SMOOTHING REACTOR AND DC LINE

→ The smoothing reactor is connected before the DC filter & in series with the converters.
→ And it also smoothing the DC, & a buffer b/w the converters and the DC lines.

* **Smoothing Reactors :-** (L.q) or S.q

The smoothing reactors have several fun's as given bellow :-

1. They reduce the incidence of commutation failure in inverters caused by dips in the AC voltage at the converter bus.
2. They prevent consequent commutation failures in inverters by reducing the rate of rise of dc in the bridge when the direct voltage of another series connected bridge collapses.
3. They smooth the ripple in the dc in order to prevent the current becoming discontinuous at light loads.
4. They decreases harmonic voltages and currents in the DC line.
5. They limit the crest current in the rectifier due to a short ckt on the DC line.
6. They limit the current in the valves during the converter bypass pair operation, due to the discharge of shunt capacitances of dc line.

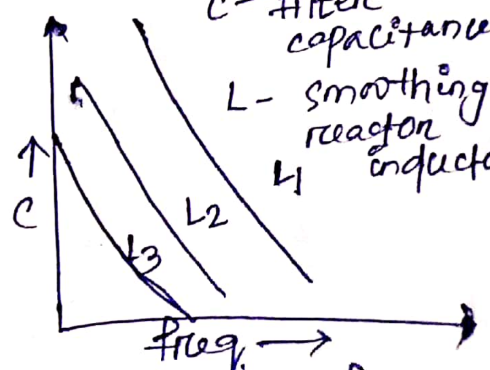
→ for back to back HVDC system, the last 3 fun's not relevant.

→ The sizing of the reactor is done, minimizing the effect of low order harmonic resonance in the AC/DC systems.

→ It is necessary to avoid series resonance of the DC system at fundamental frequency and also at the second harmonic.

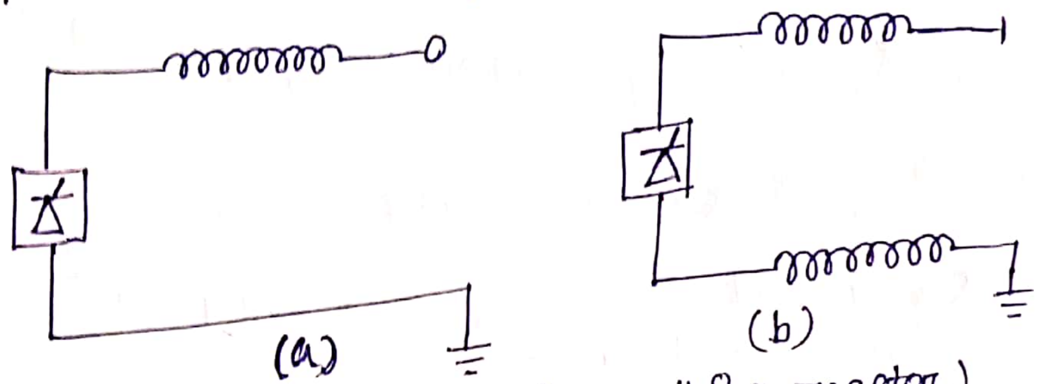
→ Effect of the inductor value on the resonant frequency as a fun of the DC filter capacitance as shown in fig. below.

→ $L_3 > L_2 > L_1$ shows the resonant freq. is reduced by increasing the inductance.



(fig. series resonant frequency as a fun of smoothing inductor and filter capacitance)

→ The location of the smoothing reactor can be either at the high voltage terminal or at the ground terminal. As shown in fig. below.



(fig. Location of smoothing reactor)

→ Reactors at ground side is that it allows the converter ground faults to be cleared by converter control.

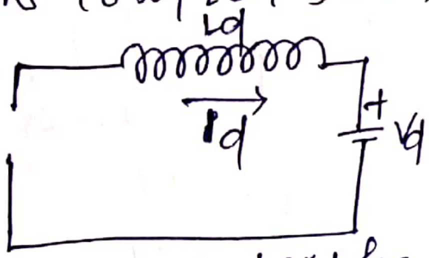
→ location of the reactor cause the insulation level of the reactor.

→ optimum size of the DC smoothing reactor. criteria used for S_i factor is defined below.

$$S_i = V_{dn} / (L I_{dn}) \quad —①$$

where V_{dn} = Rated direct voltage (in KV)
I_{dn} = Rated direct current (in KA)
L = DC ckt inductance in MH
S_i = back to back HVDC links (0.24 to 1.3 ms^{-1}) varies

→ sizing of the reactor is the ripple in the dc.



(fig. Equivalent ckt for calculating ripple)

→ The peak value of the ripple is given by

$$i_d^{peak} = (S V_{d0} / \omega_1 L_d)[1 - (\pi/p)\cot(\pi/p)] \sin\alpha \quad —②$$

where V_{d0} = no load dc voltage of a converter
S = no. of converters connected in series.
P = pulse number
L_d = inductance of the reactor.
ω_1 = fundamental freq.

Delay angle α exceeds $\bar{\alpha}$

where $\tan\bar{\alpha} = (P/\pi) - \cot(\pi/p) \quad —③$

for $P = 6, \bar{\alpha} = 10°$ and for $P = 12, \bar{\alpha} = 5°$

Former case, $i_d^{peak} = 0.0931 (s V_{do}) \sin\alpha / (\omega_1 L_d)$ — (4)

for $p = 12$

$i_d^{peak} = 0.0230 (s V_{do}) \sin\alpha / (\omega_1 L_d)$ — (5)

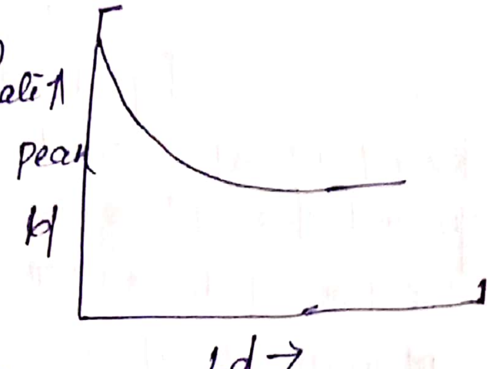
for $\alpha = 0$

$i_d^{peak} = K (s V_{do}) / \omega_1 L_d$ — (6)

K = constant

$K = 0.00947$ for $p = 6$ & $K = 0.00119$ for $p = 12$.

→ The below fig. shows the reduction in the surge current is not commensurate with the increase in L_d, beyond a certain point.



(fig. peak current as a fun^n of smoothing reactor)

Dc Line :-

Corona effects :- (L.9)

→ The corona is defined as a luminous discharge due to ionization of air surrounding a conductor caused by a voltage gradient exceeding a certain value.

→ The ionization takes place in a zone which is a very thin circumferential layer surrounding the conductor surface.

→ Here high velocity particles to collide with the air molecules.

→ Electrons are removed from the atoms of the air molecules and are accelerated towards the +ve conductor or away from the −ve conductor.

→ The effects of the corona are :

1. corona loss
2. Radio and television interference
3. Audible noise

} occurs A C lines also

4. space charge field. } peculiar to dc lines

→ The "electro static field" is defined as the field resulting from the charges on or near the conductor surface.

→ The total 'electric field' results from the superposition of the electrostatic and spacecharge fields.

Corona loss :-

The power losses due to corona can be expressed as

$$P_{loss} = [2V(K+1) K_C n r^2 g^{0.25(g-g_0)}] \times 10^{-3} \text{ KW/ckt-km} \quad -(7)$$

where V = pole to ground voltage in KV

n = number of sub conductors

r = radius of each subconductor in cm

g = Max^m conductor surface gradient at operating voltage (in KV/cm)

$g_0 = 22\delta$ KV/cm

δ = relative air density

K_C = conductor surface coefficient

$K = (2/\pi) \tan^{-1}(2H/S)$

H = Mean height of conductors

S = pole spacing

Relative air density δ is given by

$$\boxed{\delta = 2.94P/(273+T)} \quad -(8)$$

P = barometric pressure in kilo-pascals.

T = Temp. in centigrade.

The max^m gradient g, is given by

$$g = \frac{[1+(n-1)(r/R)]V}{nr \cdot m\left[\frac{2H}{(nrR^{n-1})^{1/2}[(2H/S)^2+1]^{1/2}}\right]} \quad -(9)$$

R = Radius of the circle passing through the centres of all subconductors in a bundle, in cm.

Radio Interference (RI) :-

→ RI is mainly due to +ve conductor. This is because of the fact that the corona discharges from the −ve conductor are in the form of trichel pulses disturbed over conductor surface.

→ +ve corona discharges are of 3 types → Hermstein glow → Plume discharge → Streamers.

→ These are mainly responsible for the RI.

→ The ~~operation~~ expression for RI is :-

$$RI = 25 + 10\log n + 20\log r + 1.5(g - g_0) \quad - (10)$$

It is due to +ve conductor. And RI due to -ve conductor is about 20dB lower.

→ The television interference (TVI) with DC lines & mainly due to the ion currents & is of little consequence at distances greater than 25 meters from the Right of way (ROW)

Audible noise (AN) :-

→ The corona discharges from the conductor produce compressions and refractions that are propagated through the medium as acoustical energy.

→ The portion of the acoustical energy spectrum that lies within the sonic range is perceived as audible noise (AN).

→ The sound level is expressed in decibels and is defined as

$$dB = 20\log(P/P_R)$$

Where P = Measured sound pressure level

P_R = Reference pressure level. (20μ Pascal) standard of

→ Audible noise is produced in converter stations by converter transformers and smoothing reactors due to the phenomenon of magnetostriction.

Space charge (Ion flow) field :-

→ The ions produced by corona on overhead DC lines drift through space under the action of electric field and wind.

→ The possible environmental effects due to electric fields and space charges, at the ground level are matters of concern and have to be considered in transmission planning.

→ The current induced under DC fields is due to the flow of ions.

→ The current density can be obtained from the relationship

$$j = K\rho E$$

Where K = ion mobility

ρ = charge density in ~~cou~~ coulombs/m3

E = Electric field strength in volts per meter.

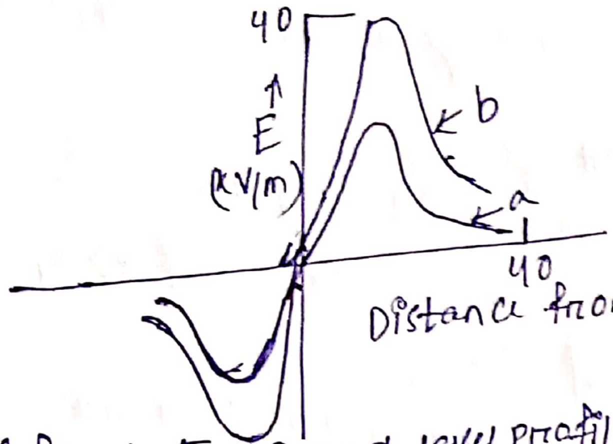
The charge density at ground level can be calculated from

$\rho = \epsilon \nabla E$

where ϵ is the electric permittivity.

→ The total electric field at the ground level is superposition of the space charge field and the electrostatic field.

→ The lateral ground level profiles of the electrostatic and electric fields are shown in below fig.



a = electrostatic field.
b = electric field (including space charge)

(fig. Lateral ground level profile of electrostatic and electric fields)

Protection of DC line :- (L.Q)

→ For fast clearing of DC line faults, it is necessary that the inverter is not allowed to operate as a rectifier and the rectifier is put into the inverter Mode by sudden increase in the delay angle to max^m limit (about 135°).

→ The converters at both terminals discharging the energy stored in the DC ckt and delivering into the AC system.

→ current and voltage in the DC line fall to zero & helps in deionizing the arc path.

→ After some time the line may be automatically energized by restarting the converters.

→ if the restart is unsuccessful, due to persistent fault, the protective action will deenergize the line again.

→ Generally 3 attempts are made to restart automatically.

→ if after 3 attempts also it failure to restart then it is permanent fault.

→ The automatic deenergization and restarting of the DC link is similar to the clearing of the fault in AC lines.

→ The difference is :-

Breakers are used in AC lines | Protective Relays are used in dc lines

Detection of line faults :-

→ The normal converter control is not clearing the fault.

→ The deenergization of the line by driving the rectifier into the inverter mode requires special control action.

→ The detection of the line fault is based on one of the following cond^ns

(i) a sudden drop in the DC voltage measured on the line side of the reactor.

(ii) sustained low direct voltage..

Mathematically the 2 cond^ns can be expressed as

(i) $V_d < K_1$ and $dV_d/dt < -A$ for a duration of $\tau > \tau_1$

(ii) $V_d < K_2$ for a duration of $\tau > \tau_2$

where K_1, K_2 and A are positive parameters that are chosen along with τ_1 and τ_2

→ criteria for selecting these parameters are
- → selectivity
- → sensitivity
- → Reliability

1. **Selectivity :-**

→ selectivity is desirable as the dead time required for deionization of the arc path in the case of DC line faults.

2. **Sensitivity :-**

→ The DC line protection must operate satisfactorily for normal values of the arc resistance. This puts an upper limit on A.

3. **Reliability :-**

→ The protection must operate reliably for all DC line faults including faults through a high resistance.

→ This is a reason for providing the voltage level unit.

Protection Against DC Line faults with VSC :-

→ The DC voltage in VSC based links cannot be reversed and the DC capacitor at both rectifier and inverter stations discharge into the faults.

→ The VSC can feed current to the fault.

→ Detecting DC line faults, the converters need to be isolated from the AC system by opening the AC breakers.

DC breaker can be employed to isolate the converters from the DC line, when a line fault is detected.

DC breakers:-

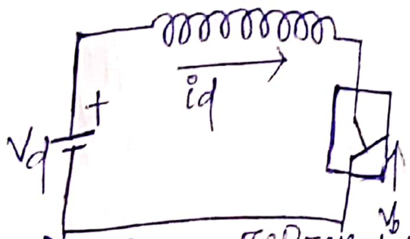
→ The development of HVDC ckt breakers has been underway in late eighties and 500 kV with current interrupting capability upto 4000A.

→ Several types of DC breakers are there and their basic concept is same.

Basic concepts of DC ckt interruption :- (L.Q)

→ ~~[illegible]~~

→ The major problem in the current interruption in DC ckts is that there is no natural current zero as in the case of AC ckts.



(fig. simple representation of DC ckt with breaker)

→ only by applying a counter voltage higher than the system voltage then only current is zero.

→ The dissipation of large energy stored in the inductance of the ckt.

→ The above figure shows the simple representation of DC ckt and breaker has a counter voltage V_b.

→ The energy abosorbed by the breaker is

$$W_b = \frac{1}{2} L I_d^2 \left(V_b / (V_b - V_d) \right)$$

→ Time required to bring the current to zero is given by

$$T_i = L I_d / (V_b - V_d)$$

where I_d = current in the breaker prior to interruption

→ Reduction of I_d has a effect on the breaker costs as W_b is decreased which results the reduced the energy capability of a breaker.

→ I_d is brought down by the normal action of current control in converters.

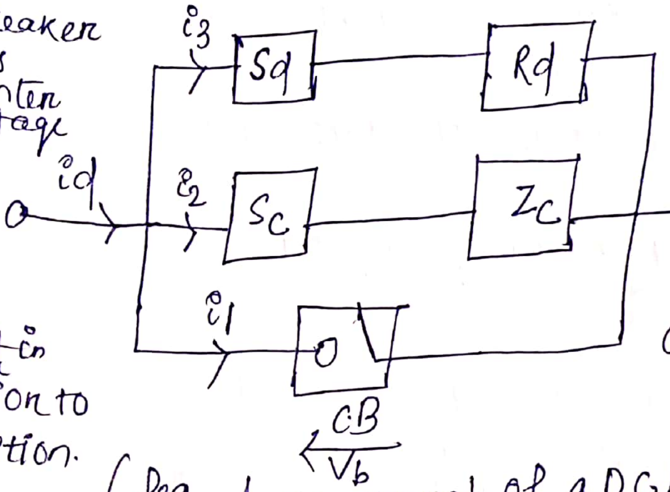
→ It requires some time, time required for interruption reduces.

→ The general arrangement of a HVDC ckt breaker is as shown in below fig.

S_q = insertion device, R_q = energy absorber, S_c = insertion device, Z_c = commutating impedance

V_b = Breaker has counter voltage

i_d = current in the breaker prior to interruption.



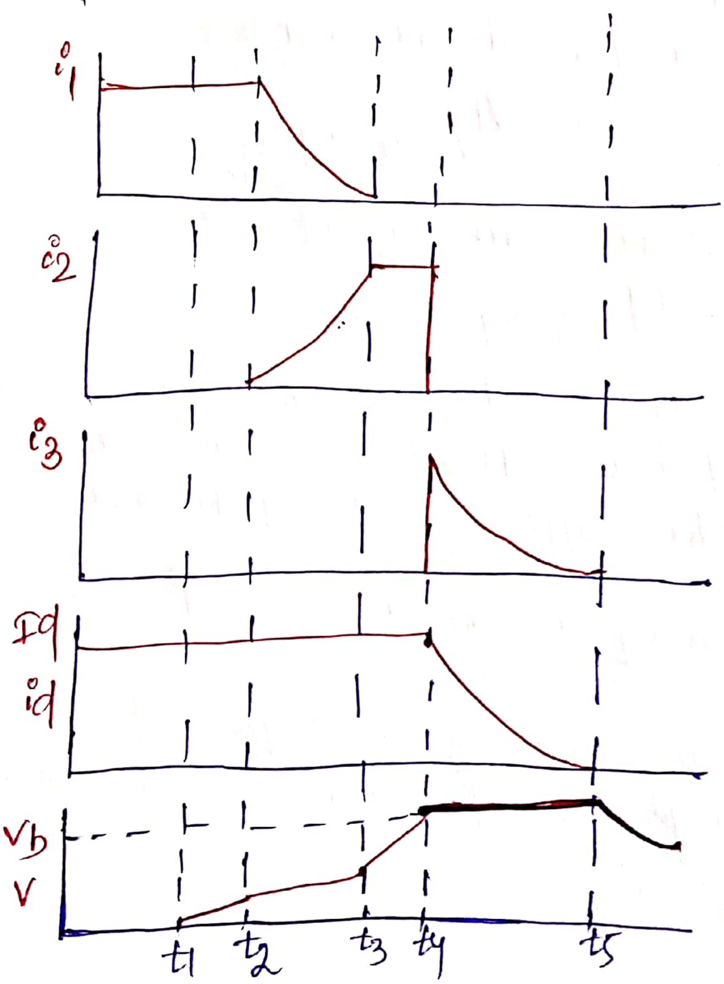
(fig. Arrangement of a DC breaker)

→ The current in the breaker is normally carried through CB with moving metallic contacts.
(it may be vacuum, oil, air blast or SF_6 device)

→ After a trip signal is given to the breaker, the breaker contacts open to draw an arc.

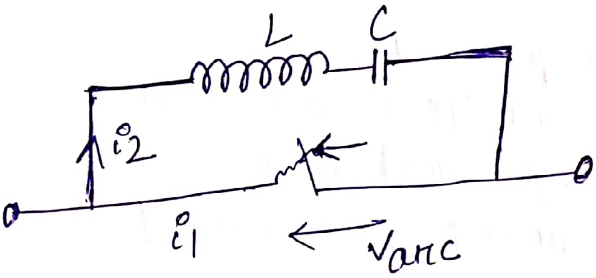
→ This initiated at time t_1.

→ The below fig. shows the wave form of current and voltage.

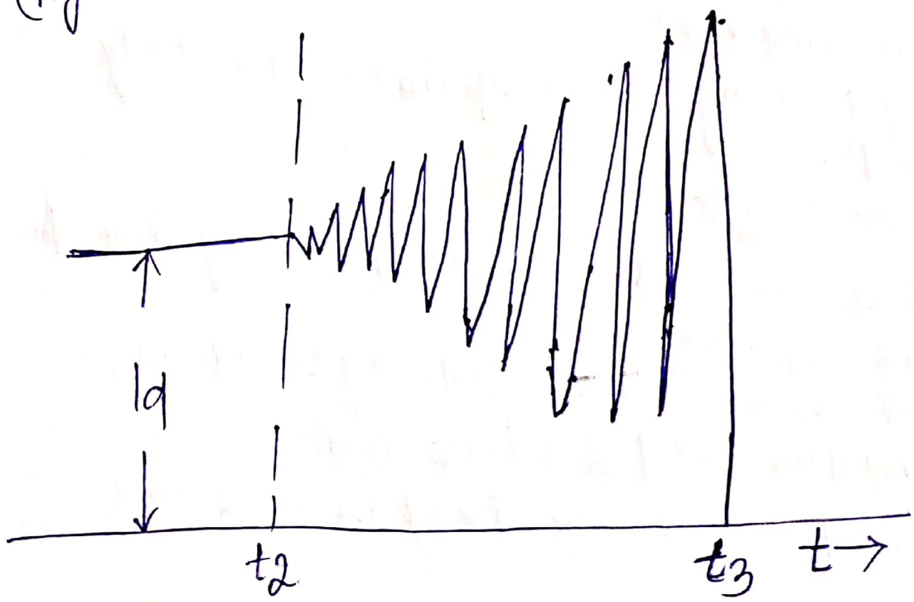


(fig. current and voltage wave forms)

→ at t_2, commutation CKt is inserted through the insertion device Sc
→ The commutating impedance is made up of a series LC CKt & the capacitor may or may not be precharged.
→ The Sc may be a triggered vaccum gap or spark gap or in the so called "passive" commutation CKt.
→ Purpose of inserting a commutating impedance is to create current zero in CB and transfer the current to Zc and current transfer is completed by time t_3.
→ id flowing through the capacitor in Zc rapidly builds up to a high voltage Vb.
→ When voltage reaches Vb at time t_4, the energy absorber Rd is inserted through the device Sd.
→ The nonlinearity of the resistance Rd acts as a switch which closes when its clipping voltage is reached.
→ The id now decays to zero by discharging its energy to Rd at time t_5.
→ The breaker operation is completed by t_5 if the 3 ||el paths CB, Zc and Rd have adequate voltage with stand capability.



(fig. commutation CKt)



(fig. current oscillations in the commutating CKt)

Characteristics and Types of DC Breakers :-

→ The breaker is characterized by four variables of interest in its application to the system. These are :-

1. Voltage capability
2. current capability
3. Energy capability
4. switching time.

→ The voltage capability is related to 2 parameters :-
(i) The voltage during the interruption process &
(ii) steady-state operating voltage and transients in the system.

→ The interrupting capability of a breaker does not have to be much above the rated current in the ckt.

→ The required energy capability of a breaker depends upon many factors such as the inductance, converter voltage and current, breaker voltage and the duty cycle.

→ in HVDC breakers, series connected modules are used to give the required voltage and energy capabilities.

→ The switching time of a breaker includes the following components :-
(i) Time required to generate the trip signal.
(ii) time required to separate the contacts in the main breaker.
(iii) Time required to commutate the current to Z_C.
(iv) Time required to commutate current from Z_C to R_d (energy absorbing ckt)
(v) the interruption time (T_I)
(vi) time required to bring the DC system back to steady-state post fault cond^n.

Applications of DC Breakers :-

→ The application of DC breakers is required mainly for fault clearing in MTDC system.

→ The DC breakers can be useful in following situations :-
1. When the converters feed 2 ||el DC lines.
2. When ||el connected converters feed the same line.