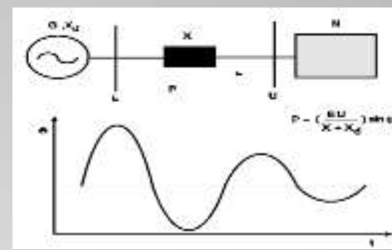
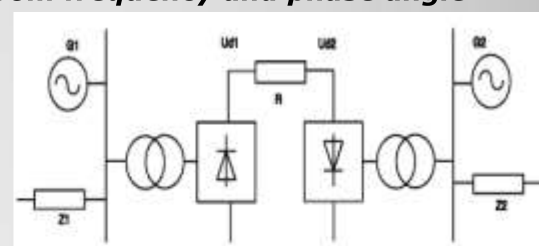
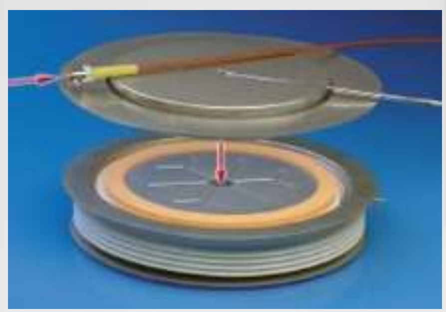
SAARC Perspective Workshop on HVDC Power Transmission



The reasons for transitioning from AC to DC power transmission .. sensitivity to electrical disturbances.....electromechanical oscillations....load flow control.....stability regaining response time....controllability....independence from frequency and phase angle



Tauqeer Ahmad P. ENG.
Alberta, Canada
HVDC Engineering Manager (EATL)



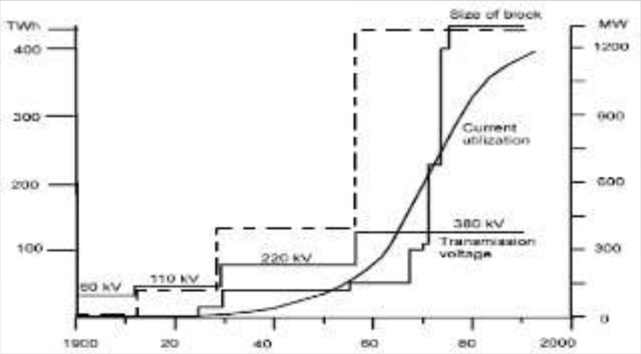
Transmission of Electrical Energy

Historical Perspective

The history of transmission of electrical energy began with direct current. In 1882, high voltage electrical energy was transmitted over a long distance for the first time from Miesbach to Munich. At that time high voltage was meant 2 KV. But it was understood that electrical energy in bulk can be transmitted with high voltage over a long distance as compared to customary distribution systems. But limitations were also shown at that time. It was understood that high voltage conversion could be possible only through transformation or conversion of mechanical energy to electrical energy via motor generator sets.

Hence transformation was possible only with AC current and posing undeniable advantage due to simple possibility of transformation of voltage. It was not possible until the **Mikhail Osipovich Dolivo-Dobrovolsky**'s ingenious invention of 3-Phase AC current asynchronous motor.

Development of AC current technology

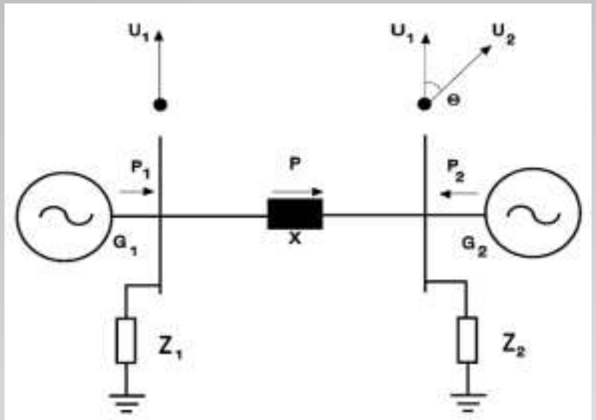


AC current transmission however, continued to be considered unsuitable for the transmission of electrical energy over the long distance.

AC current transmission of electrical energy was called leap of innovation but parallel to it there was continued discussions on DC current transmission on decades.

Advantages and limitations of AC transmission

Consider two AC networks connected through a transmission line of reactance X. They helped each other as per below equation



$$P = \frac{U_1 \times U_2}{X} (\text{Sin } \varnothing)$$

Based on above equation G1 & G2 undeniably will play their role for power balance by accelerating or decelerating in the form of excess power and deficit in power respectably but angle cannot be influenced directly until introducing a phase shift between two voltages. This can also lead to undesirable displacement of power which among other things can result into overloading of transmission line This sensitivity of alternating current transmission to disturbances of power balance and uncontrollable load flow over connecting lines are two fundamental technical properties which makes direct current transmission attractive.

In addition to above there is another electrical characteristic; electro-mechanical oscillations.

It meant that transition from one condition to other does not happen abruptly and pose a threat of instability.

The reactive power demand of load in case of AC transmission reduce the capacity of transmission line and introduction of series and shunt compensation can be of help to over come this issue but again there is a limit to release the current carrying of transmission line.

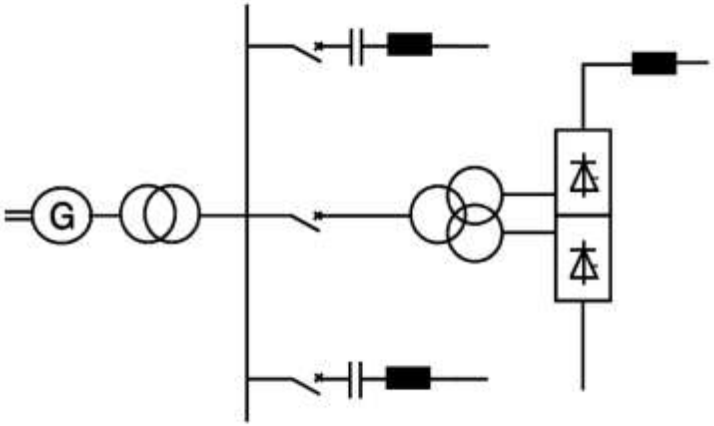
HVDC Edge

- Asynchronous connection
- Limitation of short circuit power
- Control of load flow (power reversal)
- Enhancement of stability
- Regulating functions
- Low transmission losses
- Smaller right of way

Applications of HVDC

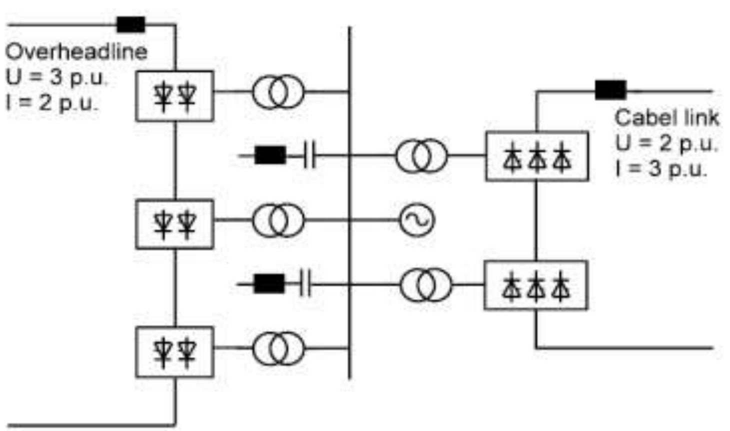
- Long distance transmission through overhead lines
- Transmission through sea cables

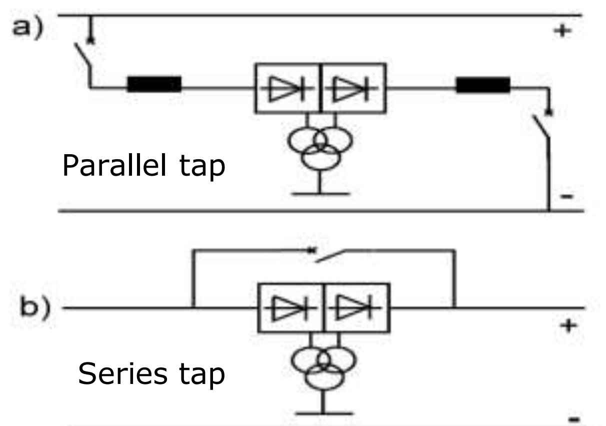
- Back to Back link



Power plant unit connection

- HVDC voltage converter (Combined Overhead line and cable)

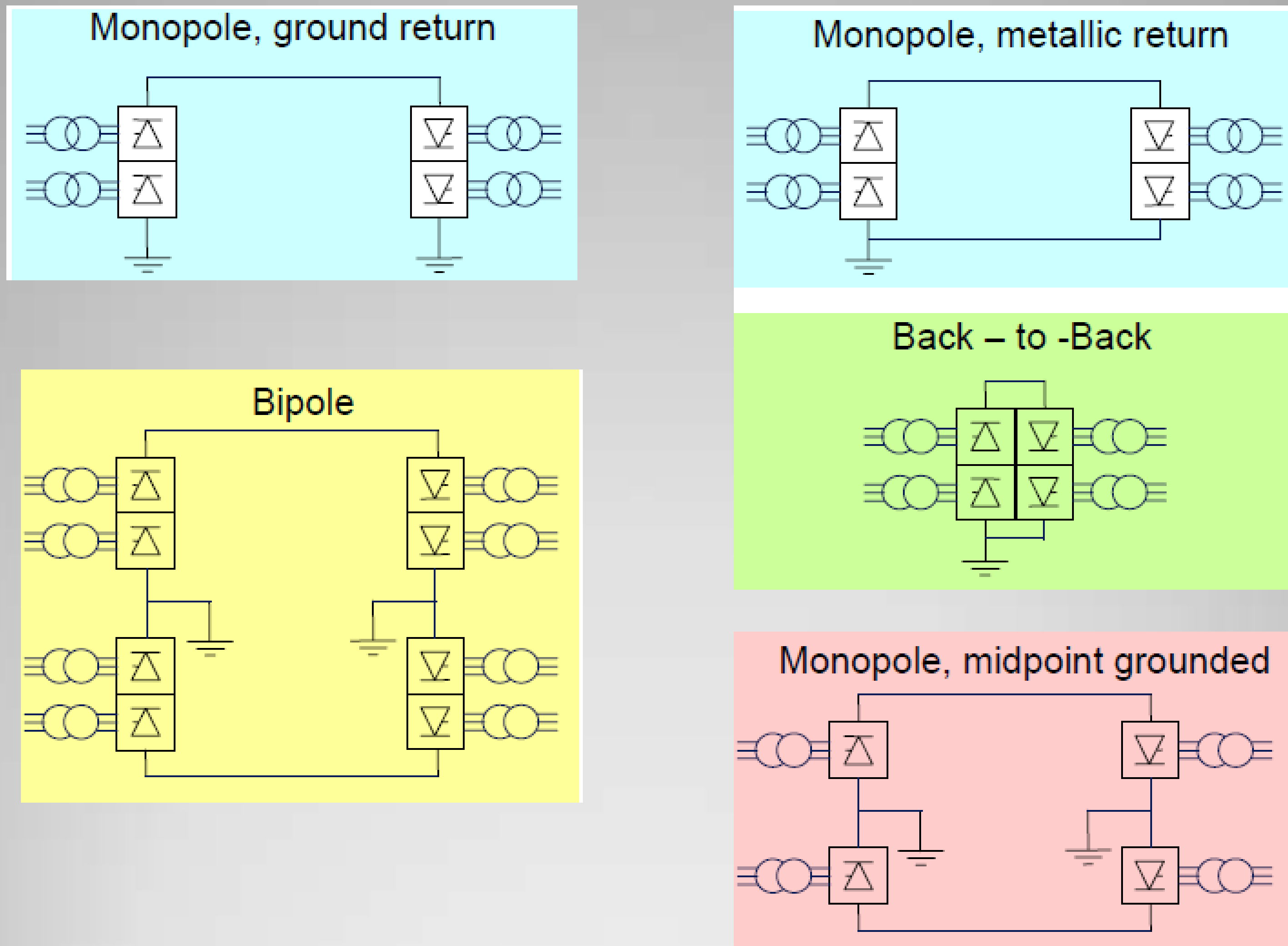




Parallel tap

Series tap

Modes of HVDC Transmission



Economic Aspects of HVDC

- Range of Power (500 MW to 6000 MW) lower limit 1000 A and upper limit 4000 A with level of voltage (±250KV to ±800KV) overhead lines

- Range of power (200 MW to 3000 MW) lower limit 800 A and upper limit is 3000 A with level of voltage (250KV to ± 500KV) cables.

- Optimal transmission voltage

Cost components of HVDC Overhead line

1) Construction cost
2) Loss costs
3) Total costs

$K_B = A + B \times U_d + C \times q$ (\$/Km)

A,B & C are cost factors determined by working groups without cost of land.

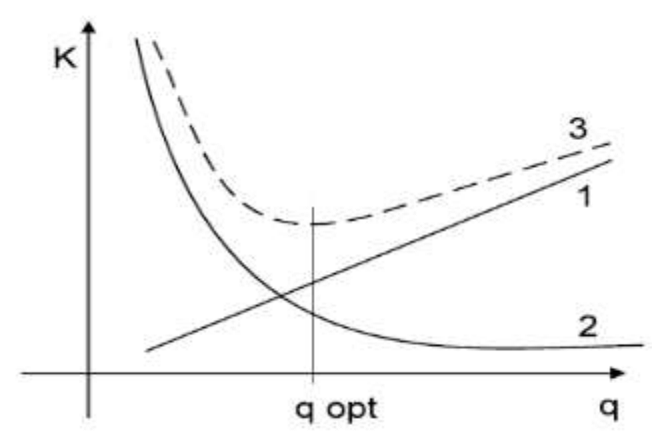


Fig. 1

Cost Factors	Year		
	1960	1990	2020
A	$6,000	$25,980	$112,493
B	$115	$498	$2,156
C	$30	$130	$562

If we compare line cost in figure 1 and 2, there is a difference in the tendency like linear and non linear which tells us that voltage does not impact linearly as compared to cross sectional area of conductor area. Selection of voltage is not the only factor to consider but Power also.

From Fig 2, it can be seen that station cost does not increase steeply with increase of voltage but this is not true because up to 500 KV it has very minimal impact but after 500 KV it increase steeply as it does for line. Figure 03 will show that how it does. The empirical formula determined by working group is significantly dependent on converter valve building is as follows:

$$F_u = 0.985 + 0.015 \times \left[\frac{U_{dN}}{400} \right]^4$$

1. Station cost
2. Line Cost
3. Total cost

Year		
1960	**1990**	**2020**
$160/Kw	$205/Kw	$340/Kw

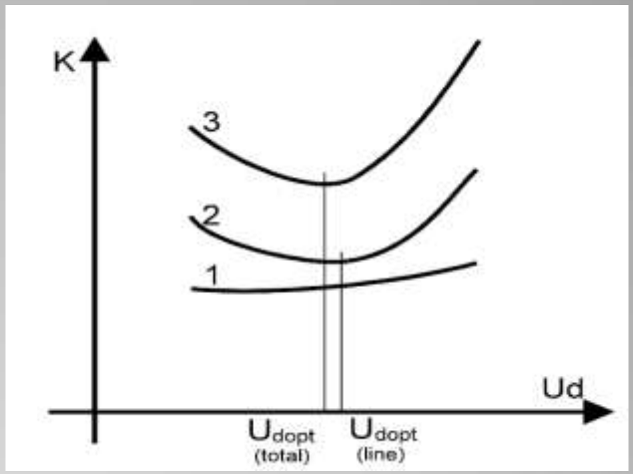


Fig. 2

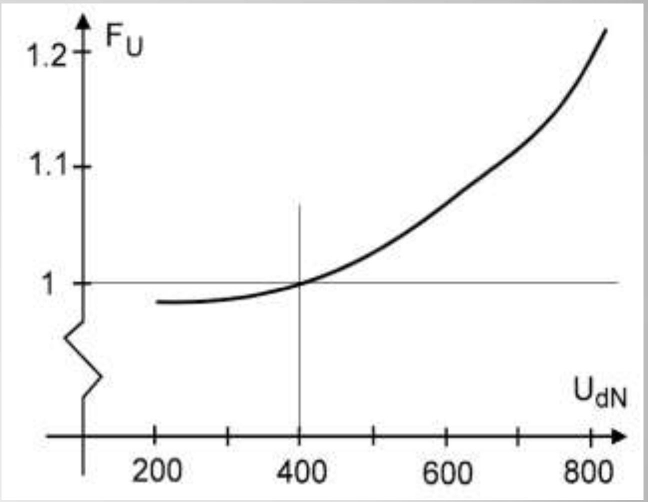
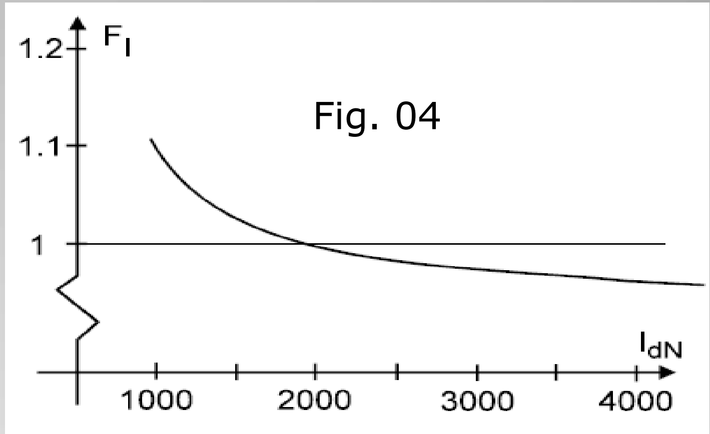


Fig. 03

This empirical formula is based on 400 KV station voltage that was considered with 2000 A and 1600 MW station power. Hence 400 KV is base for 1 P.U of station cost representation in Figure 03.

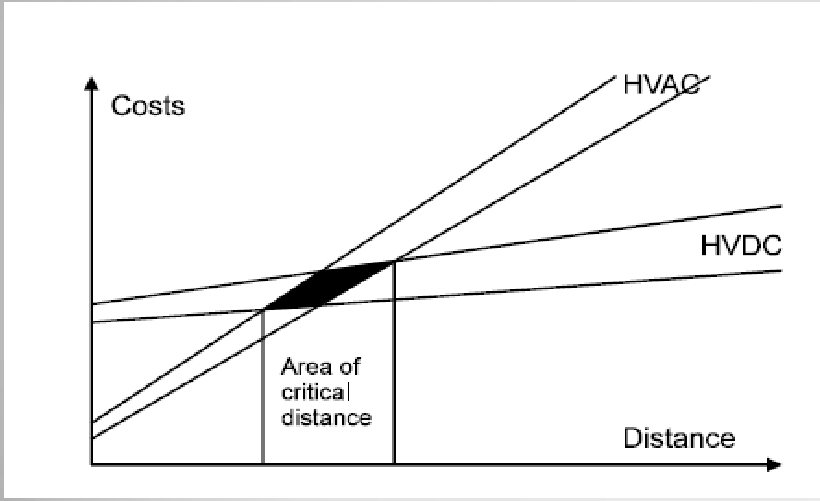
Figure 04 shows the cost dependency on current. Again reference value is 2000 A based on the following formula

$$F_i = 0.96 + 0.04\left[\frac{2000}{I_{dN}}\right]^2$$



It is clearly seen that beyond 2000 A the current does not have any significant impact on station costs even decreases slightly as current increase.

1600 MW bi-pole 400 KV with 2000 A current represents the 1.0 P.U cost estimation as reference



•Direct current fields are far less critical the AC fields

Comparison of HVAC and HVDC Transmission

•At zero distance HVDC station cost very high as compared to AC station

•For a short transmission HVDC station + line cost is high as compared to AC station + line.

•For a very long distance transmission line, in case of AC, intermediate stations are required to fulfill the Q power demand.

•Break even point is between 500 Km and 700 Km depending the country, evaluation of losses and interest rate.

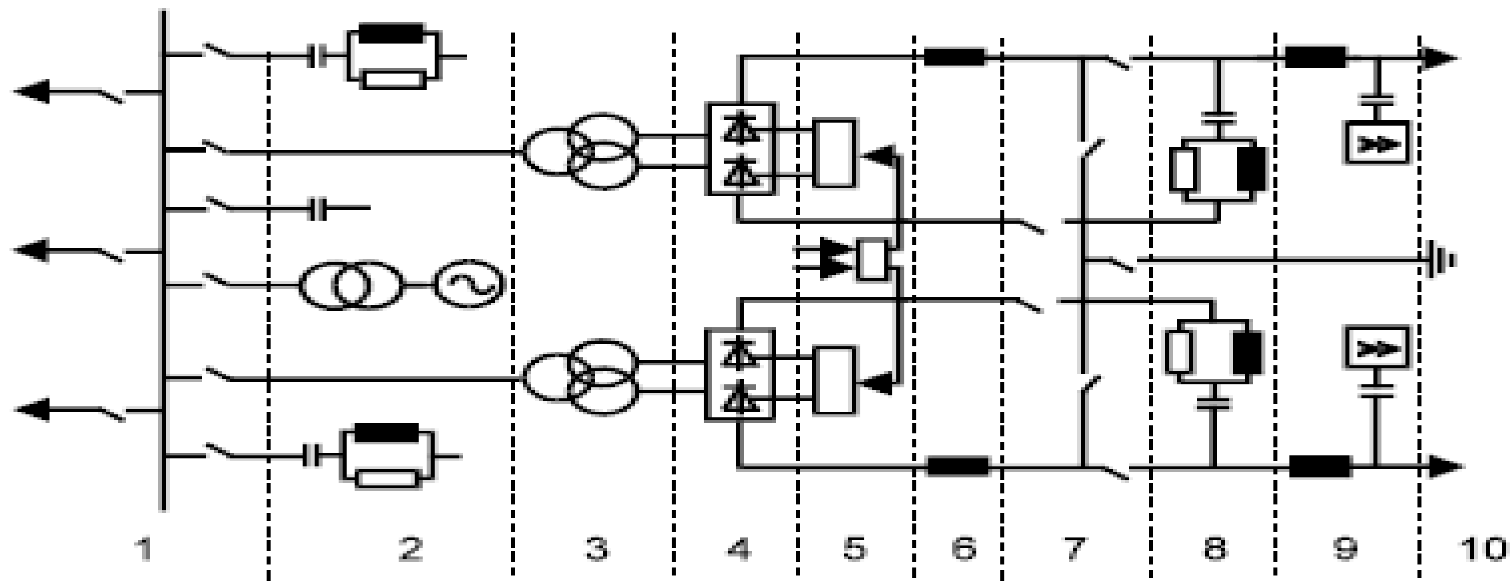
•AC transmission line need wider right of way.

•DC transmission line narrow right of way.

•System reliability. HVDC reliability higher than HVAC

•HVDC acoustic disturbances are high. (transformers).

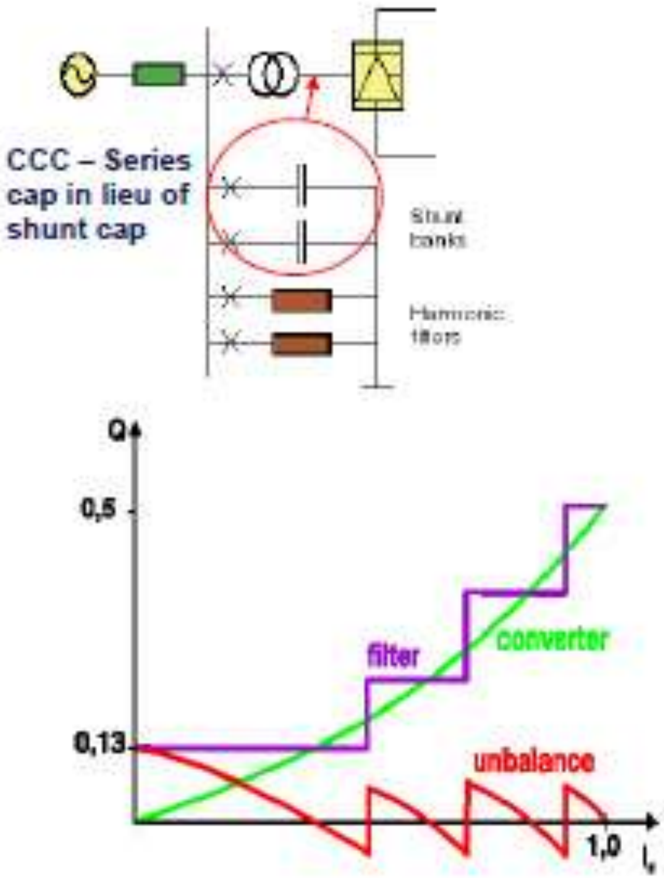
Major Components of HVDC Station



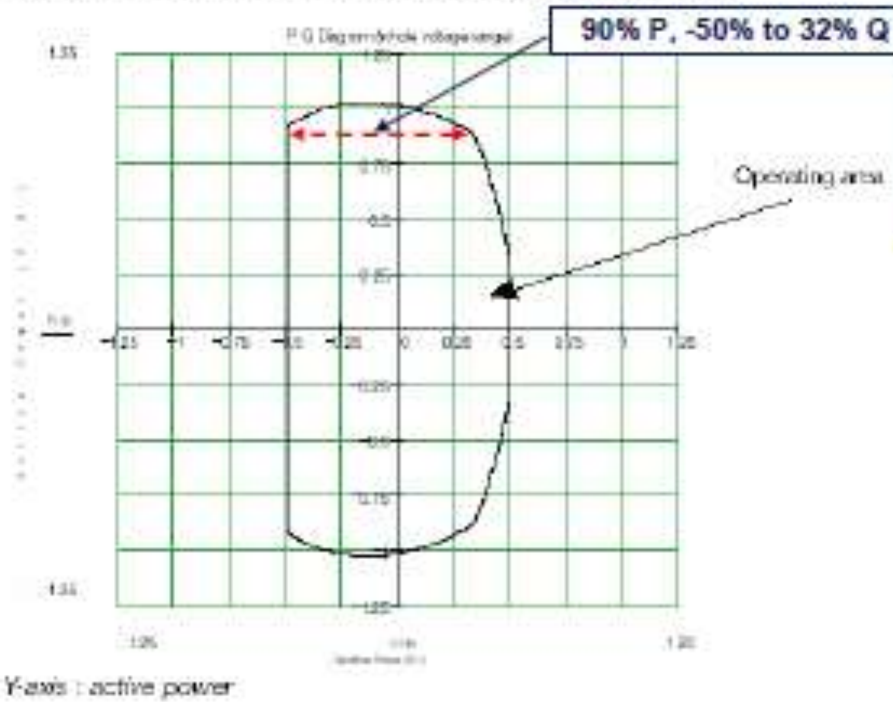
1	AC switchgear	6	Smoothing reactors
2	AC filter circuits and reactive power sources	7	DC switchgear
3	Converter transformers	8	DC filter circuits
4	Converter valves	9	PLC system
5	Control and protection	10	Earth Electrode

HVDC v HVDC Light – Reactive Power Balance

- Reactive power exchange for conventional HVDC



- An HVDC Light® can control both active and reactive power



Courtesy ABB

What's new with HVDC Light?

- Higher Power Levels – 1100 MW
- Higher Current Levels – Full 'six pack' of IGBT, more efficient heat sink
- Simpler Topology – Back to the future with 2 level converters, fewer valves, 33% less components than with 3 level converters
- Lower Losses – Optimized pulse width modulation results in losses equivalent to those for 3 level converters
- Higher Voltages - ± 300 kV
- Simplified Layouts
- Higher power density – higher power with minimal impact on footprint
- Reduced Filtering Requirements – Q fundamental = 15% of rated capacity
- Reduced Cost due to simplifications, fewer components

Courtesy ABB

Comparative Costs of 3000 MW TransWest Express Transmission Systems						
Alternative	± 500 kV double ckt	2 x ± 500 kV 2 x double ckt	± 600 kV double ckt	± 800 kV double ckt	500 kV 2 x single ckt	765 kV 2 x single ckt
Capital Cost						
Line voltage (kV)	1000	1000	1200	1600	500	765
Rated Power (MW)	3000	4000	3000	3000	3000	3000
Converter cost ($/kW)	130	150	145	160		
Stations including reactive compensation	$390,000,000	$600,000,000	$435,000,000	$480,000,000	$80,000,000	$100,000,000
Transmission Line (cost/mile)	$1,700,000	$1,700,000	$1,800,000	$2,000,000	$2,500,000	$3,200,000
Distance in miles	892	1,784	892	892	1,824	1,824
Transmission Line Cost	$1,516,400,000	$3,032,800,000	$1,605,600,000	$1,784,000,000	$4,560,000,000	$5,836,800,000
Total Cost	**$1,906,400,000**	**$3,632,800,000**	**$2,040,600,000**	**$2,264,000,000**	**$4,640,000,000**	**$5,936,800,000**
Interest Rate	10%	10%	10%	10%	10%	10%
Annual Payment, 30 years	$202,229,479	$385,364,693	$216,465,314	$240,163,418	$492,207,712	$629,771,281
Operation & Maintenance Costs per year	$1,200,000	$1,200,000	$1,200,000	$1,200,000	$1,200,000	$1,200,000
Total Costs per year	**$203,429,479**	**$386,564,693**	**$217,665,314**	**$241,363,418**	**$493,407,712**	**$630,971,281**
Cost per kW-Yr	$67.81	$96.64	$72.56	$80.45	$164.47	$210.32
Cost per MWh @ 100% Utilization Factor	$7.74	$11.03	$8.28	$9.18	$18.78	$24.01
Cost per MWh @ 85% Utilization Factor	$9.11	$12.98	$9.74	$10.81	$22.09	$28.25
Losses @ full load with 3 x 2839 kcmil	179	127	138	97	310	132
Losses at full load in % with 3 x 2839 kcmil	5.96%	3.17%	4.60%	3.24%	10.32%	4.41%
Capitalized cost of losses @ $1500 kW	$227,937,587	$161,781,293	$175,821,241	$124,001,011	$394,719,014	$168,618,486
Overload capacity per circuit (MW)	300	800	660	1380	0	700
RAS - generation trip per circuit lost (MW)	1500	0	1000	0	1500	500

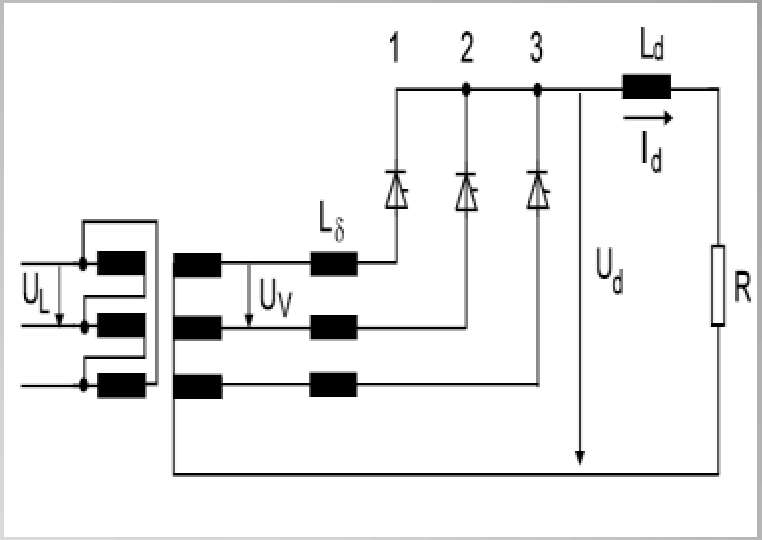
Courtesy ABB

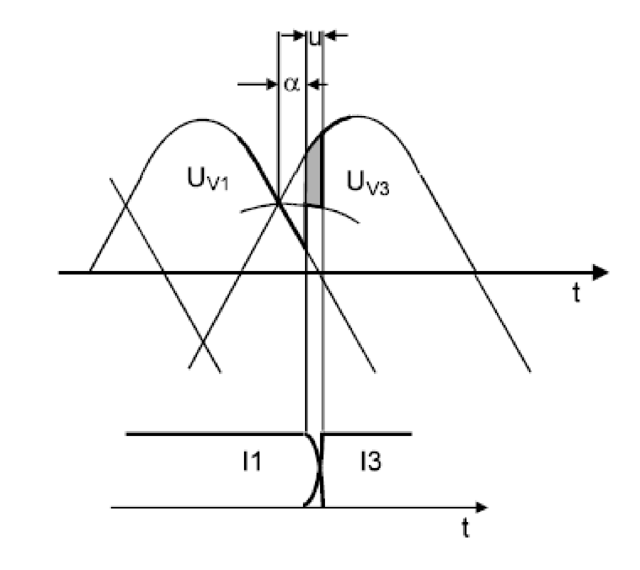
Commutation Process

To understand the concept of commutation I have presented here a simple three pulse Converter. Due to transformer leakage inductance, the current through valve does not stop instantly or in other words transition from one valve to following valve takes time. Hence leakage inductance permits a current change of limited steepness, di/dt.

Thus for a short time, releasing and receiving phases are carrying current simultaneously. This is referred to as commutation overlap and its duration is defined as overlap angle μ.

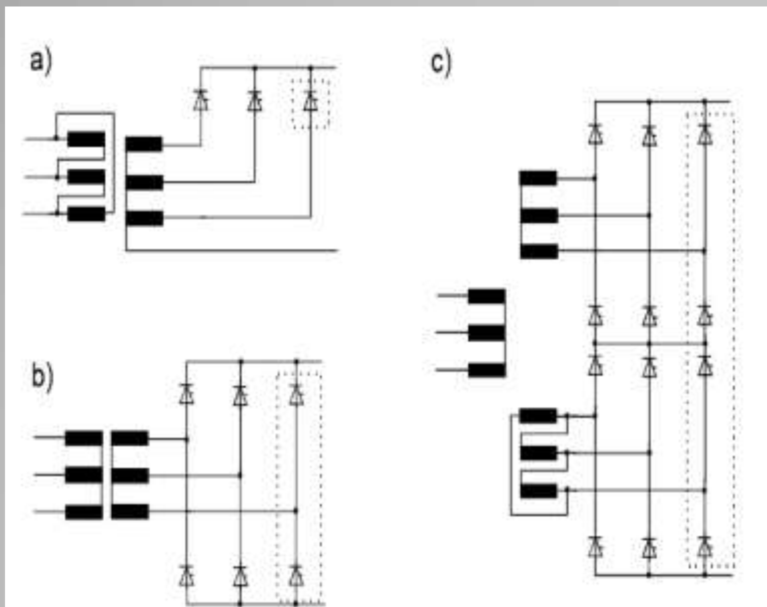
Due to this overlap, a current loop is created with U_v flowing in the forward direction through valve 3 and in the reverse direction in the valve 1 due to leakage reactance of transformer which simply referred to short circuit of the transformer. This short circuit current will superimpose on the dc current flowing the valve 1 and as soon the short circuit current equals to





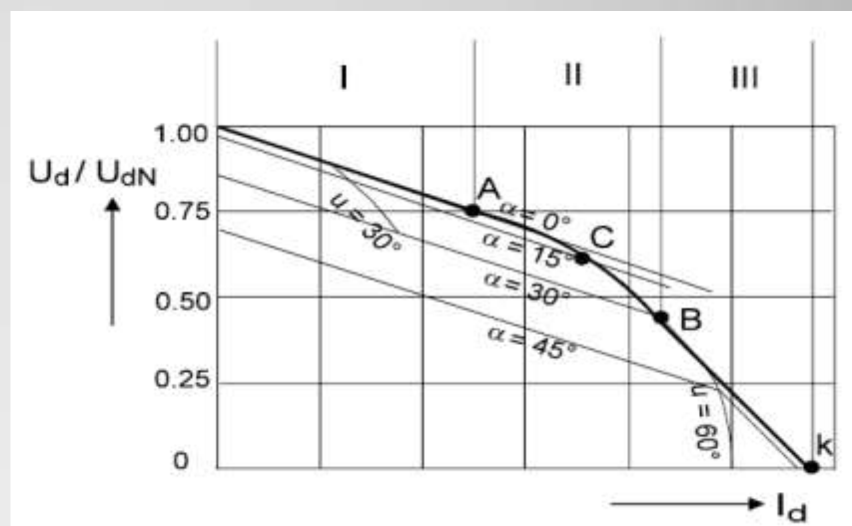
Direct current (composite current will be zero) valve 1 extinguishes. The commutation process ended and valve 3 will carry the entire dc current.

12-Pulse Converter Valve



a) Three pulse commutation group
b) Two three pulse group (double valve) or 6 pulse commutation group.
c) 12 pulse group

1. 12-pulse group is used in almost HVDC schemes
2. Two bridges have a common inductance in their individual commutation loop.
3. Two commutation will no longer run independently at $\mu = 30^o$.
4. There will be a massive reduction in DC voltage.
5. Set $\mu < 30^o$.

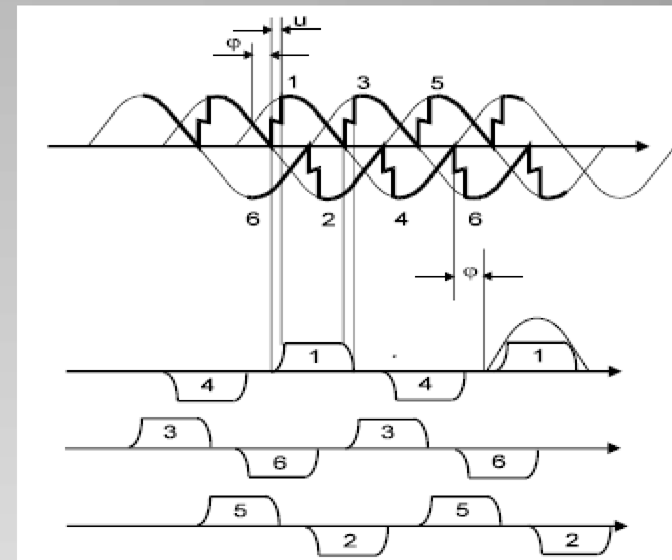


1. In Fig C, it is to be noted that two commutation groups are fed by 3-phase 3-winding transformer with Y and △ secondary windings with 30° displacement.
2. Now a days HVDC stations are designed with single phase three winding transformers and the valves related one phase are combined in one unit called thyrister/valve module.

Fundamental Frequency Reactive Power

Demand of reactive is one of the requirement for the valves and is composed of commutation and control reactor power. The control reactive is dependent on firing angle. The commutation reactive power is dependent on the overlap angle.
Hence $Q = P * \tan [\text{arc} \cos(\cos \alpha - d_x]$

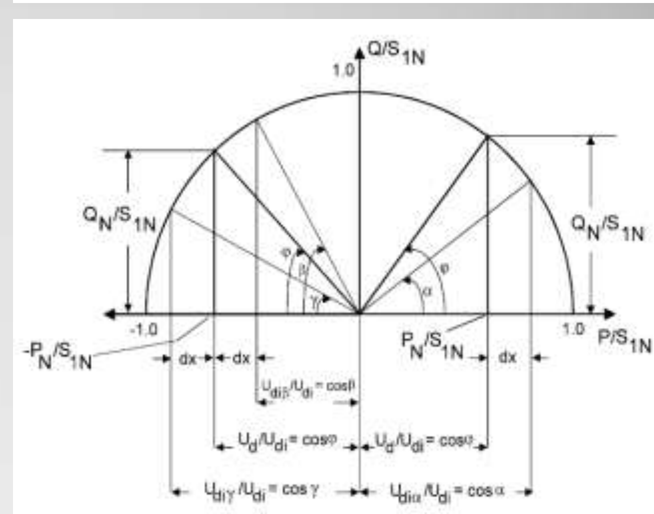
dx is function of U_k which is due to short circuit current loop in phases of transformers.



Reactive Power Control

Electronic reactive power is limited due to decrease in DC voltage and increase in current. This is due to overlap angle when increase the loop short circuit current increases and casing the decrease in voltage. However, load losses are increased as function of square of current.
Hence there is a limited electronic Q control which is applicable for light loads.

There is P-Q diagram of HVDC converter.



Harmonics

1)AC side Harmonics 2)DC side Harmonics

1) AC side Harmonics

1. Converter as rectifier acts as current source and converter connects DC side terminal with AC side terminal cyclically. Thus AC currents on the AC side are composed of sections on the DC side. Hence DC current is regulated by rectifier and AC currents are flowing on the AC side are also controlled by rectifier.
2. To understand the concept, we will assume an ideal converter and connected with Y/Y transformer.
3. AC currents in the converter will be rectangular blocks and are equal in amplitudes with DC current. With Y/Y configuration, these currents converted by turn ration will represent line currents I_L on the AC side. See on the right side.
4. After analyzing the waveform it is found that the following formula holds true.

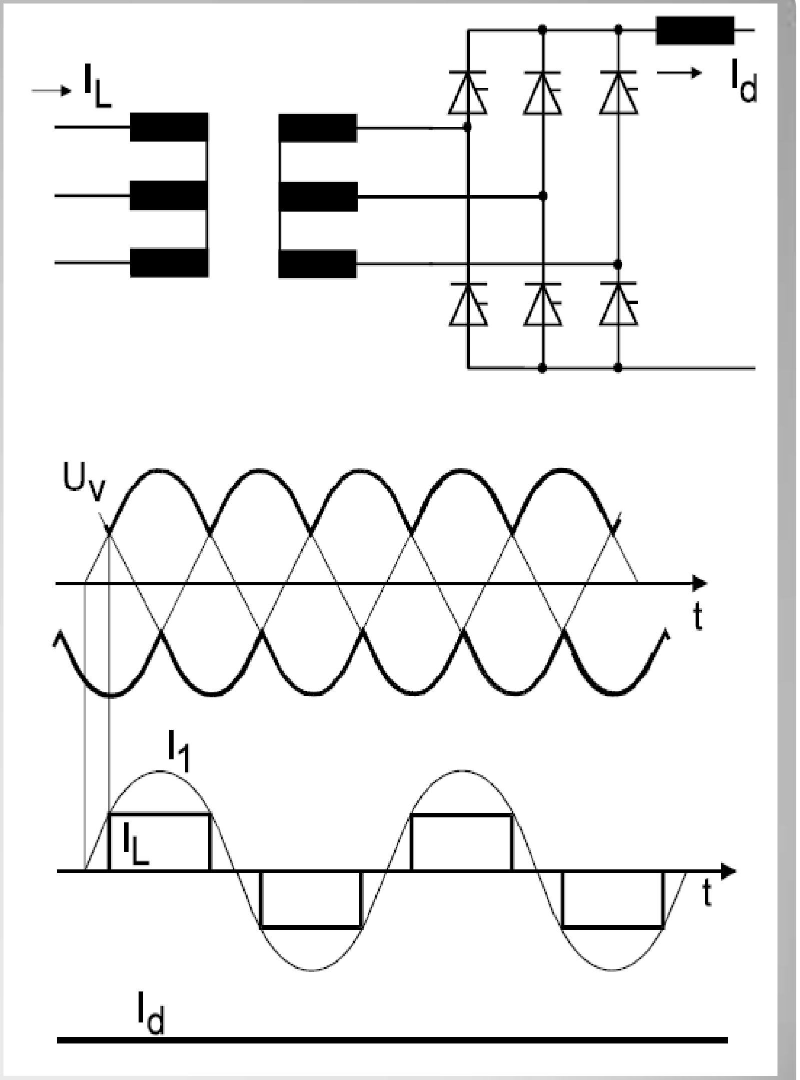
$$\upsilon = k * P \pm 1$$

υ is called harmonic number
K is integer 1,2,3…..
P is number of pulse group

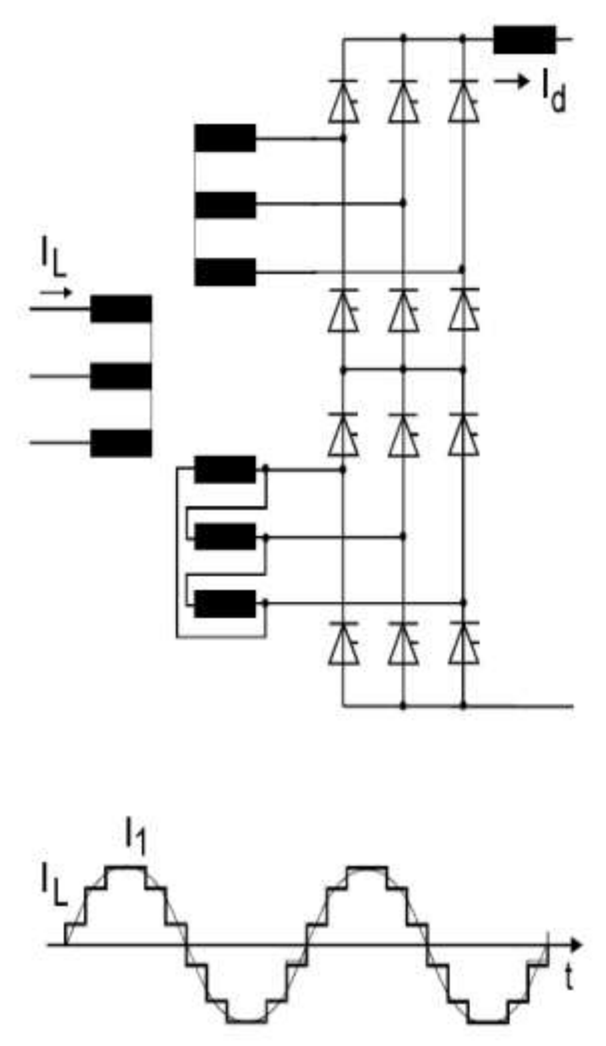
Hence only odd number harmonics are produces and

$$I_{\upsilon o} = 1/\upsilon * I_L$$

This equation tells us that as the ordinal number harmonics increase the amplitudes of the harmonic current will decrease sharply.



6-pulse converter with Y/Y transformer configuration.

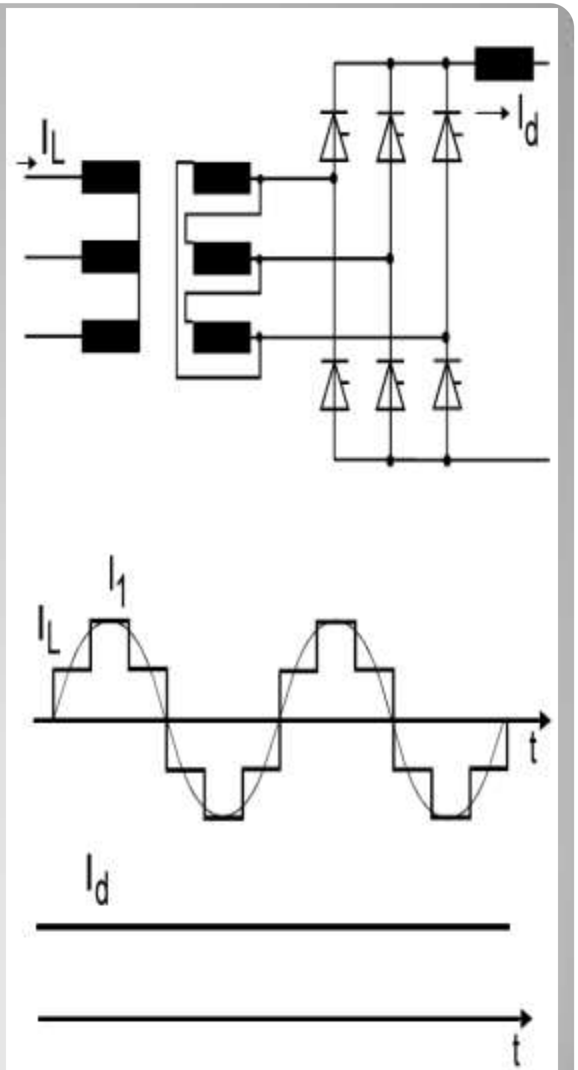


12-Pulse converter with Y/Y and Y/△ T/F configuration

With Y/△ configuration of Transformer

In this case, harmonics on the primary side are the same and same in amplitude as were in Y/Y configuration but I_L shape is totally different.
Now in case we connect these two 6 pulse converters in series to make a 12 pulse converter them out of phase harmonics will be cancelled out.

This will result into 12 pulse converter system which has only harmonics related to P=12 thus
11^{th} , 13^{th} , 23^{rd} 25^{th} ……
Hence 5^{th}, 7^{th} 17^{th} and 19^{th} order are cancelled out.
This is advantage of using 12-pulse converter to get rid of most of the harmonics.



6-Pulse converter with Y/△ T/F configuration

DC Side Harmonics

- Are caused due to superimposition of AC harmonic current on DC current (Id). As the case was for AC harmonics due Valve electronics in nature.
- Remember that AC netwrok acts as voltage source for the converter and the converter viewed from DC side acts a voltage source. This statement is correct for harmonics voltages also which are superimposed on it. See the below figure:

In this figure, AC and DC voltages are shown for 6-Pulse converter. Left side is for ideal converter and Right side is for real converter with firing angle and overlap angles. We can clearly see two voltages curves; one is on the T/F side of valve (Uv) and other is on the DC line side of the valve after conversion. Hence their shapes not smooth due to AC harmonic voltages superimposed. In case of 12 Pulse group, these voltages will be more smooth but still there will be superimposition of AC harmonics on the DC side. 12-pluse DC voltages are on the next slide

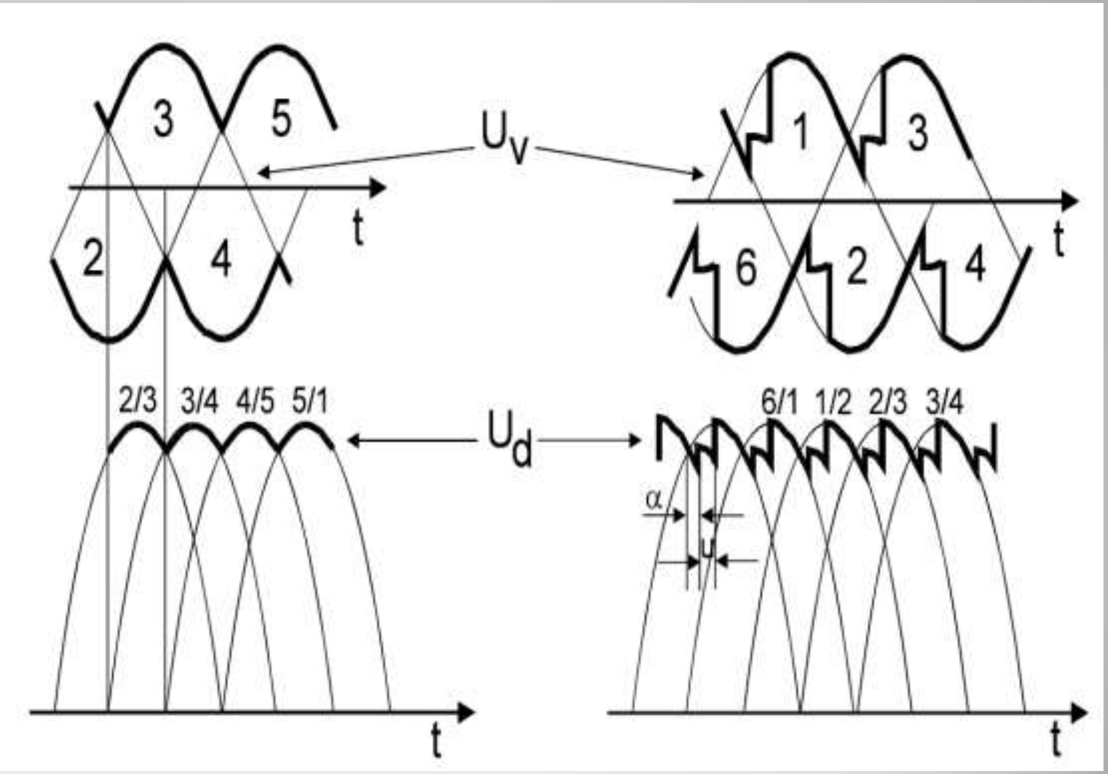


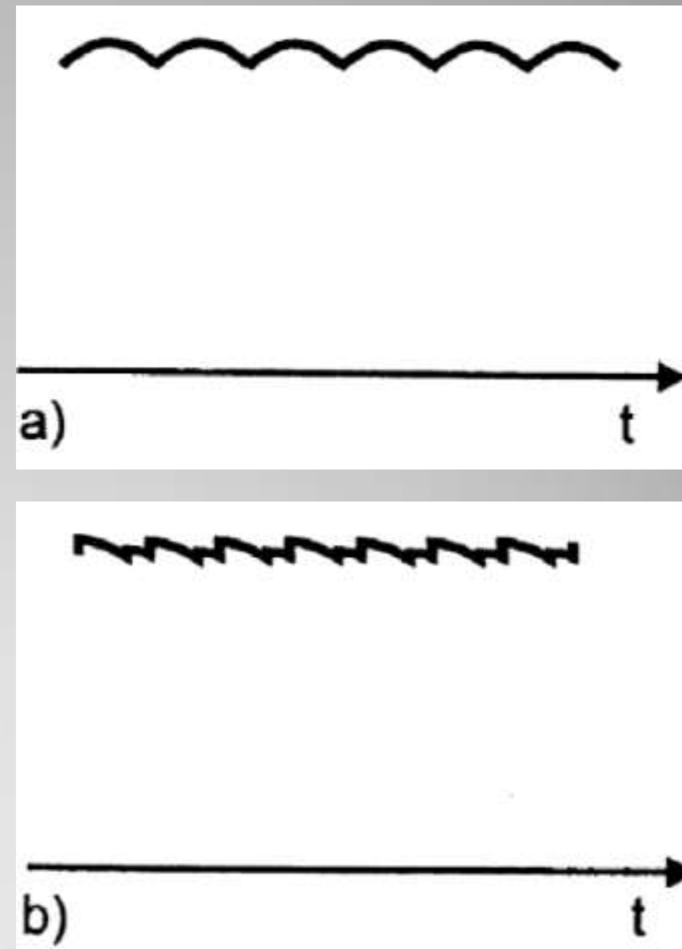
Figure a) is for ideal 12-Pulse converter and figure b) is of real converter with α and μ. These voltages more smooth because ordinal number harmonics were cancelled out due to series connection of two 6 pulse converters.

Hence characteristic harmonic on the DC side will be defined as

$\upsilon = k * P$

Where P is number pulse group & k is an integer 1,2,3……..

Like AC current & voltage non-characteristic harmonics, there are non characteristic DC harmonics which are due to i) negative sequence component presence in the 3-phase AC system ii) unequal transformer reactance among phases iii) Deviation of current inception points of valves from the equidistant of 30^{o} .



DC harmonic effects

The amplitudes of DC harmonic currents will be dependent on DC line resistance and will cause the following:

- Current zeroes on the DC line
- Ripples
- Telephone line interferences.
- If direct current is not smooth then waviness DC will be in common for both HVDC converter stations (Rectifier and Inverter). If both AC networks are not synchronous then harmonic frequency spectrum of one side is transferred into other side will cause non harmonic oscillations with frequency fluctuations.

AC Filter Circuits & Shunt Capacitors

There are two main functions of AC filters and shunt capacitors those are installed at the common bus on the AC side

1. Providing reactive power to compensate the required reactive power by Converters (limited electronic control of Q)
2. To absorb the AC harmonic currents generated by Converters and prevent flowing of harmonic current into AC network that can cause undesired distortion of AC system voltage.

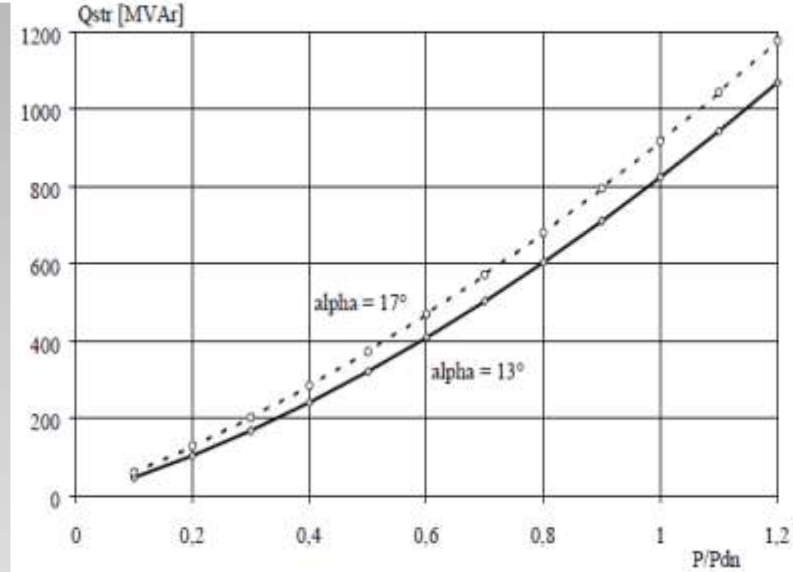
Reactive Power Supply Design Criteria

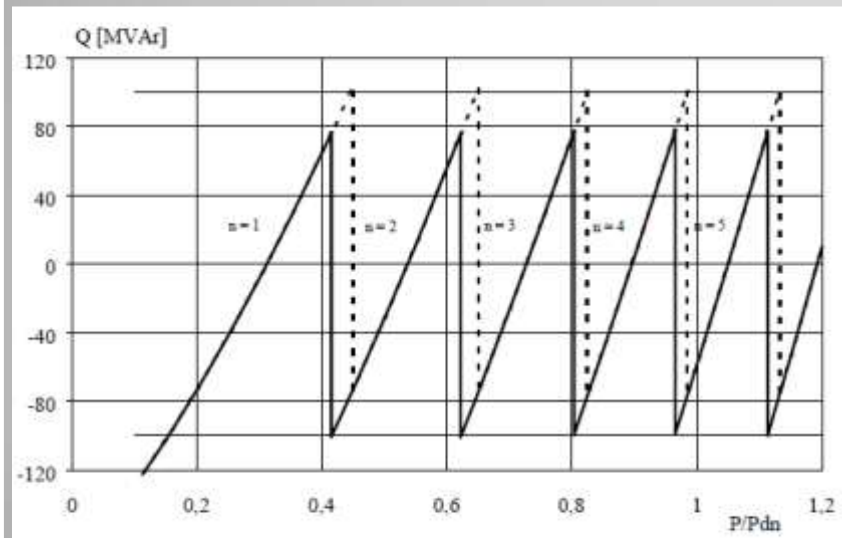
- Reactive power demand is dependent on firing angle (α and γ) and DC current I_d.
- Rectifier and Inverter are operated ideally at Cos φ = 0.8 lagging and leading respectively.
- As we are known that Rectifier regulates current I_d and Inverter regulates voltage U_d, thereby with constant terminal voltage at Rectifier, the variation in U_v will be load dependent and must considered in the design of Q elements.
- Q elements are sources of reactive power and have limitation to break capacitive currents during load rejections. Hence small units of Q elements are required to be installed with individual breakers but this would lead to cost increase.
- Reactive power switching could done by two methods:
  - Open Loop Control : Q-elements are connected or disconnected at fixed partial loads
  - Closed Loop Control: Q-elements are connected or disconnected when the measured total reactive power of HVDC station reaches the upper or lower limit of the tolerance band.
- Compliance with distortion disturbances band, it is necessary to keep the filters in connected mode that could provide over-compensation in terms of light loads and this could be non-compliance of reactive power tolerance band But some time control reactive power can alleviate switching of shunt reactor by increasing firing angle that would cause increase in current and will result into increase in losses that could be acceptable.

Understanding Reactive Power Behaviour

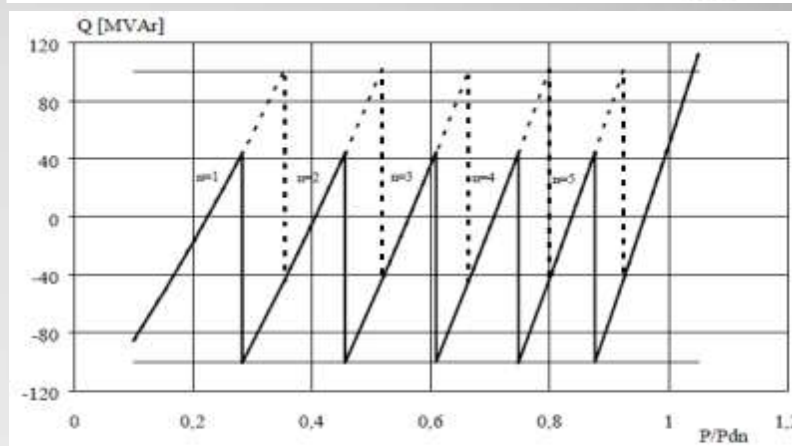
This is an example of 1800 MW HVDC station. In this example reactive power requirement as a function of real power is defined for two firing angles. At load of 1.0 p.u. with α 13° approximately 800 MVAr is required that will be managed with Q elements of 176 MVAr multiple Q elements in order to comply with ± 100 MVAr tolerance band.

The following figures explain the Q component requirement.





Total reactive power of an HVDC station at α = 13° and 1.05 p.u. network voltage (Q_C = 176 MVAr)



Total reactive power of an HVDC station at α = 17° and 0.95 p.u. network voltage (Q_C = 144 MVAr)
n = number of Q elements connected

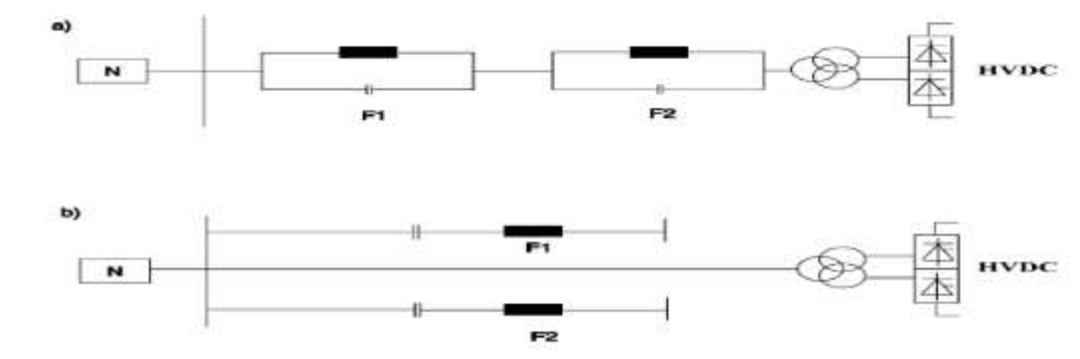
Other Components of Supplying Q power:

1. Shunt Reactor
2. Static Var Compensators
3. Synchronous Condensers

These are expensive methods to supply the Q power but only used when smaller Q components with Filters could not full fill the requirements. In case of SVCs, tolerance band of reactive power can be reduced to zero.

Filter Circuits

Absorption of harmonic currents can be achieved with installation of either series filter circuit or shunt filter circuit. Shunt filter circuits are often used because they are not rated for full current and voltage. Series filters should have high insulation equal to network voltage and full rated current.



Serial (a) and parallel (b) ac filter circuits

To absorb the harmonic currents, the network impedance is one of the most required information.

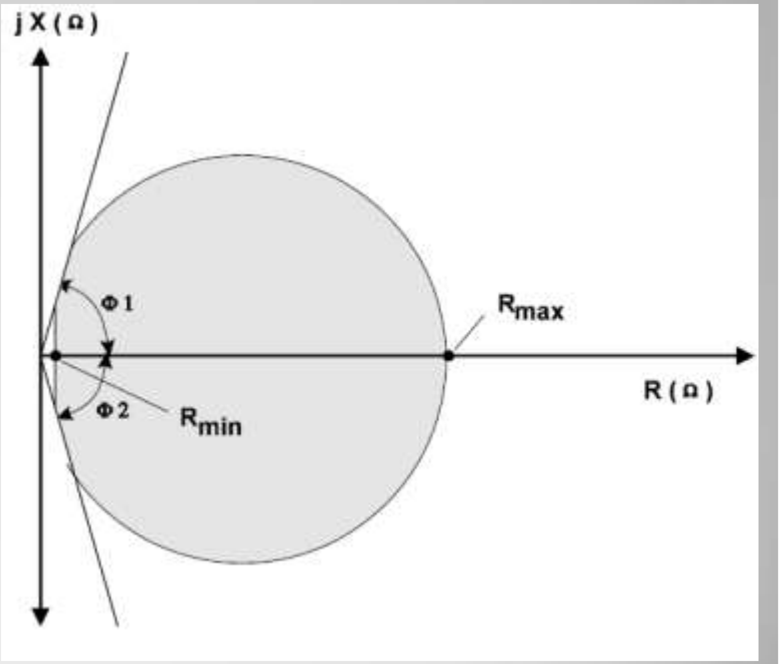
In order to assess the voltage and current distortion it is important to know the AC network impedance at each harmonic of interest the following expressions are important to understand

$I_{SN} = Z_{fn} / (Z_{fn} + Z_{sn}) * I_n$

$V_{sn} = (Z_{fn} * Z_{sn}) / (Z_{fn} + Z_{sn}) * I_n$

Where as I_n = Harmonic current in the filter
I_{SN} Harmonic current entering supply system
Z_{fn} = Filter harmonic impedance
Z_{sn} = Supply system impedance

The shaded area shows the range in which supply system impedance can lie. R min and R max can apply only for one harmonic ordinal number



AC network resonance circle

Types of Filters.

1. Single tuned filters

2. Double Tuned filters

3. High-pass filters

4. Single Tuned High-pass filters

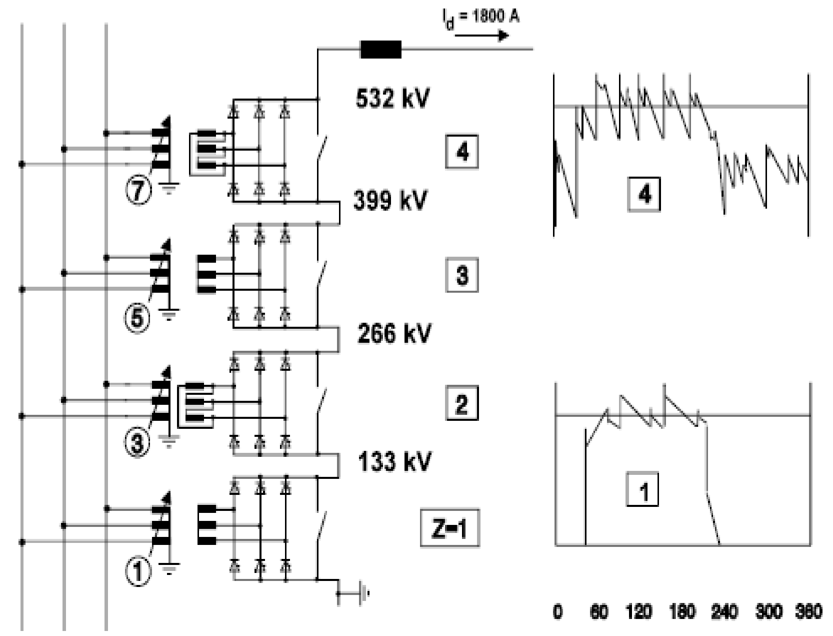
5. Double tuned high-pass filters

6. Triple tuned high-pass filters

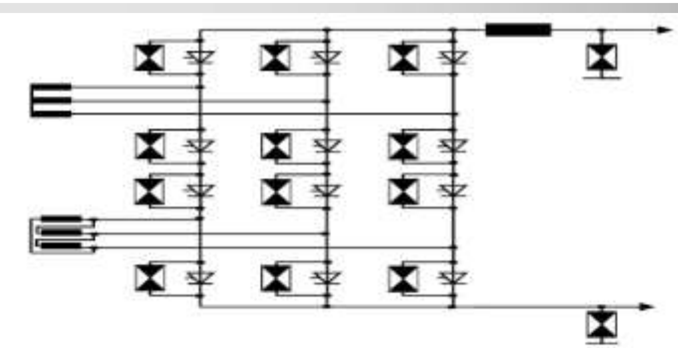
In case of harmonic voltages developed due to resonance (C & L in series) caused problem of over voltages for the circuit breakers. Hence a careful design and margins are built while transient over voltages and superimposed over voltages due to harmonics are considered.

Converter Transformers

1. Functions of the HVDC Converter Transformer
   - Provide insulation between series connections of three phase bridges.
   - Limit the short circuit current
   - Provide voltage compensation due to converter internal voltage drop and also compensation for AC bus voltage for deviation from design value due to AC netwrok distortions.
   - Converter transformers are stressed by AC voltage and DC voltages
2. Current & Voltage rating
3. Short Circuit Voltage Selection (U_K)
   1. Short CCT. Of the thyrister.
   2. Required smooth reactance inductance
   3. Real power of valves and transformer
   4. Reactive power demand of converter.
4. Insulation Coordination
   1. Provision of SA across the valves and SA on the DC terminals
5. Experience in existing systems.



Potential versus time curves for the valve-side transformer windings in an HVDC station with four three-phase bridges per pole



Thyrister Valves

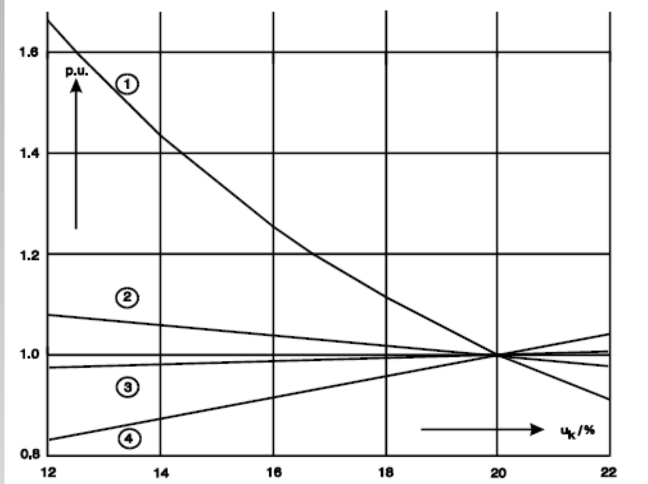
1. Thyrister as a switch
2. Series connections
3. Valve control & Monitoring
4. Valve cooling
5. Valve Mechanical design

Smoothing Reactor

1. Limit the rate of rise of current in the event of dc line fault.
2. To limit the dc ripples
3. To avoid telephone interference
4. To avoid DC side resonance

DC Switchgear

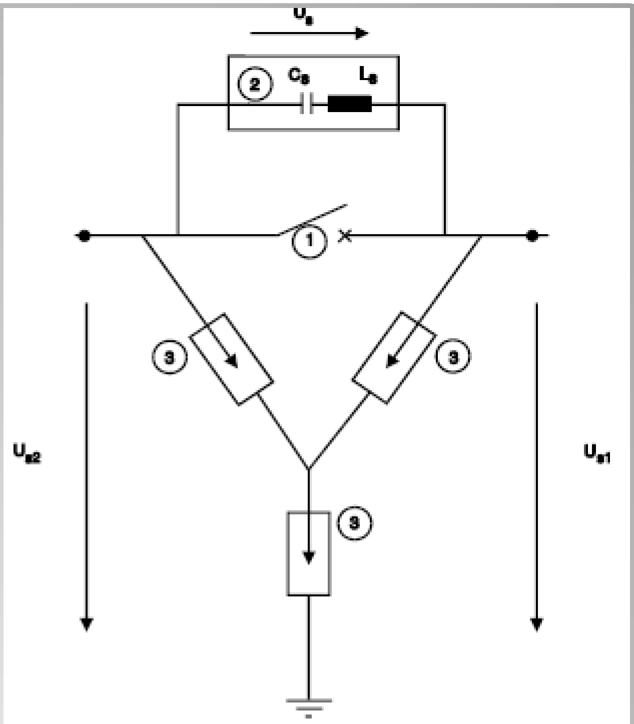
1. DC switchgear is mostly termed as disconnector in the HVDC technology operating at zero or minimum amount of current. Usually involving converter blocking of by passing with commutation circuit.



(1) Short-circuit surge current of the thyristors
(2) Required smoothing reactor inductance
(3) Rated power of valves and transformers
(4) Reactive power demand of the converter

Relationship of important data of an HVDC station upon the short circuit voltage of the converter transformer.

2. DC circuit breakers are also used based on design requirements. If DC breaker has to be installed in the main line that means it must have commutation circuit and energy absorption devices as shown in the diagram.



Overall range from Cost perspective for a 1000 MW substation

Description of HVDC major components	Ranges, US Dollars $)	
HVDC Mono Pole	From	To
Studies and Models	7,000,000	12,000,000
Preliminary Engineering	1,500,000	3,000,000
Detailed Engineering	9,000,000	16,000,000
Primary/Secondary Engineering	**17,500,000**	**31,000,000**
Civil Works	140,000,000	160,000,000
Equipment	175,000,000	225,000,000
Spares,Tools and Training	20,000,000	25,000,000
Major Components	**335,000,000**	**410,000,000**
Additional Studies, Spares, Tools and Training	1,000,000	1,500,000
Extended O&M/Warranty Support	3,000,000	5,000,000
Operator Training Simulator	1,800,000	2,200,000
Optional Price	**5,800,000**	**8,700,000**
	358,300,000	449,700,000

Question Answer Session

THANK YOU

HVDC classic application with two SVC installed at Newell end to overcome the system weakness from low short circuit MVA perspective.

Newell Alberta Canada 1000 MW Converter Station