered as both characteristic and non-characteristic

*) Odd harmonics in both balanced condition are called as AC harmonics.

*) Odd harmonics under unbalanced condition are called as triplen harmonics.

imp **AC Filters:**

odd / Ac harmonics - balanced
DC -> Unbalanced & balanced

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

Ac harmonics are not critical
DC -> critical

Types:

i) Single Tuned filter
ii) Double Tuned filter } Elimination of lower order harmonics
iii) Second order high pass filter
iv) Second order high pass 'c' type filter } Elimination of higher order harmonics

Single Tuned Filter:

It is used to filter out harmonics of single (same) frequency.

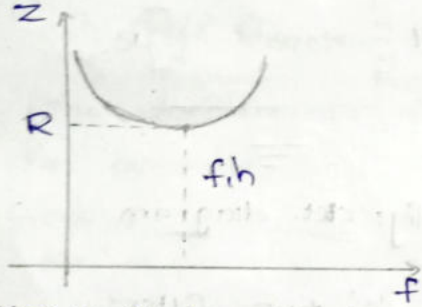


fig: Z Vs f characteristics

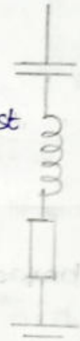
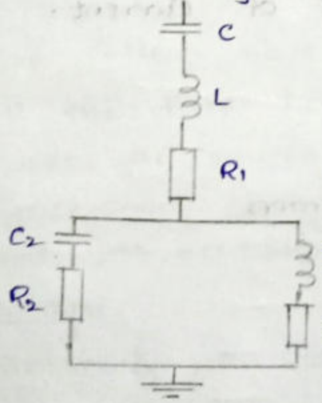


fig: ckt diagram

Double Tuned Filter:

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



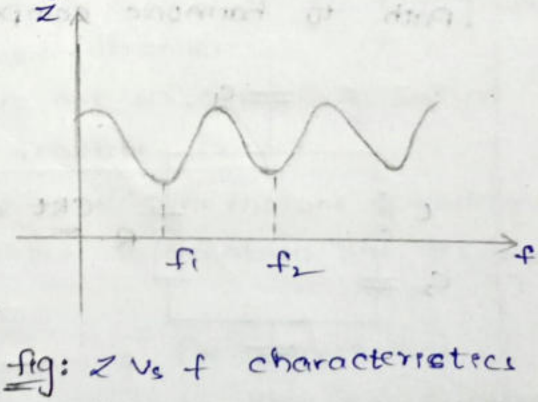


fig: Z Vs f characteristics

Advantages:

*) Only 1 inductor is subject to full line impedance voltage

*) Reduced power losses at fundamental frequency of harmonic component current.

{Note: lower order harmonics → upto 12 Pulse

$1\times6 \pm 1 = 5, 7$ 　　　 5, 7, 11, 13, → lower order

$1\times12 \pm 1 = 11, 13$

Higher the ~~lower~~ Pulse number, lower order harmonics are eliminated

Upto 12 pulses, single & double tuned filters are used (to eliminate lower order harmonics) }

iii) <u>Second Order High Pass filters</u>:

It is used to filter out higher order harmonics. (i.e > 13 pulses)

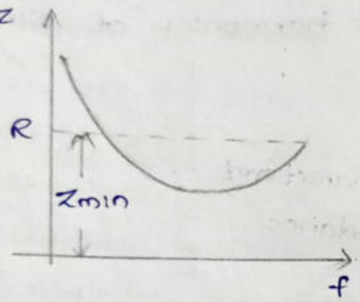


fig: <u>Z Vs f characteristics</u>

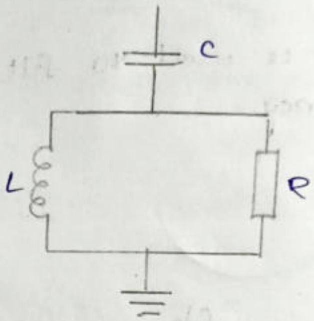
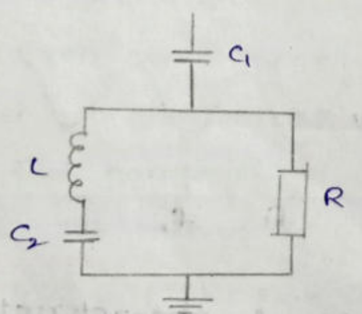


fig: <u>ckt diagram</u>

iv) <u>Second order High pass 'c' type filter</u>:

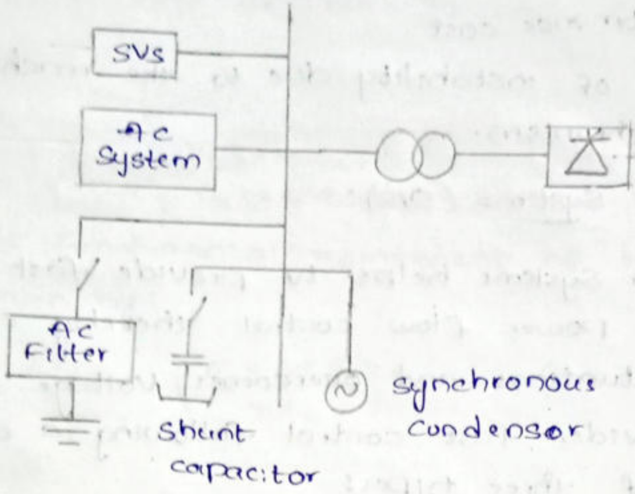
Losses at fundamental frequency can be reduced by a 'c' type filter in which capacitor 'c' is in series with inductor 'L' provides low impedance shunt path to harmonic component of current.



<u>ckt diagram</u>

v.Imp

Sources of reactive power:



SVC - Static Var Systems

Fig: Reactive power Sources of 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 condensers and static var systems (SVS).

For slow variations in load to provide control switched capacitors and filters can be used to provide control synchronous condensors and static Var Systems provides continous control of reactive power. It can follows fast load changes.

All the filter branches are in capacitive nature. They acts as source of reactive power.

Synchronous condensors are syn. motors operating at no-load with excitation control to maintain the terminal v/g.

Advantages:

1) Availability of voltage source for commutation at the inverter if connection to the AC system is temporarily disconnected

2) Better voltage regulation during transient due to the maintenance of flux linkages in rotor windings.

Disadvantages:

v/g source is series with a capacitor
current source

1) High maintenance cost

2) Possibility of instability due to the machine going out of synchronism.

control turn ON (CT)
uncontrol turn OFF (UTO)

V.Imp **Static Var Systems (SVS):** - SCR is used.

Static Var Systems helps to provide fast control of reactive power flow control thereby controlling voltage fluctuations and overcomes voltage instability.

*) SVS provides fast control following a disturbance. they are of three types:

i) Variable impedance Type SVS - CT, UTO

ii) Voltage source Type SVS
iii) Current source Type SVS } FACTS ↓ eg STATCOM ; CT, CTO

i) Variable impedance Type SVS:

Variable impedance Type SVS is commonly used for power system applications.

*) Variable impedance type SVS devices are:

i) Thyristor Controlled Reactor (TCR)

ii) Fixed capacitor thyristor Controlled Reactor (FCTCR)

iii) Thyristor switched capacitor (TSC)

i) Thyristor Controlled Reactor:

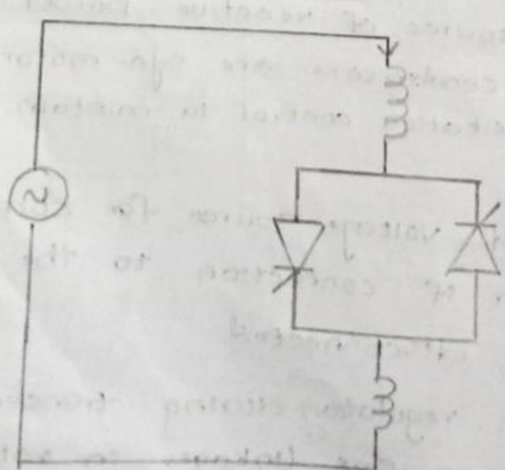


fig: single phase TCR

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

*) For $\alpha = 90^\circ$, current is maximum

*) For $\alpha = 180^\circ$, current is zero

the fundamental component of inductor current is given by:

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

where,

X_L = Fundamental frequency reactance

V = RMS voltage across SCR

σ = conduction angle

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

eqn. (1) can be written as: $I_1 = B(\sigma) V$

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

B = susceptance $= \dfrac{1}{\text{reactance}}$

~~Harmo~~

*) the harmonic component of current corresponding to harmonic order of 'h' is given by:

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

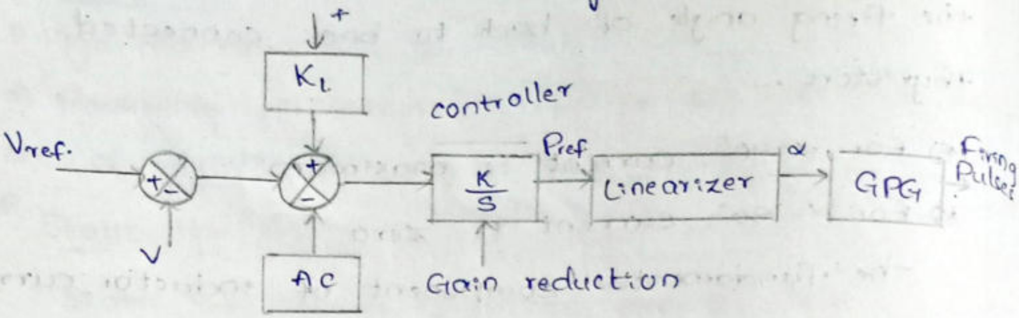
h = 3, 5, 7 triplen harmonics → Non. characteristic

~~thyristor~~

*) Triplen harmonics are eleminated by Δ connecti-on of 3 single phase TCR's. the control ~~syste~~ signals are obtained from the v/g and reactor current.

*) the controller is usually an integral controller with variable gain to avoid problems of control instability. the auxillary control signal V_c may be

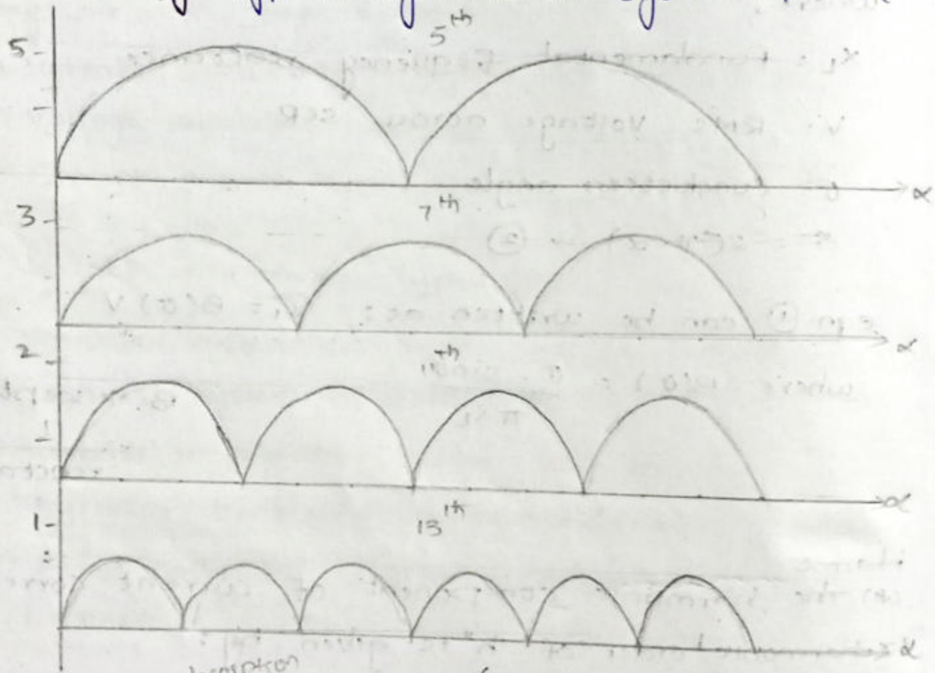
derived from the bus frequency.



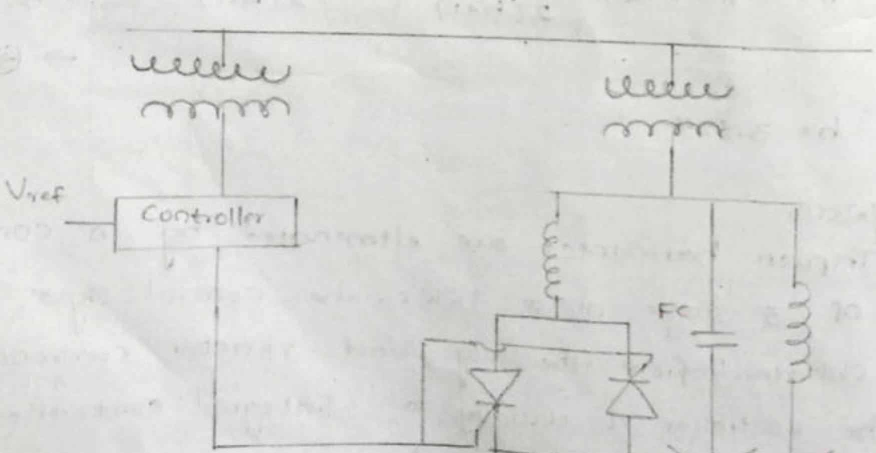
AC = Auxillary controller

GPG = Gate Pulse Generator

fig: Typical layout Control system of TCR

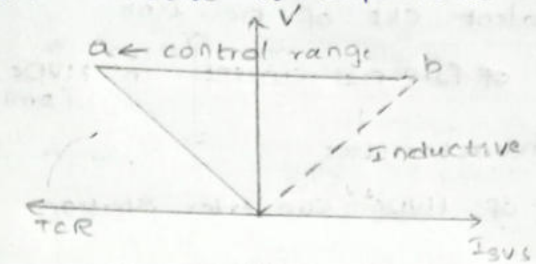


Fixed capacitor (FC) TCR: absorption



Harmonic order w.r.t Conduction

TCR's are usually operated with fixed capacitor to provide variation of reactive power consumption from inductive to capacitive.



Thyristor Switched Capacitor (TSC):

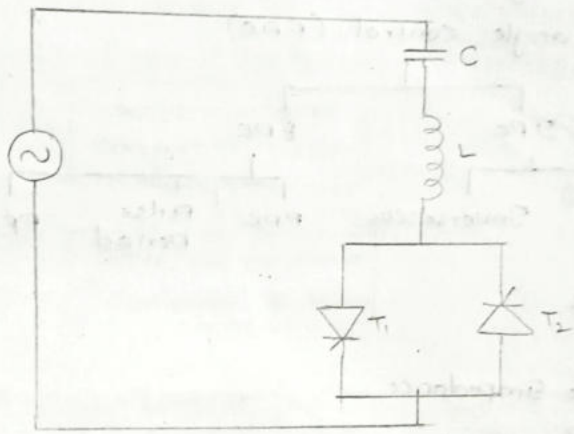


fig: thyristor Switched Capacitor

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

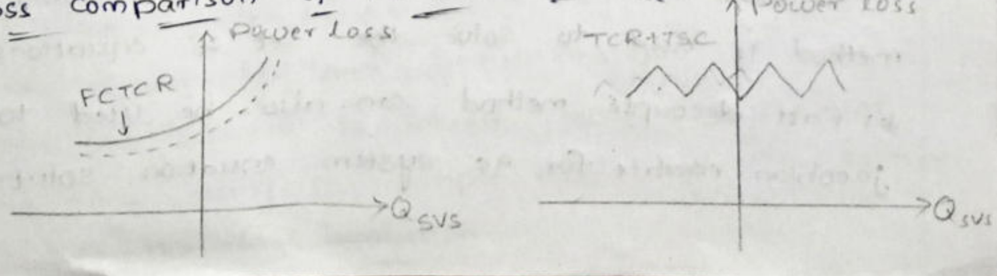
A inductor is usually connected in series with capacitor to reduce the rate of change of current.

Advantages of TSC over TCR:

*) Required rating of TCR can be reduced.

*) Reduced power losses in inductive operation.

Loss comparison of FC-TCR & TCR-TSC:



(1)

→ Principle of DC link control

→ Steady state equivalent ckt of DC link

→ Derive the expression ~~of~~ for DC current in HVDC tr. (2m)

(2) Converter Control characteristics

→ V_d-I_d characteristics of HVDC Converter Station

(3) Hierarchial control of Structure of HVDC (or) Block diagram of HVDC control

→ Firing angle control (FAC)

- IPC
  - Con. α
  - Inverse cos
- EPC
  - PPC
  - Pulse Period
  - PFC

(4) Filters

(5) SVS

→ Variable Impedance

⇒ TCR

Imp **Solutions of AC/DC load flows:**

the solution methodology of AC/DC can be classified as

1) Simultaneous (or) Unified method

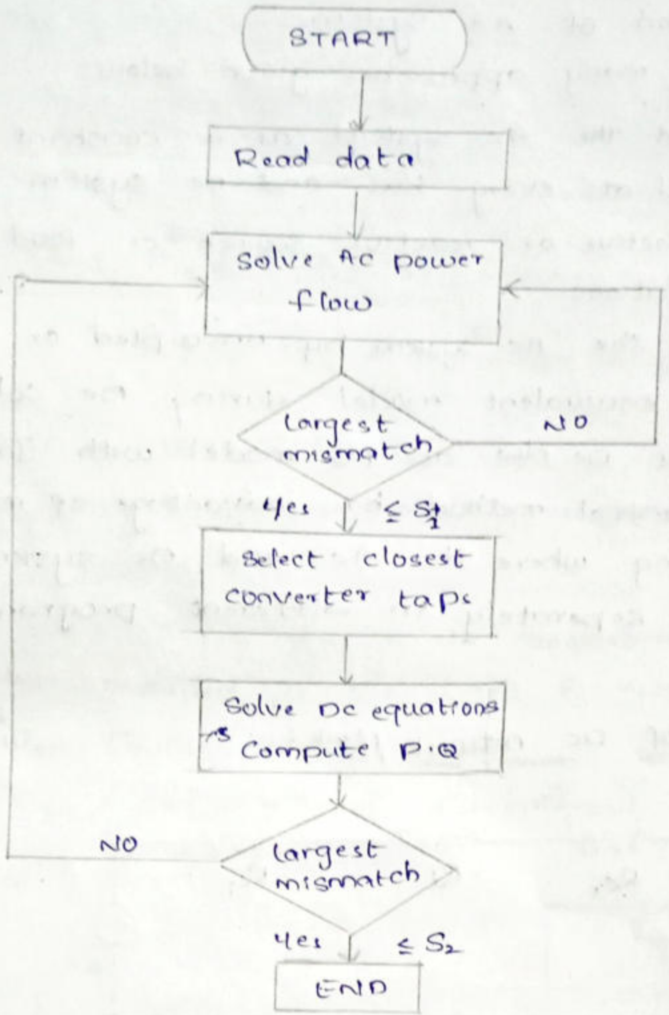
2) Sequential (or) Alternating method

In the first approach, the AC & DC quantities are solved together. The simplest implementation of this approach is to consider all the equations (AC & DC quantities) combined into one set of non-linear algebraic equations.

*) Jacobian matrix is then constructed & newton raphson method is used to solve the set of equations.

*) Fast decouple method can also be used to solve jacobian matrix for AC system equation solutions.

Flow chart of Ac/Dc load flow:



P → real power

Q → reactive

$$\begin{bmatrix} \frac{\Delta P}{\Delta V} \\ \Delta Q \\ \frac{\Delta V}{\Delta R} \end{bmatrix} = \left[\begin{array}{cc|c} B' & 0 & A' \\ 0 & B'' & A'' \\ 0 & B & A \end{array}\right] \begin{bmatrix} \Delta Q \\ \frac{\Delta V}{\Delta x} \end{bmatrix}$$

Here, x is the vector of dependent variables for the Dc system and ΔR is the vector of mismatches Dc system equations.

2) Sequential or alternating method:

In this method, Ac & Dc system equations are solve seperately and sequentially.

*) The Ac system is solved some degree of convergence using a simple model of Dc system based on its last solution

k) The Dc system is solved in a simplified representation of Ac system.

l) There are many approaches given below:

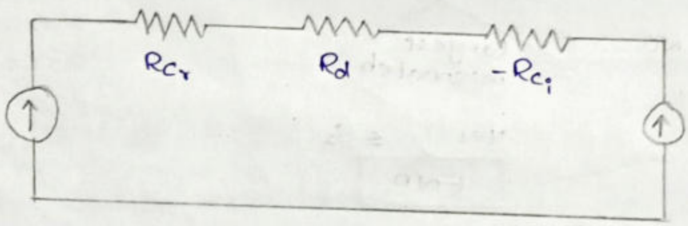
1) Represent the Ac system as a constant voltage angle model at every bus and Dc system as a constant active or reactive source or load during the Ac solutions.

2) Represent the Ac system by uncoupled or coupled thevenin's equivalent model during Dc solutions.

3) Represent Dc n/w as PQ model with Jacobian term sequential method has advantage of modulating programming where the Ac and Dc systems are modelled seperately in different program segments.

Modeling ↓ why? Load flow ↓ P.Q

Modeling of Dc network / link:



The Dc network consists of Dc links, smoothing reactors and converters can be viewed as a resistive network excited by current (or) v/g sources in steady state.

Depending on series or shunt connection of converters it may be approximate to consider loop resistance (or) nodal conductance matrix.

The converters are not ideal sources but are described by converter controller equations.

In general the elements of Dc network can be represented into the tree, branch & links. The converters can be divided into either tree, branches (or) links.

The equations describing the DC network are:

$$-[g] V_g = i_g \rightarrow (1)$$

$V = IR$

$$i_g = -B_{Lg} I_{dL} \rightarrow (2)$$

$$i_{dT} = -B_{LT} I_{dL} \rightarrow (3)$$

$$V_{dL} = B_{Lg}^t V_g + B_{LT}^t V_{dT}$$

$$= B_{Lg}^t [g]^{-1} B_{Lg} I_{dL} + B_{LT}^t V_{dT} \rightarrow (4)$$

where g = matrix of conductance element (diagonal)

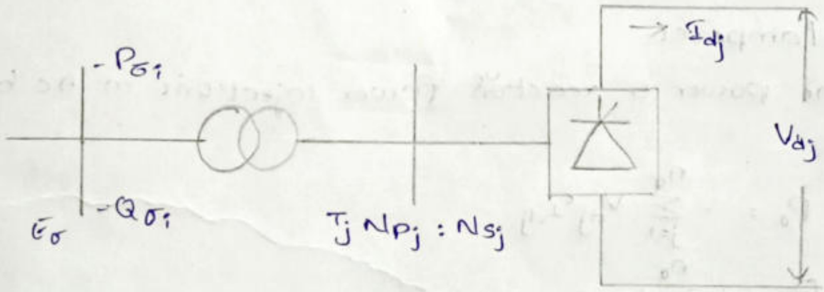
V_g, i_g = v/g & current vectors corresponding to conductance.

i_{dL}, i_{dT} = Currents through the converters that are included in the links & trees.

V_{dL}, V_{dT} = Counter voltages

B_{Lg}, B_{LT} : Components of fundamental cutset matrix

Modeling of DC converter:



Schematic diagram of converter

It is assumed that 'N' converters can be put into 'm' groups such that for all the converters in the group the converter bus is identical.

Normally all the converters in the ~~i^{th} group is~~ in a station can be grouped together

The number of converters in the i^{th} group is η_i.

It is obvious that,

$$\sum_{i=1}^{n} \eta_i = N \rightarrow (1)$$

the v/g equation for the converter 'j' in group σ is

$$V_{dj} = \left(\frac{3\sqrt{2}}{\pi}\right)\left(\frac{N_{sj}}{N_{pj}}\right)\left(\frac{E_\sigma}{T_j}\right) V_{b\sigma} \cos\alpha_j - \left(\frac{3}{\pi}\right) X_{cj} I_{dj} \rightarrow (2)$$

$$\frac{3}{\pi} X_{cj} = R_{dj}$$

T= Tap changing

where,

$V_{b\sigma}$ = Base of v/g of the converter bus 'σ'

T_j = off nominal tap ratio of the t/fr

E_σ = pu Ac v/g at the converter bus

N_{sj}, N_{pj} = Nominals turns ratio of the primary & secondary windings.

X_{cj} = Leakage reactance of the t/fr refer to secondary

*) All the Ac quantities are represented in p.u system

*) All the Dc quantities are represented in volts/amperes.

*) The power & reactive power injections in Ac bus are:

$$P_\sigma = -\sum_{j=1}^{n_\sigma} V_{dj} I_{dj}$$

$$Q_\sigma = -\sum_{j=1}^{n_\sigma} V_{dj} I_{dj} \tan\phi_j$$

It is to be noted that both V_{dj} and $\tan\phi_j$ are negative

this results in P_σ being positive while Q_σ is negative.

UNIT-3

Introduction to FACTS concepts

Flow of Power in AC system:

In electrical power systems, if there is sufficient electrical storage, the electrical generation and load must balance at all times.

*) If generation is less than the load, the voltage and frequency drop and there by load goes down to equal the generation minus transmission losses.

*) If v/g is popped up with reactive power support then load will go up & consequently frequency will keep dropping & the system will collapse.

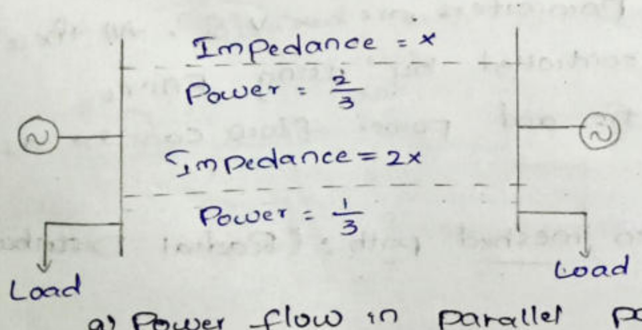
*) Alternatively if there is inadequate reactive power, the system can have voltage collapse.

*) When adequate generation is available, active power flows from surplus. generation areas to deficit areas and it flows through all parallel paths available.

*) By using parallel or meshed path power flow can be controlled as desired.

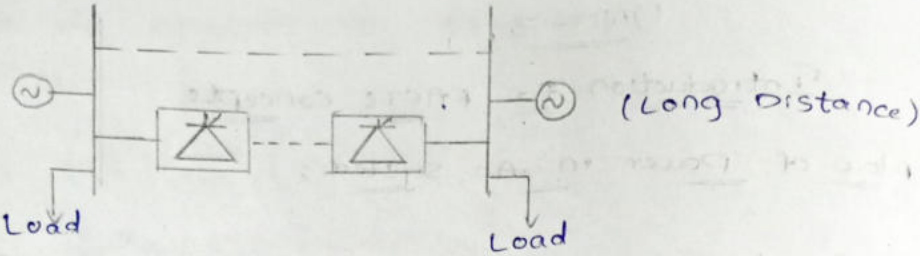
Necessity of AC power flow in parallel/meshed path:

(2m) Power flow in parallel paths:

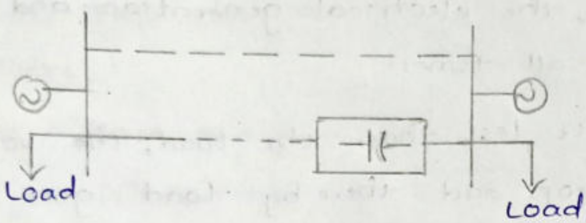


(Short Distance)

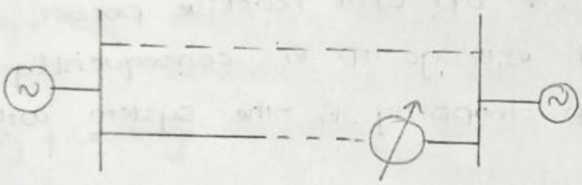
a) Power flow in parallel paths



b) Power flow control in HVDC



c) Power flow control with variable impedance



d) Power flow control with phase angle regulator

*) Power in AC systems is given by $P = \frac{V^2}{X} \sin\delta$

*) Power can controlled by varying 'x' and 'δ'

*) If the distance involved is long, power can be controlled by current control and HVDC transmission is performed.

*) Variable impedance is obtained by using variable capacitance.

*) Variable phase angle is obtained by using AVR - Automatic v/g Regulator / Phase Angle Regulator

*) the controlling Parameters in AC are x, V, δ. All these parameters are controlled by using FACTs devices in AC tr. and power flow can be as desired.

<u>Flow of power</u> in <u>meshed</u> path : (Radial Distribution Line)

Meshed path is used when interconnection of lines ~~and~~ 'δ' is required. and it provides power division.

*) When overload occurs, in order to compensate that meshed system in adopted. The controlling parameter in meshed system are V, $\overset{X}{\cancel{\delta}}$, and δ

*) Also v/g can be easily injected in meshed system.

*) In mesh network, if any one of line is overloaded, the line power can be controlled by FACTS controllers.

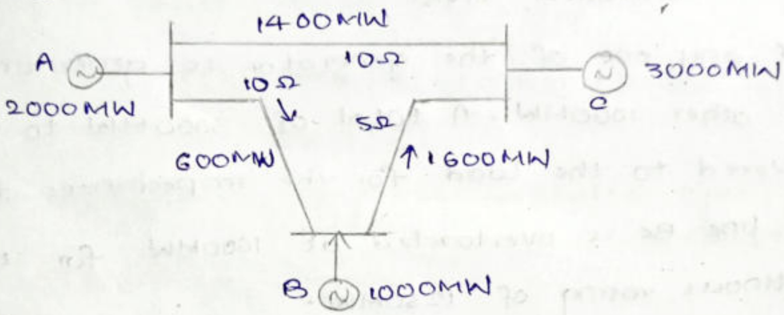


fig: Power flow in meshed system

Suppose lines AB, BC and AC have continous ratings of 1000MW, 1250MW and 2000MW respectively. They can carry twice those ratings in case of loss on any one of the line.

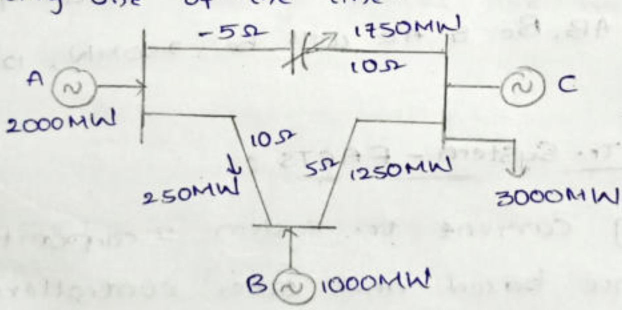


fig 1: Power flow control by using thyristor controlled series capacitor

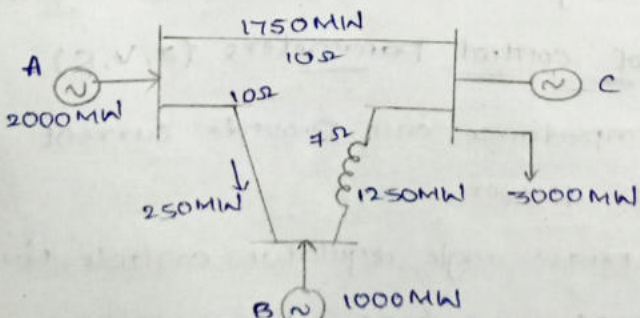


fig 2: Power flow control by using thyristor controlled series reactance.

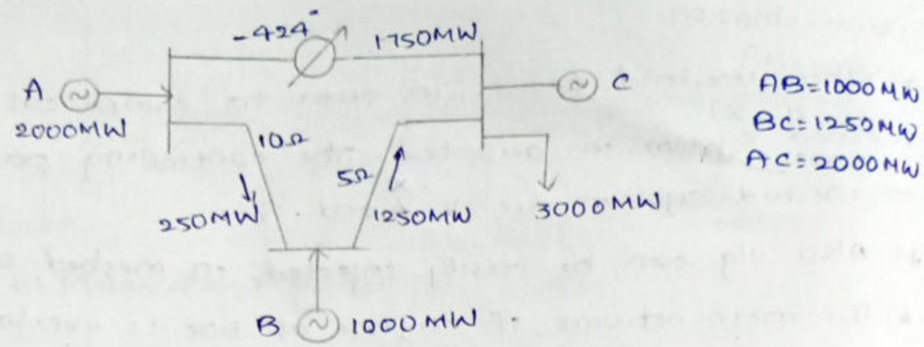


fig 3: Power flow control by using thyristor Controlled AVR.

If any one of the generator is generating 2000MW and other 1000MW. A total of 3000MW to be delivered to the load for the impedances shown. the line BC is overloaded at 1600MW for its continous rating of 1250MW.

Generation has to be decreased at B and increased at A in order to meet the load without overloading line BC. the capacitance whose reactance is -5Ω is inserted in L line it reduces the line impedance from 10Ω to -5Ω so that power flow in the lines AB, BC & AC will be 250MW, 1250MW and 1750MW.

Flexible AC Tr. System - FACTS :

Alternating current tr. system incorporating power electronic based and other controllers to enhance controllability and increase the power transfer stability.

4m V.I

Importance of control parameters (Z, V, δ)

i) Control of impedance can provide current control & other power.

ii) Control of phase angle regulator controls the V/g and current and hence the active power when angle is not large.

iii) Injecting the vlg in series with the line and with any phase angle can control the magnetic & phase of line current.

12m Types of FACTs Controllers : Why?

1) Series controllers — To compensate reactive power

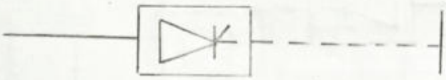
2) shunt controllers

3) Combined series - series controllers

4) Combined series - shunt controllers

FACTs controllers provide control of one or more Ac tr. parameters (V, x, δ)

1) Series Controllers (eg: SSSC -> static syn. series compensator)



All the series controllers inject vlg in series with line as long as the vlg is in phase quadrature with line current.

Series controllers consumes (or) supplies power. Every controller has storage devices like battery, capacitor fuel cell, SCMEs.

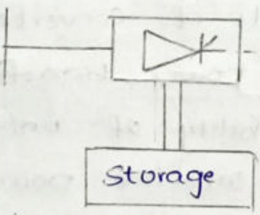
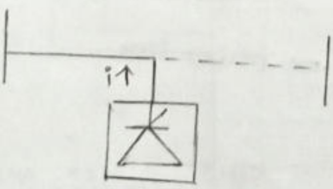


fig: Series controller with storage (battery)

2) Shunt Controllers : (eg: STATCOM)



All the shunt controllers inject current into the system line as long as injected current is in phase quadrature with line voltage.

Shunt controllers acts as a source (or) absorber of reactive power. Every controller has storage devices like battery, capacitor fuel cell. SCMES.

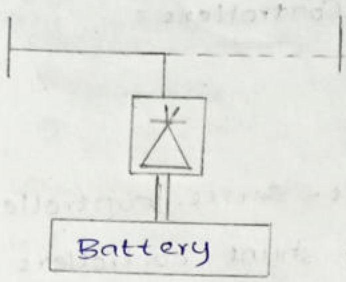


fig: Shunt controller with storage (battery)

3) Series - Series Controllers:

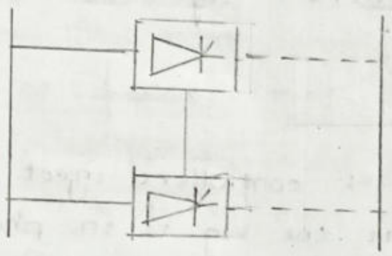
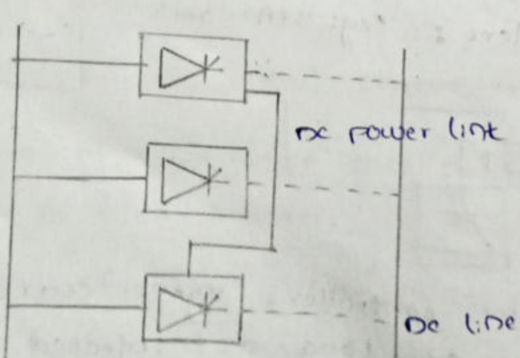


fig: Series - Series capacitor

It is a combination of series controllers coordinated in a multiline transmission system.

*) It is also known as unified controller. Unified means all the DC terminals of converters are connected together to real power transfer. The real power transfer capability of unified series controller is referred as interline power flow controller if it transfers both real & reactive power.



Note:

shunt, series → 2 line tr.

Series → v/g (Reactive power injected)

shunt → Current (Absorbed)

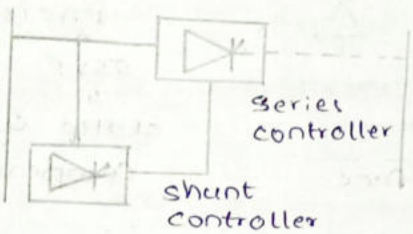
If any 2 controllers are interconnected then only series-series if there's no interconnection then only series controller.

Real power → UPFC - Unified Power Flow Controller

IPFC - Interline Power Flow Controller

Real & Reactive power

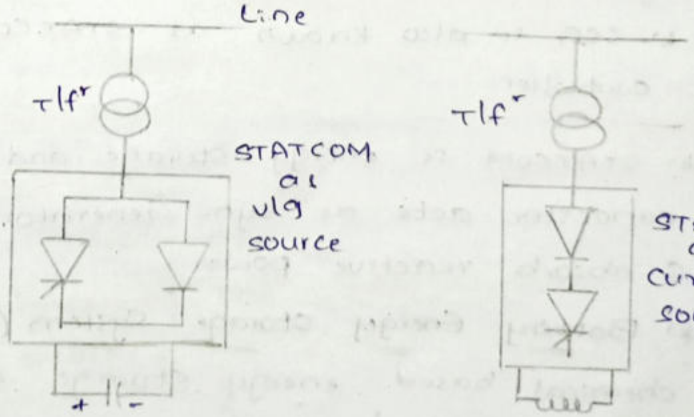
Series-Shunt Controller:



It is the combination of series & shunt controllers that provides control of real & reactive power.

STATCOM - Static Synchronous Compensator

Shunt controller



*) STATCOM is a type of shunt controller

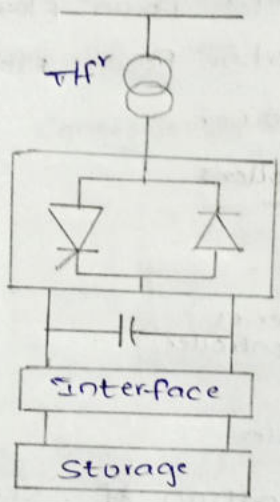
*) A STATCOM acts as v/g source if it is connected with capacitor & acts as current source if it is connected with reactor.

*) STATCOM is preferred to be act as v/g source rather than current source so that you can inject v/g into the system.

*) Diode is connected in parallel to make the commutation process easier.

*) shunt elements are always provided with external energy source i.e transformer.

Static synchronous Generator (SSG):



Interface is always w.r.t 'Dc'

FACTS ↑ SSSC ↓ static syn. Series Compensator

All the thyristor controlled devices are Impedance type (only reactor is controlled in impedance)

All the switching type devices are static type

*) SSG is also known as STATCOM / shunt controller

*) STATCOM is energy storage and large DC capacitor acts as syn. Generator to supply & absorb reactive power.

*) Battery Energy storage System (BESS): A chemical based energy storage system using shunt connected v/g source converters capable of rapidly adjusting the energy supplied / absorbed from Ac systems.