

* MODULE 1:

* Evolution of Power Systems.

Late 1870s Commercial use of electricity

1882 1st electric Power System (Gen → DC, cable, fuse, load) by Thomas Edison at Pearl Street station in NY.
- dc system (LV), 59 customers, 1.5km radius
- 110V load, underground cable, incandescent lamp

1884 Motors were developed by Frank Sprague.
→ with motor the type of load wasn't any longer restricted to 'lamps' & widespread applications were facilitated.

1886 Limitation of dc became apparent.
- High losses & vg drop
- Transformation of voltage required

Transformers & ac distribution (150 lamps) developed by William Stanley of Westinghouse

1889 1st ac Xmission system in USA between Willamette falls & Portland, Oregon.
- 1ϕ, 4000V, over 21km.

1888 N. Tesla developed polyphase systems & had patents of gen. motor, transformers, Xmission lines. Westinghouse bought it.

1890 Controversy on whether industry should standardise 'ac' or 'dc'.
Westinghouse advocated ac
- Voltage increase, simpler & cheaper gen. motors
(Hence, dc system got dismantled & ac become popular)

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1893 - 1st 3ϕ line 2300 V, 12 km in california
- ac was chosen at Niagara falls (30 km).

Early Voltage (Highest)

1922	165 kV — Vg was less due to ↓ advancement in insulating materials
1923	220 kV
1935	287 kV
1953	330 kV
1965	500 kV
1966	735 kV
1969	765 kV
1990s	1100 kV.

Standards are 115, 138, 161, 230 kV — HV
345, 500, 765 kV — EHV.

Earlier frequencies were
25, 50, 60, 125, 133 Hz : USA - (60 Hz) → US & canadian countries & some countries (50 Hz) - Europe & Asian countries
(It was realised 'f' should be same for interconnections, so the 'f' level along with 'Vg level' was standardised)

HVDC Xmission System:
A system of HVDC transmission was designed by a french engineer, Rene Thury when the ac system was in their infancy.

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1880 – 1911 At least 11 thury systems were installed in Europe. The prominent was Moutiers to Lyons (France) in 1906, 180 km (4.5 km underground cable) 4.3 MW, 57.6 kV, 75 A

DC series generators were used
– Constant current control mode of operation (DC).

- Safety issues
- Series Gen maintaince

⇒ In ac system, voltage is kept constant & 'I' varies as per load demand. In CCM the current is kept constant & the voltage is varied to control power.

1938 – 1920 All the thury systems were dismantled
Transverter were developed. It is poly phase transformer commutated by syncronously rotating bus gear. But not used commercially. (Used for Experimental purpose)
mechanical converters
After this, thury systems were forgotten & 'ac' systems dominated again

1950s Mercury Arc Valves → converters

1954 1st HVDC transmission between Sweden & Gotland island by Cable.

* Limitations of HVAC transmission

① Reactive Power loss:

$P_L = I^2R.$

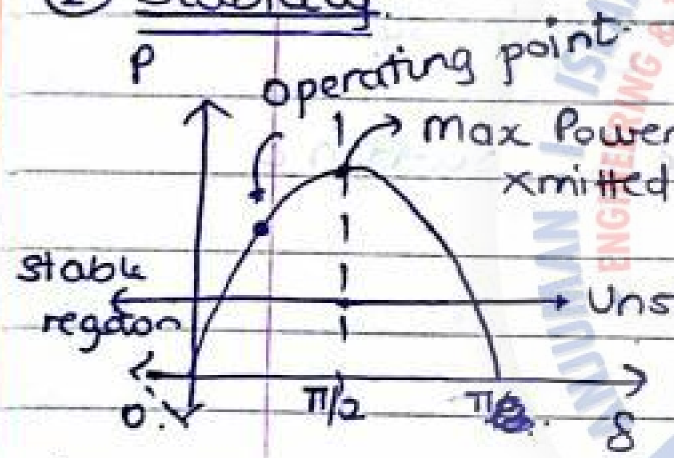
$Q_L = I^2X_L - \frac{V^2}{X_C}$

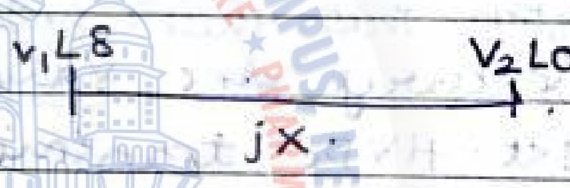
I^2X_L: Reactive Power consumed by element

$\frac{V^2}{X_C}$: Reactive Power generated by the element.

'X' is only prevalent is 'ac' & not in dc.
Hence no 'Q_L' loss in dc.
- Current has active & reactive component : No X, No reactive component : More active component can be transmitted ∴ ↑ Performance

② Stability:



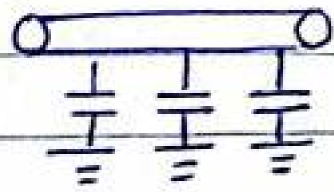


$P = \frac{V_1V_2}{X} \sin\delta.$

(1) Operating pt is always between '0' to '90'. Beyond 90° is unstable region.
(2) Normally δ is 20-30°
(3) In dc, there is no 'δ' only 'V'. ∴ no stability issues

③ Current Carrying Capability:

$I \rightarrow I_o + jI_m.$



(1) Active Current flow reduces if the reactive current flow is more on account of Capacitances over longer distance

(2) > 50 km the current carrying capability of 'ac' system is very less & its advised to go for the 'dc' system.

④ Skin Effect & Ferranti effect.

Skin effect : 'Tendency of ac current to flow on the surface.'
Effective area of current flow is ↓
$R = \frac{\rho L}{a}$ ∴ a↓ & R↑ & I^2R ↑.

- In dc no skin effect, so no loss.

∴ Rac is always > Rdc.

Ferranti Effect: 'At lightly loaded, or no load conditions recieving end voltage > sending end voltage, due to charging of capacitance to ground in long lines'

- Reactors are applied in order to reduce VR.

⑤ Power flow control:

Smooth control
- Its not possible in 'ac'. Power cannot be reversed. FACTS are used nowadays to control power in ac but before 90's it was not possible, so HVDC was used.

- So various HVDC links were set up for enabling control of power between regions.

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* Advantages of HVDC transmission.

(1) No reactive Power loss.
(2) No stability concern.

- In ac systems there are 3 governing factors of power transmission
  (1) Thermal limit (Governing limit when distance is ↓)
  (2) Stability limit (Governing criteria when distance is ↑)
  (3) Voltage regulation limits
  These three limits are to be taken care of
- In dc systems there is only one limit ie
  (1) Thermal limit (We can load Xmission line upto loading limit of what its designed without concern for stability & V.R limits)

(3) No charging current.

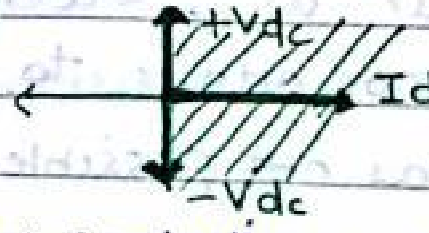
(4) No skin effect & Ferranti effect

(5) Power control is Possible.

→ $P_{dc} = V_{dc} I_{dc}$. } Here V_{dc} can be varied or I_{dc} can be varied or both can be varied to control P_{dc}
→. It is desired to have I_{dc} = constant & V_{dc} varyable.

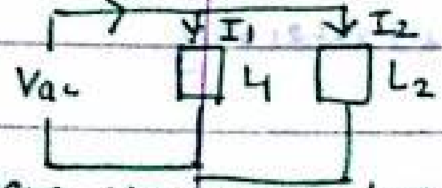
Pac =.

→ $P_{ac} = V_{ac} I_{ac} \cos\phi$. } We have a two quadrant operation ie
✓.



by controlling V_{dc} is '+' or '−' quadrant Power flow reversal can be obtained by keeping 'I_{dc}' constant.

- In ac system voltage is kept constant & current varies as per the load for eg.



Here Vg across load is same & current is divided ie loads are always connected in parallel.

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(6) Requires ↓ space as compared to ac for same voltage rating & size

- Consider 400 kv system. 400 kv is rms value. We have to design system in terms of peak value

$\therefore V_{peak} = 400\,kv \times \sqrt{2}$.

$P_{dc} = 2 V_{dc} I_{dc}$

$P_{ac} = 3 \frac{V_{ac(peak)}}{\sqrt{2}} I_{dc} \cos\phi$.

$\therefore$ for same voltage Rating $P_{dc} \equiv P_{ac}$

$\therefore$ Saving in ; (1) Insulators (because ac req 3 conductor & DC only 2 conductor)

(2) Cross-Arms.

(3) Towers.

(4) Substation clearance.

(7) Ground can be used as a Return conductor :

- There are 3 types of links : (i) Monopolar
(ii) Bipolar
(iii) Homopolar.

- In monopalar there is one wire & ground is used as a return ~~conductor~~ path.

∴ Cost of conductor is ↓

- It has disadvantages (i) Communication Interference
(ii) Erosion of mettalic bodies under the earth ie pipes
(iii) Safety hazards.

- Hence is it used in emergency condition ie when there is problem in one pole then the ground can be used as return path for limited time.

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(8) Corona Loss & Radio Interference :

(1) Corona loss ∝ f + 25
- in dc no 'f' so ↓ Corona loss.

(2) RI frequency is zero ∴ very low Radio interference due to haromics only.

⑨ Cheaper for long distance transmission

⑩ Asyncronous operation is possible
⑪ No switching transient
⑫ No transmission of SC power
⑬ No compensation problem.
⑭ Low SC current
⑮ Fast fault clearing time.

* Disadvantages of HVDC transmission.

① Cost of terminal equipment is high
② Introduction of harmonics
③ Blocking of reactive power
④ Point to point transmission
⑤ Limited overload capability
⑥ Huge Reactive Power Requirements at Converter terminals

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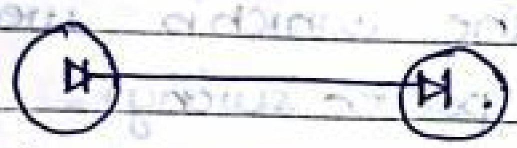
*3 configurations of HVDC systems

① **Bulk Power transmission** (Long Distance).



- Transmission of huge power over long distance without tapping
- Generation cost is high for high loads seperated by a long distance. (HVDC).
- For eg if power is to be transmitted from North-east of India to central part. Huge HVDC links are required
- Concept of just transmitting the power.

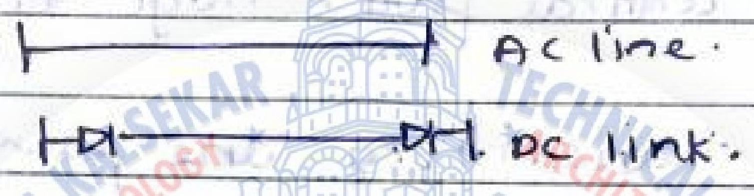
② **Back to Back HVDC.** (Control of Power).

- Here concept is to control the power.

- The two converters are installed very close to each other maybe less than 1km
- Purpose is we can monitor the power from one region to another region. Hence its called Back to Back.
- Here we dont want to transmitt Bulk power, but we want to control the power based on the contract or negotiations.
- If there is a problem in one region, then with a back to Back connection we can open the link & dissallow the propogation of the fault to the other heathy region.
- In the above case, if it was ac line, the disturbance will be certainly propogate to the other end. If both system is not protected well then both collapse

③ Modulation of Ac (Stability).

- Consider you have an ac line which is weak ie there are power oscillations, power swings.
- A small HVDC link can be constructed to support the ac line such that when there is a problem in ac line, the dc link can be controlled to modulate power in ac line.



- Hence the link is used to improve the stability of ac line.

Note:

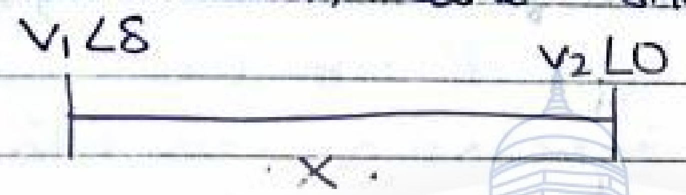
(1) In HVDC transmission we have the generation of power in 'ac' & then its converted into 'dc' by rectifiers transmitted over long distance, converted back to 'ac' by means of inverters and the 'ac' is used for powering the load.

(2) We can have the integration of renewables into the grid after 'dc' to 'ac' conversion.

* Comparision between HVAC & HVDC transmission

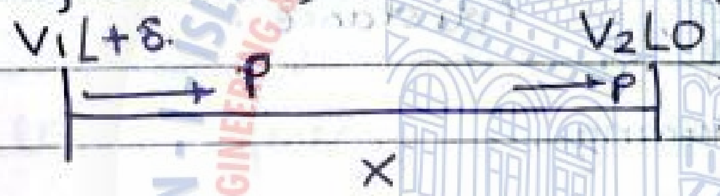
* Voltage control:

Consider a transmission line shown below;



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

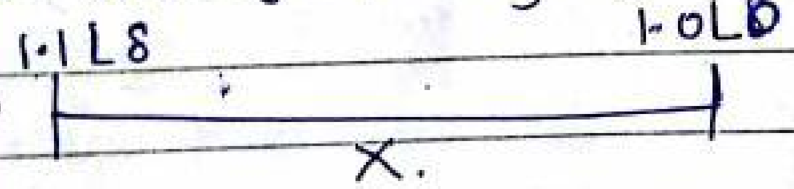
- If δ is positive, Power will flow as follows & it will be unidirectional)



- If δ is negative, the 'P' is reversed.
- In other words P flows from higher 'δ' to lower 'δ'.

- And, Q flows from higher 'V' to lower 'V'.

Consider the following eg;



In the above case it seems reactive power flows from 1·1 to 1·0 end but that doesnt hold true. Because that depends on the transmission line loading as well.

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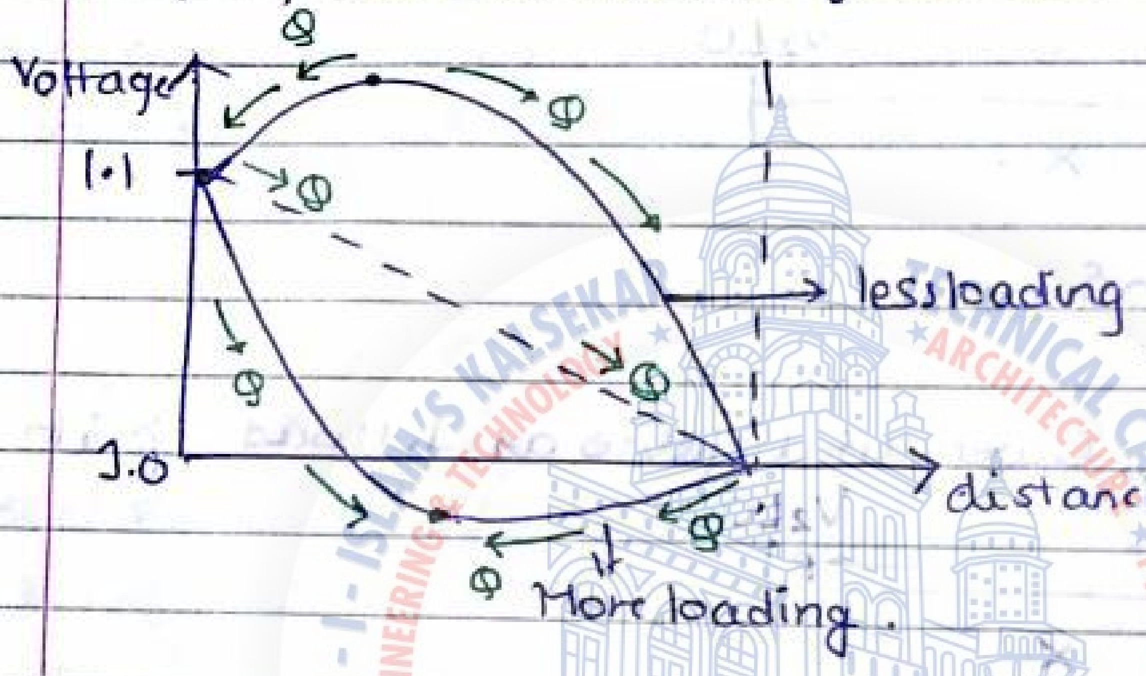
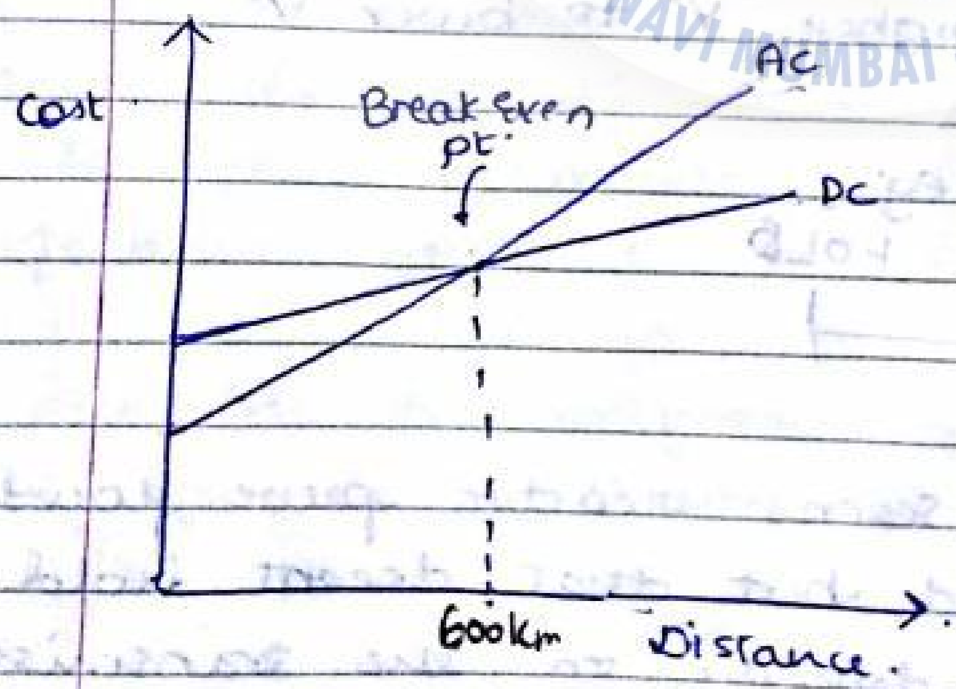
- No doubt 1·1 > 1·0, we dont know the voltage profile of the line. There may be distributed capacitances in the line causing the voltage to increase or decrease.

- The voltage profile of the line for different loading are;



- From above, it is clear that 'Q' is not unidirectional but 'P' is.

• Cheaper for long distance Xmission:



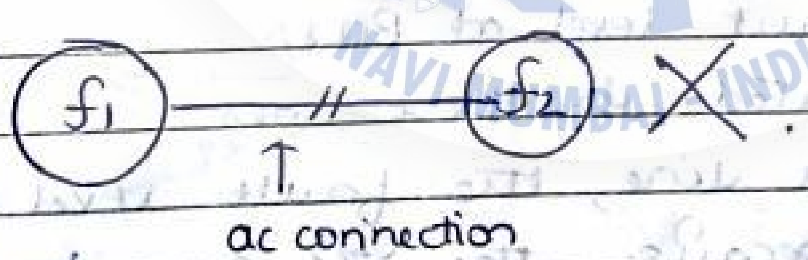
- < Break even pt 'dc' is expensive
- > Break event pt 'ac' is expensive.
  - → use of compensation of large charging 'I'
  - use of compensating devices to control voltage at various points

- Above 600kms 'dc' is a better option.

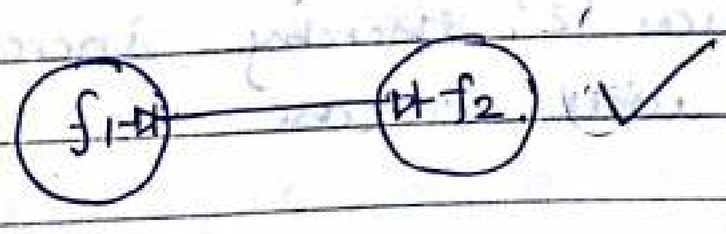
- If our intention is just the control of power maybe between 1km distance instead of flow of Bulk power over longer distance; HVDC can be employed in terms of 'Back to Back' connections. Here Price shouldn't be an issue since 'control' is of primemost importance.

• Asyncronous Operation is possible:

- In an ac system, the freq of the interconnection should be the same in the steady state.
- If the two systems are at different frequencies you cannot connect them via 'ac'. Option is you have to connect via 'dc' system.
- For eg If we have a system operating at freq f_1 & another system having freq f_2 then we cannot connect the two by 'ac'.



Instead we have the 'dc' interconnections.



- This is known as asyncronous connection where two frequencies are connected by dc lines.

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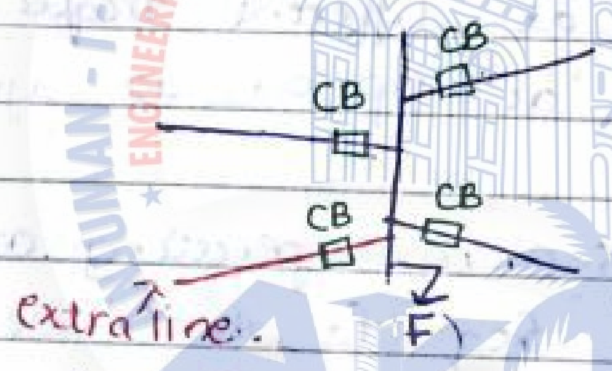
• No switching transient

- Switching transients arise due to energy storage elements ie 'L' & 'C'. If the ckt is purely resistive, there wont be transient at all. But the presence of 'L' & 'C' results in transients whose magnitude depend on the magnitude of 'L' & 'C', their distribution, (No of elements)
- There is no 'L' & 'C' in 'dc'

• No transmission of Short Circuit Power.

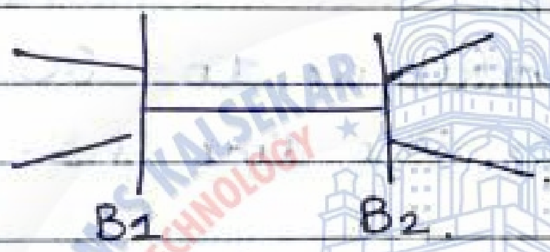
- In AC system consider many lines connected to a bus;



- We calculate the fault level at the Bus. We go for the 3ϕ SC and calculate the fault level at Bus.
- The fault is contributed by these lines
- If you connect extra line, the fault level of the bus will increase because the 'Z' seen by the fault to ground will be the parallel of the 'Z' of lines which reduces 'Z', thereby increasing fault level & the SC current will increase

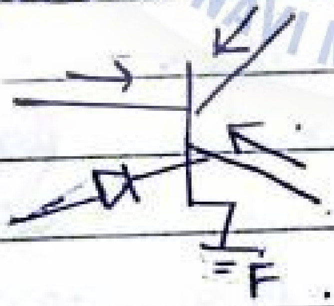
- There are many cases in india where a single bus connects large no of lines. So if there is a fault at the Bus, the CBs of the lines should be tripped. The rating of the CB is decided by this fault level.

- As the lines are connected, the CB of the other lines need to be changed as the fault level has been increased.
- In the case above where alot many lines are connected, we go for bus splitting.



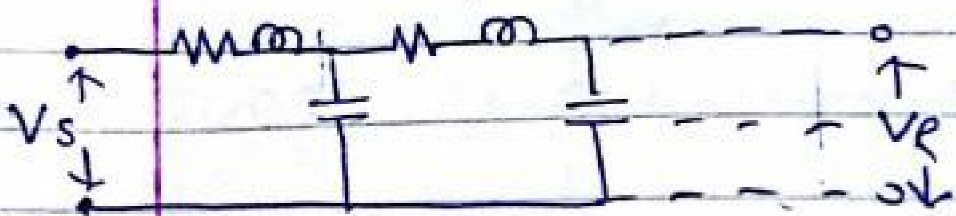
- With this arrangement the fault level at each bus is reduced & the cost of replacement of CB can be avoided.

- With the HVDC system there is no contribution to the SC power by the dc line as it can be controlled. ie it blocks the fault current to the bus



• No compensation problem:

- The general eq ckt of a long ac line is



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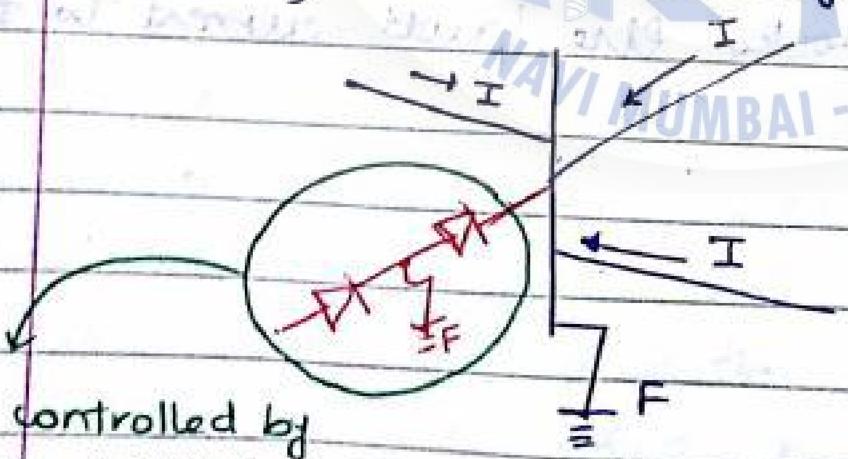
- Due to the presence of capacitance, there is generation of reactive power & some means has to provided for absorbing the same [compensating device].
- In 'dc' no such problem arises & therefore no requirement of compensation.

• Low Short Circuit Current:

- As the 'HVDC' link do not contribute to SC power at a bus with multiple lines. The line has a low S.C current.

• Fast fault clearing time:

- By controlling the switching of the device in a fast manner & effectively, we can maintain the stability of our system.
- Fast clearing can be therefore achieved.



Can be controlled by controlling switching to avoid the fault to propagate to the bus.

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- Basically in ac system, the fault clearing is done by a combination of relays & CB. Relays sense the fault & signal the CB to trip. The CB after a certain time lag trips. The CB is a mechanical device as opposed to fast electronics used in HVDC to clear faults.
- ∴ HVDC fault clearing is extremely fast than 'ac' system.

* more Reliable than AC
* Ground 'Z' is ↓ for DC

* Disadvantages of HVDC transmission

• Cost of terminal equipment is high.

- Initial cost is high due to the equipments used especially the converters, cooling devices for converters, use of filters, cooling arrangements for filters therefore a lot many auxiliaries are required for 'DC' transmission.
- With the advancement of power electronics devices the cost will reduce in near future but the present case scenario is that the cost of 'HVDC' station will be much more than an 'ac' station for the same rating.

• Introduction of Harmonics:

- In the beginning the use of valves was widespread, then came the thyristors, then GTOs and now the IGBTs for the converter technology.

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- When thyristors were used there was an inherent problem that it could not be turned off automatically. It required some components or devices to turn it off
- Now with GTOs we can turn on/off and we can go for pulse width modulated converters thereby we can reduce the harmonics
- In conventional gate thyristors we have the harmonics as,

$$= np \pm 1$$

n → integer, p → No. of pulses.

• $n = 1$; $np \pm 1 = (1)(6) \pm 1 = 5, 7$

• $n = 2$; $np \pm 1 = (2)(6) \pm 1 = 11, 13$

- For 6 pulse converter, using conventional thyristors 5, 7, 11, 13, ... are the harmonics produced & they are known as the "Characteristic Harmonics".

- There are other harmonics generated due to overlapping of one valve conducting & other valve is going to be off with a time lag. These are known as "Uncharacteristic Harmonics"
- If these are not removed/filtered out properly they will propogate to ac system & cause so many other problems.
- So filters have to be employed to remove these unwanted harmonics.

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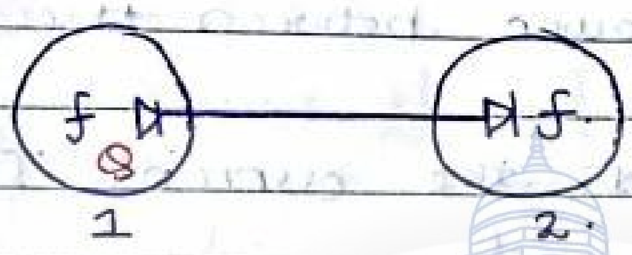
• Blocking of Reactive Power:

- Consider there are two regions connected by HVDC link. The frequency at the two ends are same.



- If reactive Power were to be transmitted from Region 1 to 2, it cannot be possible because 'DC' does not support reactive power concept.
- Now the Question arises 'why we req. the Reactive Power in Region 2'?
- Reactive Power supply/absorbtion is a local phenomena, we dont want the Reactive power to flow from Region 1 to 2. Reactive Power should be compensated locally. Real power on the other hand is a global phenomena & so the freq of the two systems should be the same.
- Sometimes during emergency conditions, Region 2 may require some reactive Power support due to some problem in Region 2.
- The HVDC system thus cannot supply 'Q' in these emergency conditions ie it blocks the reactive power.

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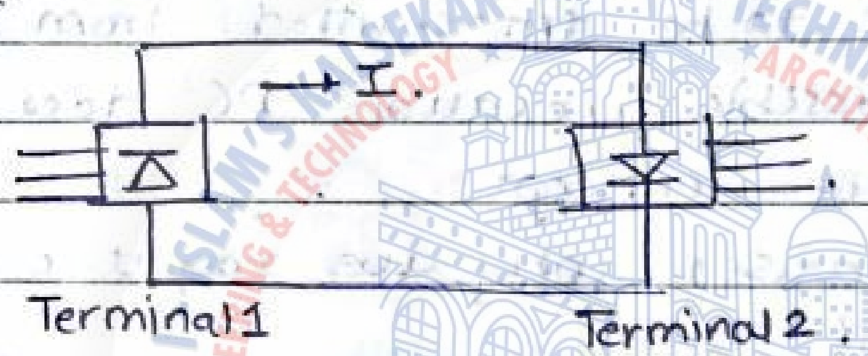
• Point to Point transmission.

- Fig shows the basic connection of HVDC transmission with the rectifier & inverter at either ends.
- Point to Point transmission means that there cant be any tapping of power between the two converters
- This is due to the fact the current 'I' in the link is held constant



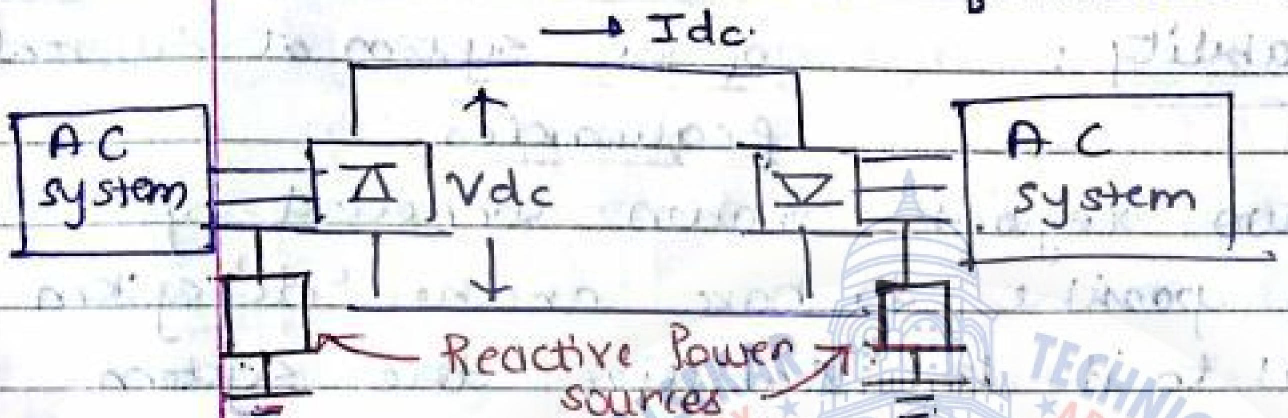
- This is the two terminal HVDC link & the power injected from one end can only be tapped out the other end.

• Limited overload Capability.

- The converters employ power electronic devices which have limits on voltage & current rating.
- Hence exceeding that rating results in excessive loss and there is a possibility that the switching device may damage.
- Hence, converters have limited capabilities & even for short duration we cannot go for high power transfer/overloading of the power system.

• Huge Reactive Power Requirement at the converter terminals.

- As shown in the fig, we have the rectifier end & the inverter end which form the terminals.



- As a thumb rule if the rating of this line is 100MW then the reactive power requirement at the two ends is 60% of Reactive power sources at both end of convertors
- No doubt that there is no reactive Power involved between the converters.
- The Reactive Power is requird at the converters thyristors ; we have

$\cos\phi = \cos\alpha$ → firing angle.

- So by changing α, Vdc will be varied to control power
- With increase in 'α' value, cos φ reduces & therefore we require compensating device to maintain that we should not draw huge Reactive Power from ac system

- With PWM techniques applied to GTOs & IGBTs the '60%' value can be reduced but still the requirement of reactive power at the terminals will be said to be high.

* Applications of HVDC.

① Bulk Power transmission

② Power flow Control.

③ To provide stability :

④ The underground / submarine cables

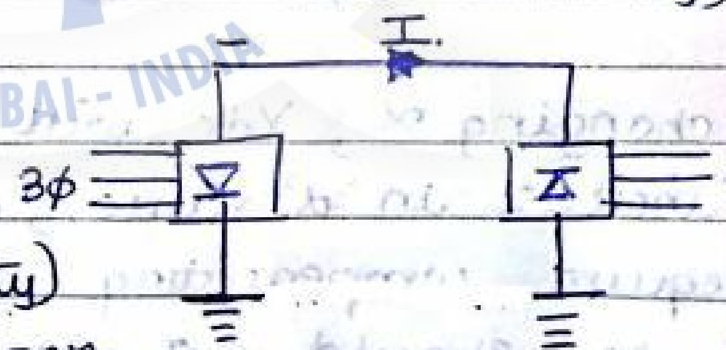
⑤ Asyncronous connection of ac system at different frequencies.

- Consider the two regions shown connected by ac tie line. It's possible to have another 'dc' system running parallel to it to stabilize the system
- If the 'ac' tie line is weak and some problem occurs the tie line may be tripped
- With the 'dc' system we can quickly control the power flow from region 1 to 2 & thereby stabilize the system very efficiently.

* Types of HVDC links:

(negative Polarity)

(1) Monopolar. (One wire)



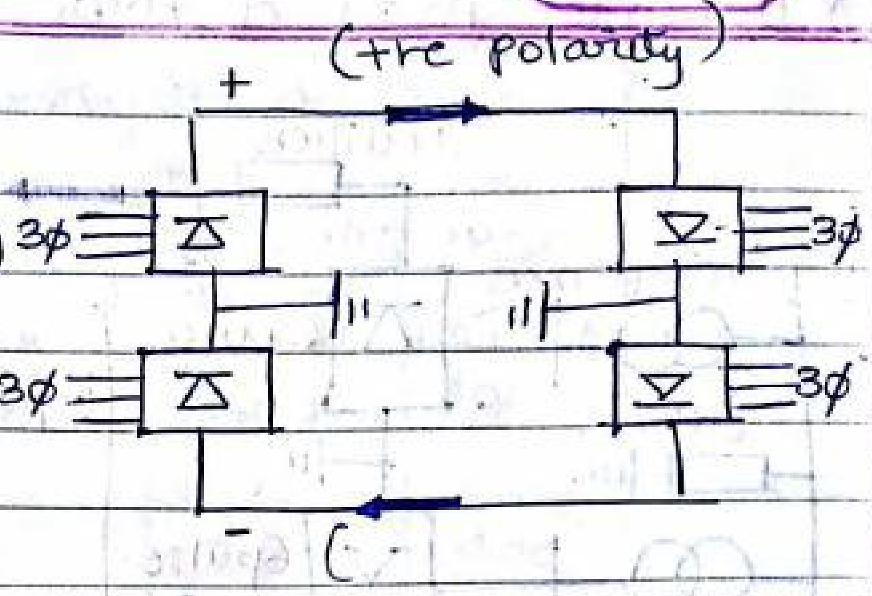
- Having one conductor (-ve polarity) & ground is used as return path.

- Negatively Polarity has the less corona loss than +ve polarity.

DisAdv

- Major drawback is that if there is problem in the conductor, we have to stop power flow.
- The current in the ground causes corrossion of metallic parts underneath earth eg pipes

(2) Bipolar (Two wires)

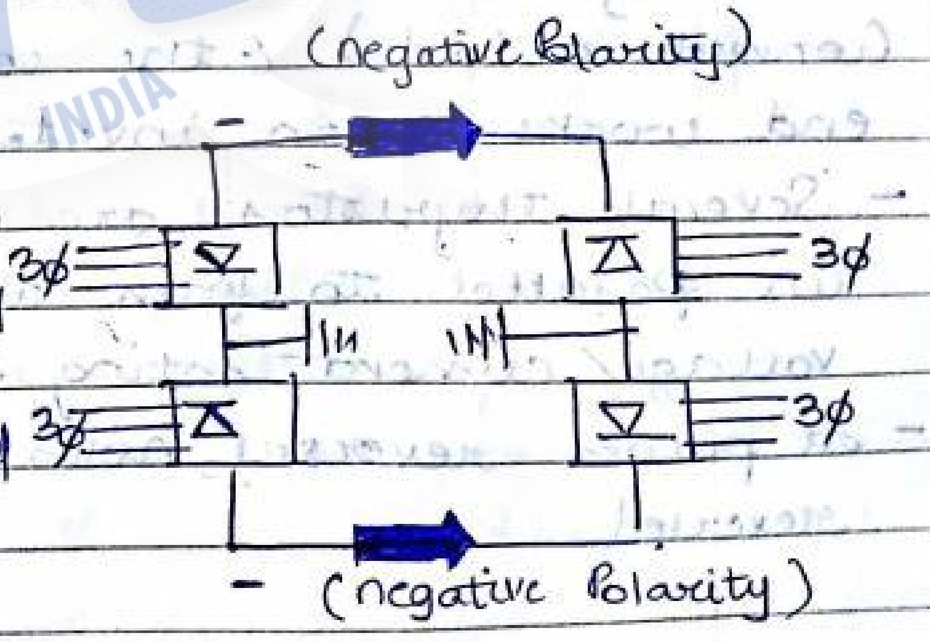


- There are two conductors (Poles)
- One operates at +ve polarity and other is on −ve polarity
- During fault in one pole, it works as monopolar.
- Under normal operation there is no dc current in ground.

Advantage:
- If there is any problem in one pole, it can be dissconnected & half the link can be operated in monopolar fashions with ground return ∴ ↑ reliability

- Rihand To Dadri HVDC system is operated at ± 500 kV the '+' & '−' sign indicate the polarity of the links of the bipolar system. Note: "Twice of the Power flows since we have +500 kV & −500 kV"
- Most popular & widely accepted system.

(3) Homopolar



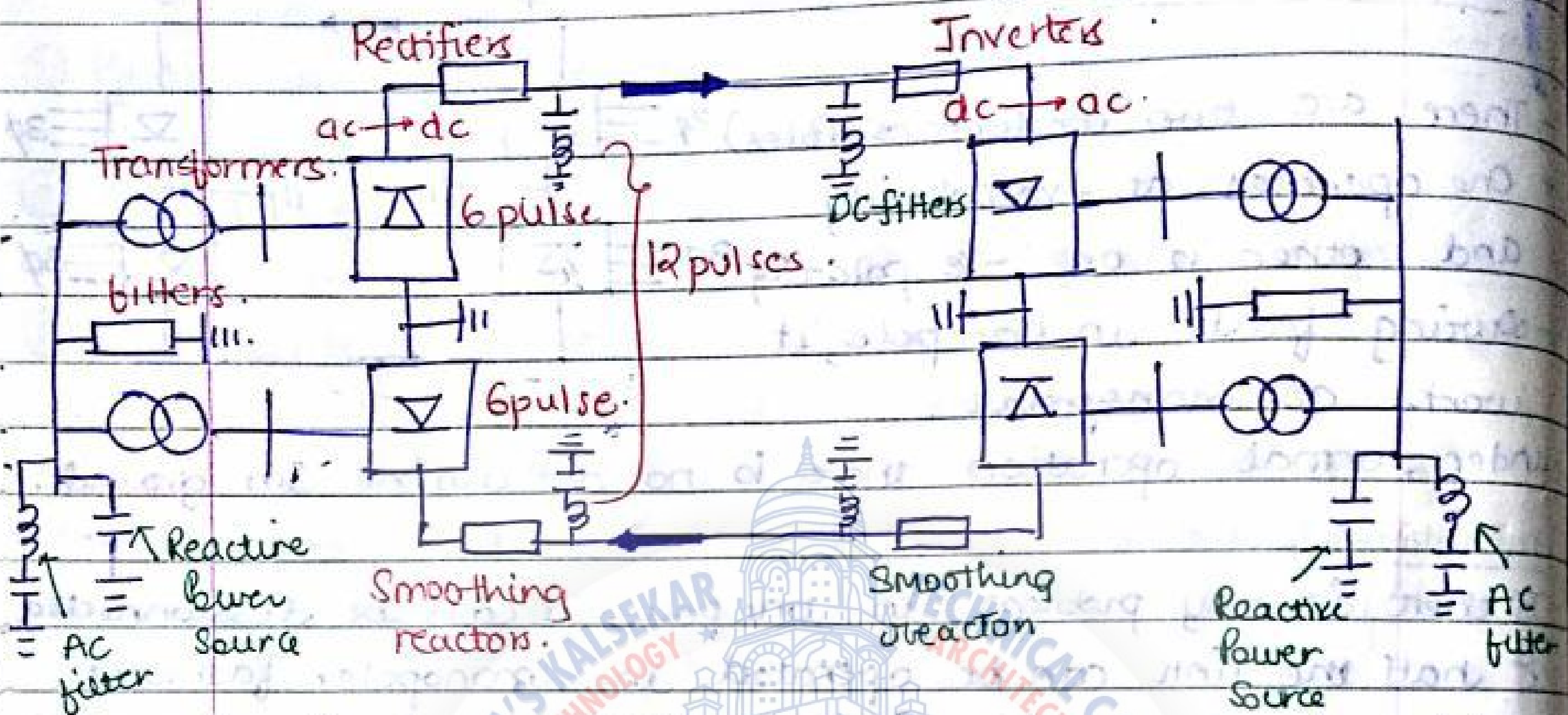
- Two or more conductors having the same polarity
- Normally (−ve polarity) is used (↓ Corona loss & ↓ RI)

DisAdv
- Ground is always used as return path.

Adv
- During faults in one pole it works as Monopolar.

Note: "Here also twice the power flows"

* Principle parts of HVDC system:



- Normally 6 pulse or 12 pulse operations are adopted in HVDC systems.

① Converter

- Converters are the main parts of HVDC system.
- Each HVDC line has two converters one at each end.
- Sending end converter works as a rectifier (converts ac to dc) & the converter at the recieving end works as an inverter (converts dc to ac)
- Several thyristors are connected in series/and or in parallel to form a pulse to achieve higher voltage/current rating.
- At power reversal, roles of rectifier & inverter are reversed.

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• Comparision of power semiconductor devices

	Thyristor	GTO	IGBT	SI thyristor	MCT	MOSFET
Max vg rating (V)	8000	6000	1700	2500	3000	1000
Max 'I' rating (A)	4000	6000	800	800	400	100
Voltage blocking	Sym/ Asym	Sym/ Asym	Asym	Asym	Asym/ sym	Asym
Gating	Pulse	Current	Voltage	Current	Voltage	Voltage
Conduction drop (V)	1.2	2.5	3	4	1.2	Resistive
Switching freq (KHz)	1	5	20	20	20	100
Development target max voltage rating (KV)	10	10	3.5	5	5	2
Development target max current rating (KA)	8	8	2	2	2	0.2

* SI – Static Induction.

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- Consider an eg; For a monopolar operation we require 100 kV, 1 kA, 100 MW.

No of 5kV thyristors required in series = 20.
But we always go for higher no of thyristors in series for redundancy.

- Now if the thyristors are rated 5kV, 1kA, again we need to provide thyristors in parallel for improved capability.

- We have to go large no of series/parallel combination to increase voltage/current rating

- Sometimes instead of having valves we have the converters in series to increase voltage/current capability

- The current rating of converter stations can be increased by putting
    - Valve in parallel
    - Thyristors in parallel
    - Bridges in parallel
    - Combination of above.

- Voltage rating of converter stations can be increased by
    - Valves in series
    - Bridges in series
    - Combination of above.

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- Bridge converters are normally used for HVDC transmission system

→ The major Requirement of the valves:

- To allow current flow with low vg drop across it during the conduction state & offer high resistance during non-conducting state
- To withstand PIV (Peak Inverse Voltage) during non-conducting period.
- To allow resonably short commutation margin angle during inverter operation
- Smooth control of conducting & non conducting phases.

- Types of converters:
- Two versions of switching converters are feasible depending on wheather the DC storage device is utilized is
  - an inductor → called current source Converter (CSC)
  - a capacitor → called voltage source (VSC)

- CSC is used in traditional HVDC transmission
- VSC is used in SVC, STATCOM, active filters etc.

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CSC	VSC
Inductor is used DC side	Capacitor is used in DC side
Constant current	Constant voltage.
Higher losses ['I' is constant. I^2R loss is constant]	More efficient [Depending of load 'I' varies so I^2R varies].
Fast accurate control.	Slow control [Due to capacitor]
Larger & More expensive [req smoothing reactor]	Smaller & less expensive
More fault tolerant & more reliable.	Less fault tolerant & less reliable comp
Simple Control	Complex control.
Not easily expandable in series	Easily expanded in parallel for increased rating

- HVDC transmission requires the use of 'CSC' converters.

② Converter transformers:

- For 6 pulse converter, a conventional 3ϕ or 3 single phase transformers are used.

- For 12 pulse converter configuration, following transformers are used
  - 6 single phase two winding
  - 3 1ϕ three winding
  - 2 3ϕ two winding

- In converter transformer it is not possible to use winding close to yoke since the potential of its winding connection is determined by conducting valves.
- Hence entire winding is completely insulated.

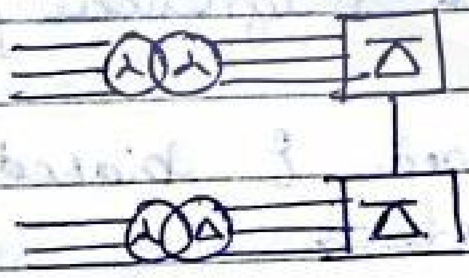
- These are special type of transformers equipped to handle harmonics & transients associated with switching.
- These are the OLTC (On line tap changing) type. They have tappings that keep on changing very frequently.

- leakage flux of the converter transformer contains very high harmonic contents it produces greater eddy current loss & hot spots in Transformer tank.

$P_{hys} = K_1 f B_m^n$ ($\because n = 1.6$)
$P_{eddy} = K f^2 B_m^2$

} They are related with 'f'. More 'f' of harmonics more Ph & Pe losses & so hot spots in Xmer.

- In case of 12 pulse configuration, if 2 3Ø transformers are used, one will have λ-λ connection, other will have λ-Δ connection to give phase shift of 30°.



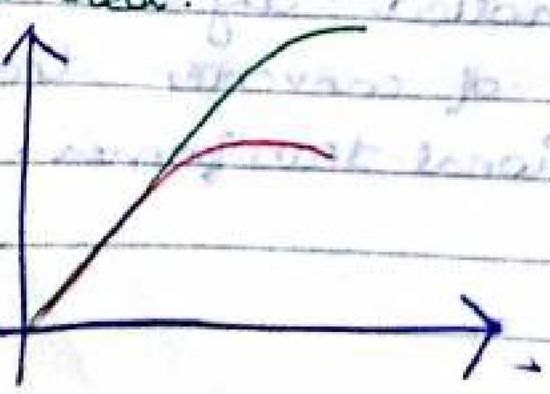
[it is shifted by 30° to get '12' pulses in one cycle].

- Since fault current due to fault across the valve is predominantly controlled by transformer impedence the leakage impedence of converter transformer is higher than conventional transformer.

- On line tap changing is used to control Voltage & reactive power demand.
[There are two kinds Off line Tap changer where the Xmer is disconnected & tap is changed & then it is reconnected & On line tap changer where one side taps are provided to automatically vary voltage applied to converters during operation. Some special arrangements are made to avoid sparking during change of taps. Controllers used at the converter vary converter voltage to output a constant 'I'. In case this is not possible it controls the converter transformer tappings to control the voltage]

③ Smoothing reactors

- These reactors are used for smoothing the dc current o/p in the dc line
- It also limits the rate of rise of fault current in the case of DC line SC (Short circuit)
- Normally partial or total air cored magnetically shielded reactors are used
- Disc coil type winding are used. & braced to withstand the short circuit current.
- The saturation inductance should not be too low
[Saturation slope should be as shown by green as opposed to red.



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④ Harmonic filters :

- Harmonics (characteristic harmonics (5, 7, 11, 13)) generated by converters are of the orders of np ± 1 in AC side & np is DC side where p is no of pulses and n is the integer
- Filters are used to provide low 'Z' path to the ground for the harmonic currents.
- They are connected to converter terminals so that harmonics should not enter AC system
- However it is not possible to protect all harmonics from entering ac system.
- Magnitudes of some harmonics are high & filters are used for them only.
- These filters also provide reactive power compensation at the terminals.

[tuned filters are employed which are tuned to a specific harmonic freq & offer ↓ Z path to that harmonic current & at the fundamental freq it offers reactive power support]

⑤ Overhead lines :

- Monopolar transmission scheme is most economical & the 1st consideration is to use ground as the return path for DC current
- But use of ground as conductor is not permitted for longer use & a bipolar arrangement is used with opposite currents in both poles.

- In the event of failure in any poles, ground is used as a return path temporarily
- The basic principle of design of DC overhead lines is almost same as AC line design such as configurations, towers, insulators etc.
- Bundling of conductors is done to reduce corona loss. In India for 500 kV dc. 4 subconductors are employed to form one whole conductor
- In dc the operating voltage = Peak voltage.
in 'ac' ~~operating voltage~~ Peak voltage = $\sqrt{2}$ Vrms.

- The number of insulators & clearances are determined based on dc voltage.
- The choice of conductor depends mainly on corona & field effect considerations.

⑥ Reactive Power Source :

- As such converter does not consume reactive power but due to phase displacement of current drawn by the converter & the voltage in AC system, reactive power requirement at the converter station is about 50-60% of real power transfer, which is supplied by filter, capacitors & synchronous condensers.
- Syncronous condensers are not only suppling the reactive power but also provide 'ac' voltages for natural commutation of the inverter.

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- Due to harmonics & transients, a special designed m/c is used (in syncronous condensers).

⑦ Earth Electrodes.

- The earth resistivity at upper layer is higher (~4000 ohm-m) & electrodes cannot be kept directly on earth surface.
- The electrodes are burried into the earth where resistivity is around 3-10 Ω/m to reduce transient over-voltages during line faults & also gives low DC electric potential & potential gradient at the surface of earth.

- The location of earth electrode is also important due to
  - Possible interference of dc current ripple to power lines, communication systems of Telephone & railway ~~systems~~ signals etc.
  - Mettalic corrosion of pipes, cable sheaths etc.
  - Public safety.

- The electrodes must have low resistance <0.1Ω & burried upto 500m into earth.

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*Choice of Voltage Level:

- Consider that the system is to be operated at 1000 MW. It is decided to go for bipolar lines. We now have to decide what will be the voltage level.

$P_{dc} = 2 V_{dc} I_{dc}$ (2 → Bipolar)

*Modern trends in HVDC technology:

- The major contribution of these developments is to reduce the cost of converter stations while improving reliability & performance.

① Power Semiconductors & Valves:

- Cost of the converters come down if the no of series / parallel connected devices is reduced.
- The recent technology has enabled the voltage & current ratings of the thr device to increase
- The development of light triggered thyristors (LTT) should improve reliability of system.
- By using zinc oxide gapless arrestors & protective firing methods the cost of valves has reduced
- Power rating of thyristors is increased by better cooling methods. Deionized water cooling has reduced losses in cooling.

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- The power rating of 12 pulse converter has increased to 3000 MW at 500 kV.
- (LTT) valves rated at 125 kV, 2400 A are used at Sakuma freq converter station in Japan
- (LTT) Valves rated at 133 kV, 2000 A have been in operation in the Celilo converter station
- (GTO) thyristors are available at 6 kV, 4000 A.
- (IGBT) converters are available at ±150 kV and 350 MVA rating.

② Converter Control:

- Microcomputer based converter control equipment has made it possible to design systems with completely redundant converter control with automatic transfer between systems in case of malfunction.
- FOR (forced outage Rate) of the control equipment is reduced & also it is possible to perform scheduled preventive maintainence on the standby system when the converter is in operation
- Use of mini-simulator to check vital control & protection functions.
- hybrid-optical measuring systems have been used to replace the traditional transducers which are bulky & prone to problems during transients.

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③ DC breakers :

- Prototyping & testing of DC breakers are done & may be the upcoming trend of HVDC.
- With DC breakers tapping of existing DC link is possible.
- There may be development of MTDC (Multi-terminal DC links) with the advent of DC breakers.

MTDC

④ Conversion of existing ac lines:

- Some utilities are are exploring the option of converting existing AC systems to DC in order to increase the power transfer limit & to get rid of ROW (Right of way) problems.

⑤ Operation with weak AC systems:

- The strength of AC systems connected to the terminals of DC link is measured in terms of SCR (Short Circuit Ratio) which is defined as

$$SCR = \frac{\text{Short circuit level at Converter Bus}}{\text{Rated DC Power}}$$

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- use of fast reactive power control at converter bus by applying static VAR systems is a solution.
- Also by the use of converter control the dynamic overvoltages have been limited.

⑥ active DC filter:

- A hybrid filter made up of active filter (VSC) in series with passive filter has been developed to improve filtering of harmonic currents flowing in HVDC lines.
- This filter eliminates both characteristics & well as uncharacteristic harmonics.
- In india, chandrapur - Padghe HVDC project uses active filter in each pole.

⑦ Capacitor commutated converter: (CCC)

- This involves the connection of commutating capacitors in series with valve side windings of the converter transformer.
- Advantages of CCC:
  - Improved voltage stability when operating with weak AC systems.
  - Reduced risk of commutation failures
  - Less load rejection overvoltages
  - less reactive power requirements.

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⑤ UHV DC transmission:

- Ultra high voltage DC transmission ± 800 kV is being considered for transmission of large blocks of power above 3000 MW for distances beyond 1500 km in China, India, etc.
- A Bipolar HVDC line operating at ± 800 kV can transmit power in the range of 5000 - 6000 MW with 2 twelve pulse converters / pole.

* Some operating Problems:

① Converter transformers:

- Major problems areas are
  - turn to turn failures
  - leads & cleat failure
  - DC bushing failure

- During high firing angle operations, the commutative transients cause problems in converter transformer
- In addition to commutation transients, other high frequency transients generated by adjacent system (AC or DC) may cause internal winding resonances that can pose problems.

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② Flashover performance of HVDC converter station insulators:

- Insulators such as wall bushings, capacitive voltage dividers, voltage transformers suffer external flashovers caused by rain, fog snow & ice.
- Recently dry type bushing (with SF_6 insulation) have been developed which are also safer from fire risks.

③ Valve Hall fires:

- Leakage in cooling system may cause the fire in in the converters.
- Valve hall fires have been experienced in Itaipu (Brazil), Rehand (India), Sylmar (USA) & Gezhouba (China).

④ Problems of Ground Returns:

- Creates problems with buried metallic structures & 3ϕ transformers with grounded neutral.
- The dc current may flow through neutral of transformer & into AC lines & saturate the magnetic cores unequally.
- At higher value of DC currents the transformer may overheat due to increased iron losses.

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- We can use blocking devices (Capacitor in shunt with protection arrestor), neutrals can be grounded through resistors, capacitors may be connected in series with three phases of the line to which transformers are connected.

- The problem of ground return can be avoided if;

① Monopolar operation with or without dedicated metallic part. The scheme without a dedicated metallic return path (& electrodes) is grounded only at one of the terminals & results in lowest cost.

② Restriction on the ground current flowing during the monopolar operation.