CHAPTER-2 Thyristor Valves

→ HVDC converters are combination of valves which have the property of conducting in the forward direction and blocking in the reverse direction.

→ The Term "valve", carried over from mercury arc valve, is applied now for thyristor valves which are made up of series and parallel connection of many thyristor cells or devices.

→ Thyristor valves are used in line commutated converters, IGBT valves are used in voltage source converters.

→ The major problem with the mercury valves is occurance of arc backs (back fires) which result in the destruction of the rectifying property of the valves.

→ Arc backs are random phenomena, result in failure to block in reverse direction.

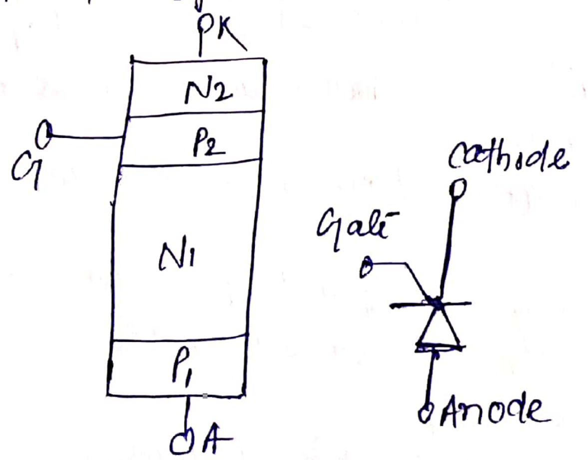
→ Arc backs can be reduced by carefully that to be partially, Arc backs are non-self-clearing and result in line to line faults which stress transformer windings and anodes in the valves.

→ Thyristor valves were developed in late sixties have eliminated all these problems.

Thyristor device:-

→ Thyristor is defined as a range of four layer (PNPN) semi-conductor switches. It is also known as silicon controlled rectifier (SCR).

→ The structure of a thyristor with the 3 terminals and its electrical symbol are shown in below figure.



Layer structure and symbol of a thyristor.

→ The device is uni (one) direction from anode to cathode and conduction can be controlled by the gate.

→ Avoids the necessity of ||el connections, the voltage rating is insufficient to make up a high voltage valve. Thus, a series connection is introduced and it have some problems which are considerable.

→ increasing the voltage rating of a thyristor is easy, but it is at cost of increased losses, turn-off times and reduced peak allowable junction temp.s.

→ The capacity of a thyristor to stand high voltages depends on the d. material of a device is made up.

Device characteristics :-

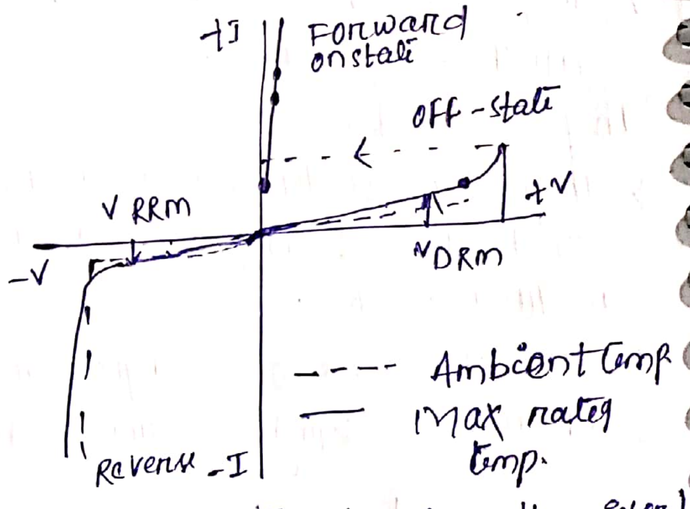
→ The device have following 3 states :-

i. Forward biased and blocking
ii. Forward biased and conducting
iii. Reverse biased and blocking.

→ The second state is called turn-on, and the third state is called turn off.

Steady state characteristics :-

OFF - state :- The volt - ampere characteristics of the device are shown in below figure.



(characteristics of a thyristor)

→ During the Off state (both forward and reverse blocking), only a small magnitude of leakage current flows (100 mA).

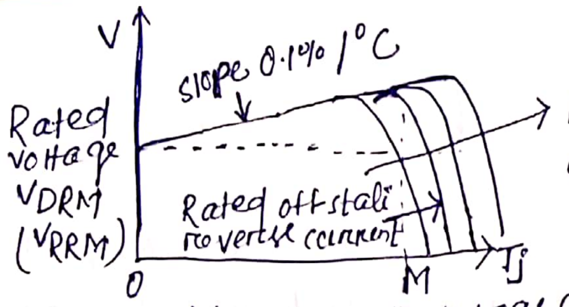
→ The blocking capability with gate open is specified in terms of limiting repetitive peak forward (V_{DRM}) or reverse (V_{RRM}) voltages.

→ A non repetitive peak reverse voltage rating (V_{RSM}) is specified and rated junction temp of the thyristor (typically 125°C)

→ Variation of jun voltage ratings with jun temp. is as shown in fig. below. for different levels of rated reverse current.

Here M = Maxm rated jun temp.

→ Effect of increasing the reverse current is to increasing the ratings.



VDRM = Repetative Peak forward voltage
VRRM = Repetative Peak reverse voltage.

(Fig. Typical thyristor off-state voltage characteristic as a fun^n of jun^n temp.)

→ The behaviour of thyristors under transient voltages is not well understood. However, according to one particular study, the following conclusions can be drawn.

1. The transient breakover voltage of a thyristor is independent of its voltage ratings.
2. The forward breakover voltage of a thyristor under a transient voltage may be lower than its voltage rating and decreases with increase in jun^n temp.
3. The instant of forward break over of a thyristor can frequently occur on the tail of the applied voltage wave. This is due to minimum charge and time delay of the thyristor.
4. The reverse breakover voltage levels of a thyristor under slow transients (30/600 μs) can be lower compared to fast (1.2/50 μs).

→ Reverse direction of thyristor can cause energy losses which is cause variation of the reverse avalanche current with the voltage magnitude of the reverse voltage.

→ The transient voltage blocking of a thyristor is related to the critical power to damage the device.

→ Cumulative effects due to transients with less than critical power cause in degradation the device.

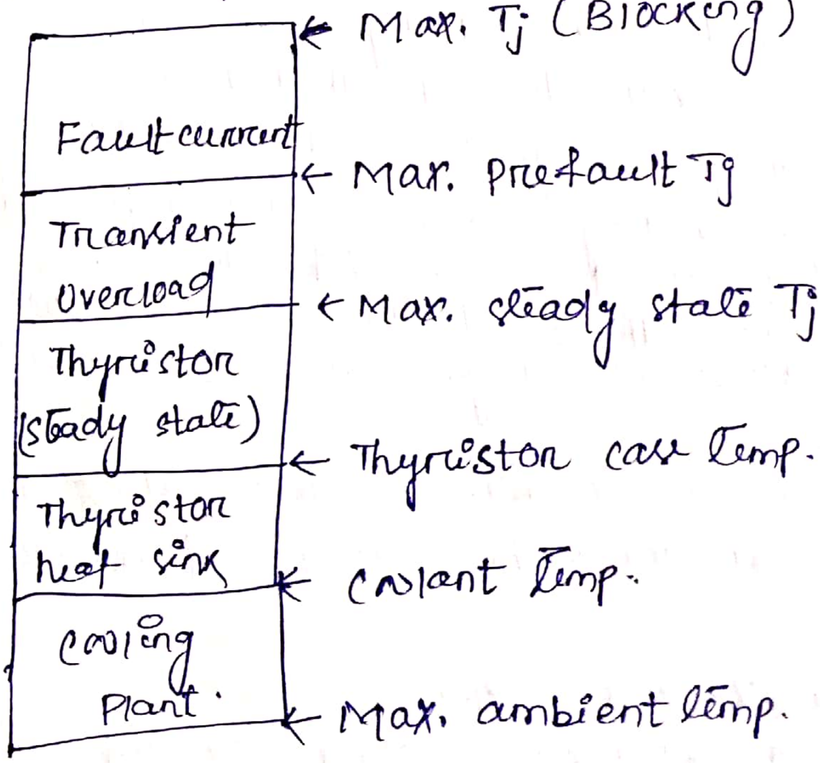
On-state :-

→ There are a number of electrical and thermal parameter that characterize the on-state behaviour. Some of these are as follows.

1. on-state Voltage (V_{TM})
2. Mean (average) on-state current (I_{TAV})
3. Root mean square value of the on-state current (I_{TRMS}
4. Surge (non-repetitive) on-state current (I_{TSM}).
5. NON-repetitive survival rating ($\int i^2 dt$)

6. Holding current (I_H)
7. operating temperature range
8. Junction to case thermal resistance (R_{THJC})
9. contact thermal resistance.

→ Thyristor on state, in forward conducting state, voltage is anode to cathode. and also it having forward voltage drop.
→ it is an important to affecting the power losses during on-state & the ||el operation of the thyristors.
→ on-state voltage depends on a number of factors.
→ The power losses at current density around 100A/cm² is due to recombinations.
→ The power losses at current density around 1000A/cm² is due to Ohmic heating.
→ silicon wafers of small thickness and long carrier life time give to low on-state voltages, so increasing the carrier life time also increases turn off time. if optimize both may result the reverse recovery current.
→ current ratings of on-state is determined by the jun temperature it must be kept below the value necessary to ensure that can be block recovery voltage after a worst case credible over current.
→ Fig. below shows the temp. build up in a thyristor valve.



where Tj = jun temp. of a thyristor.

(fig. Temp. buildup in a thyristor)

→ The surge current capability of a thyristor is based on its filamentation temp.

→ The requirement to have surge suppression capability result in operation of the thyristor at reduced jun temp.

→ The maxm. jun temp. attained due to the cummulative effects caused by passage of repeated current surges should below thyristor filamentation temp.

→ Holding current (I_H), it required minimum current to maintain thyristor on-state.

→ Forward current reduced, the turn-off occurs when recombination causes.

→ The I_H reduces with ↑ in jun temp.

Switching characteristics :-

Switching characteristics
- Turn on (Delay time + Rise time + spreading time)
- Turn off ($T_{gr} + T_{rr}$)

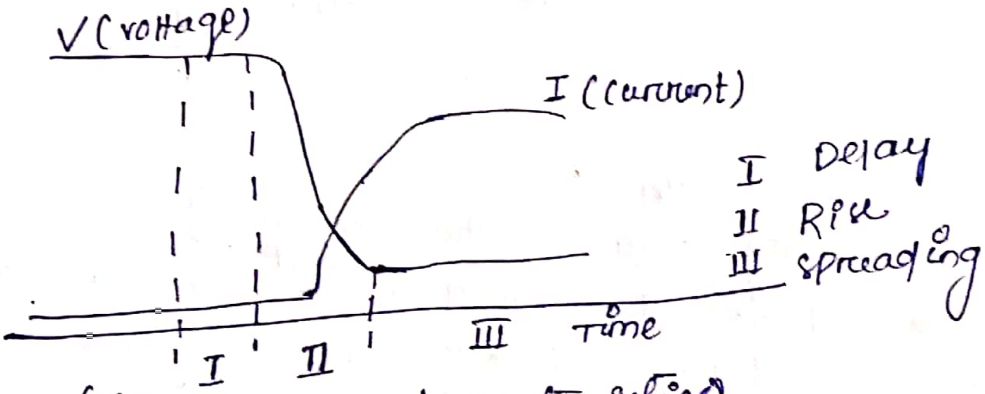
Turn-on :

→ A gate drive is applied with the forward voltage above latching voltage, turn-on occurs.

→ Because of finite sheet resistance of the P-base region, only regions of the cathode near to the gate are influenced by gate current.

→ ~~Regenerat~~ the establishment of current flow over the cathode area follows by outward spreading from this conducting plasma by diffusion.

→ There are three phases of turn-on shown in fig. below.



(Fig. Turn on characteristics)

→ The delay time is associated with the establishment of regenerative action in response to the gate current.

→ Regeneration is well established during the rise time.

→ The current continues to increase during the spread time.

Turn-off :-

→ All the three jun^ns are forward biased during on state and the base region contains excess minority & majority charge.

→ This charge must either be swept out by an electric field or decay through regenerative processes within the silicon.

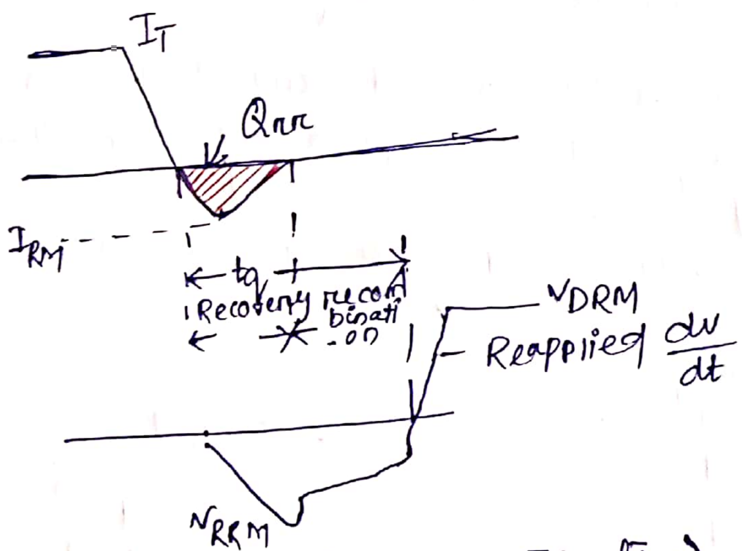
→ The ckt voltage is reversed, the current falls to zero at a certain rate. Once the current reaches zero, the flow reverse, since the minority carrier ~~connections~~ concentration at the jun^ns can supports this current by diffusion without building up of depletion layer.

→ Peak value of reverse current is reached when excess hole concentration at the anode jun^n fallen to zero.

→ At this time, thyristor is reverse voltage with depletion layer & the current decays as a result of charge recombination within the n-base region.

→ The current is depend on the mean life time of carriers in n base region.

→ The Turn-off process is show in figure below.

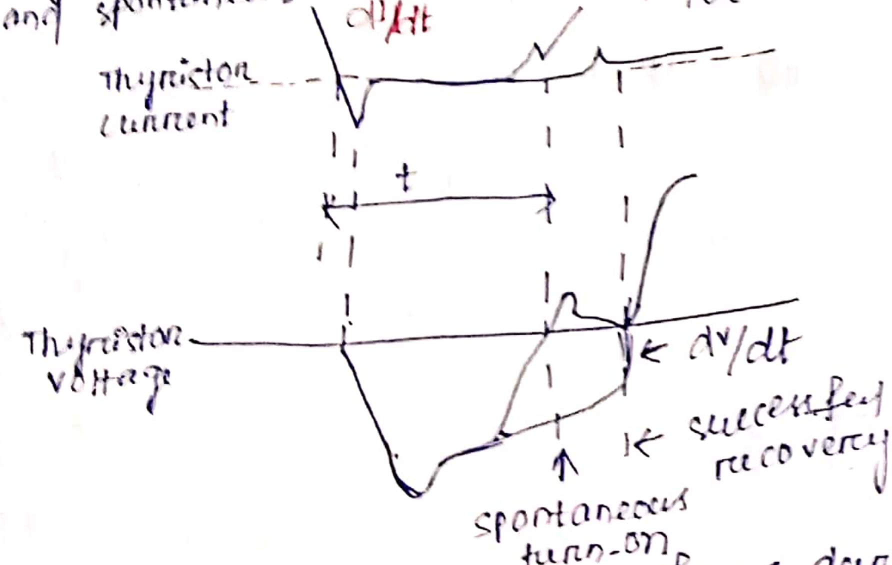


(Fig. Turn off characteristics)

→ After current zero, thyristor doesn't ~~allow~~ support forward voltage. It acquires forward blocking capability but it withstand forward dv/dt.

→ off state dv/dt attain only millisecond on has elapsed from current zero.

→ fig. below shows the current and voltage waveforms for a recovery and spontaneous turn on for a fixed dv/dt transient.



(fig. current & voltage waveforms during the recovery)

Gate Drive :- I.g

→ A drive with rise time is to turn on the device with large di/dt.

→ A single short pulse is to turn on the device, it doesnot have below Holding current during conduction time.

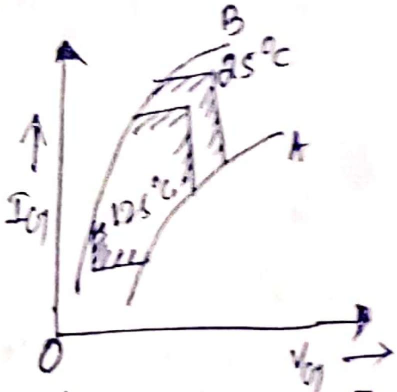
→ long pulses are to avoid blocking of the device.

→ The gate V-I characteristics are show in figure below.

→ Gate trigger is bounded by two lines A & B.

→ The Gate voltage and current having lower & upper limits.

→ The upper limits are funs of the juno temp.



(fig. Gate characteristics)

* Modern HVDC thyristor valve are fired from the optical signals.

→ These signals in turn are generated from the converter controller.

→ The source is provided to each Module by power supply unit.

→ The gate pulses are generated in the gating and logic units in response to optical signals, transmitted via fiber-optic light guides separately to each Module.

→ The gating and thyristor status are monitored at the ground level from the signals sent through light guides (LED)

→ The diagram of typical Module with one thyristor per Module is shown in below figure.

LED = Light emitting Diode

L_S = Saturable reactor

C_D, R_D = AC Voltage grading and damping ckt

R_{DC} = DC voltage grading resistor.

C_H, R_H = High frequency voltage grading

1 = Thyristor voltage monitor

2 = power supply unit

3 = Break over diode (BOD)

4 = Gating and logic unit

5 = Gating status LED

6 = Thyristor status LED

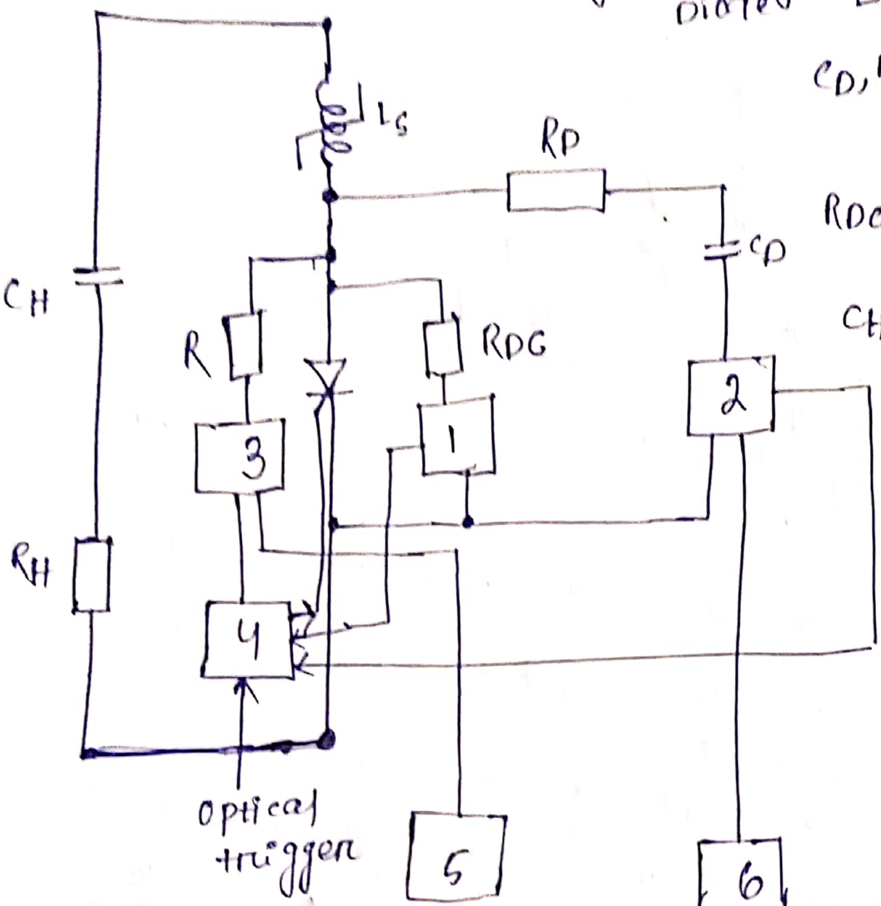


Fig. Typical valve Module (Source: Reference 22)

→ The use of break over diode (BOD) is to sense overvoltage across the device & protect it by generating gate pulse.

→ BOD firing, used for back-up when gating & logic unit fails.

→ AC voltage grading is provided by resistor R_D & capacitor C_D in series.

→ The resistor RDC provides for DC voltage grading & it is also used for voltage measurement.

→ The saturable reactor is used to protect the device against di/dt.

→ CH & RH are used for high frequency voltages as grading ckt.

Thyristor valve :- (L.q)

→ A thyristor valve Made up no. of devices are connected in series to provide voltage rating and connected in parallel to provide current rating.

→ so Modern devices does not need parallel connections.

→ series connection of thyristor is for device ratings, transient over voltages & protection.

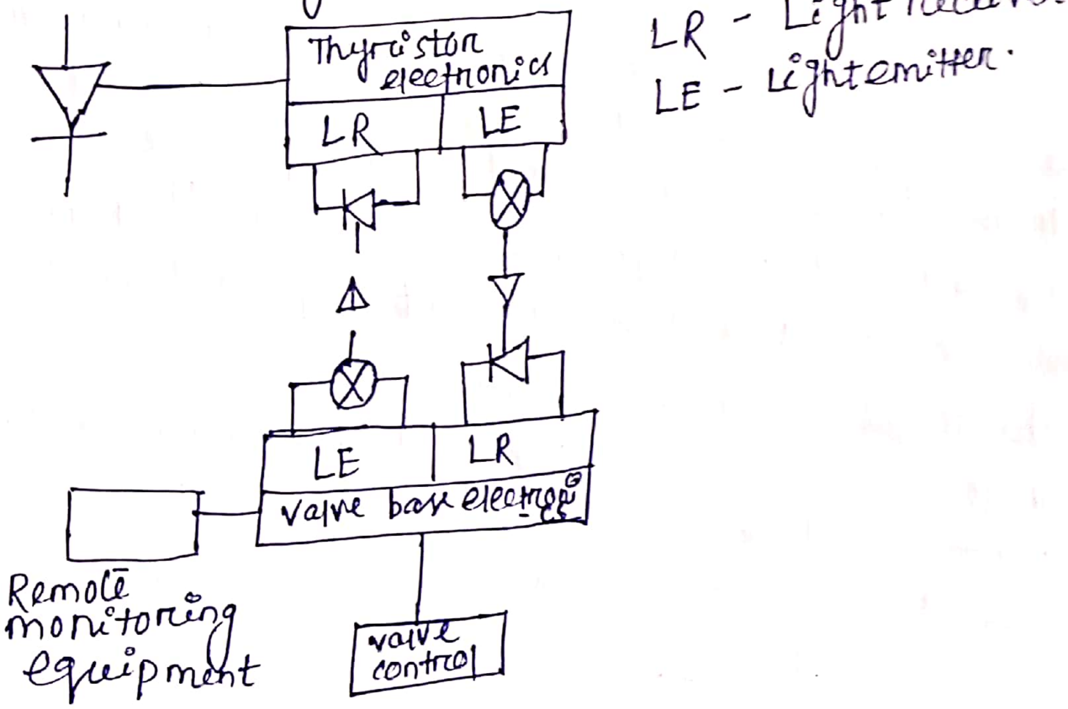
→ valves placed indoor in a valve hall to protect against contamination and dust.

→ valves are arranged in a single, double or quadrivalve configuration.

→ valves are air circulated and cooled using air, water, oil or freon. so normally use is water.

→ **Valve firing :-**

→ The basic valve firing scheme is shown in below figure.



(Fig. valve firing scheme)

→ The valve control generates firing signals.

→ Each thyristor level receives the signal direct from separate fiber-optic cable.

→ Each thyristor level is independent it only sharing duplicate light source at ground potential.

→ Present day valve control unit is used return pulse system coupled with short pulses firing scheme.

→ A light guide is send a return pulse, when the voltage across the thyristor is enough and power unit is charged.

→ at the time if firing pulses are demand it send to all thyristors control unit at a time.

→ During normal operation only one light pulses are generated in a cycle for each valve.

→ Many light pulses are generated due to discontinuous current

Valve design considerations :- (L.q)

→ Design of valve must consider voltage and current stress during the normal & abnormal condns.

→ The voltage is excess it cause short ckts on AC and DC systems.

→ Due to dynamic overvoltage, it is crucial to determine the voltage ratings.

→ The magnitude of dynamic voltage is depend on AC system strength.

→ The over current cause the short ckts across a converter bridge.

→ The surge current ratings of a valve is limited both by transformer leakage and system impedance,

→ The overload ratings of a valve is a fcn of the size of the device as well as ambient temp. and the cooling system.

→ The losses in a valve include :-

(i) The losses during on-state and switching losses.

(ii) Damper and grading ckt losses.

(iii) losses due to auxiliary power required for cooling.

(fig. voltage on last firing thyristor)

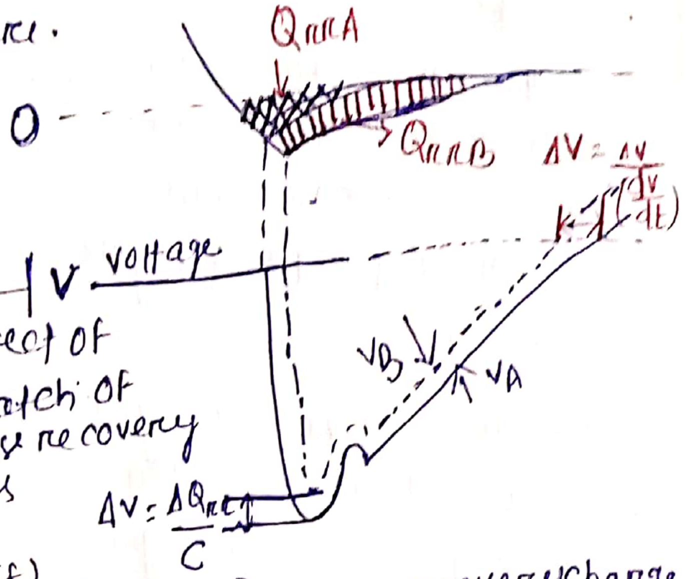
→ ~~[struck out]~~ generalized overvoltages and the design of valve component viz damper ckts is facilitated by digital computer programmes which can be model the non-coherent turn on and turn off of the thyristor devices in a valve.

→ The non-coherent turn on of a valve, ... last level to be fired.

→ The differences in the stored charges result in varying commutation margins in individual devices in an inverter valve & it is as shown in below figure.

→ The below figure is the effect of charges during turn off.

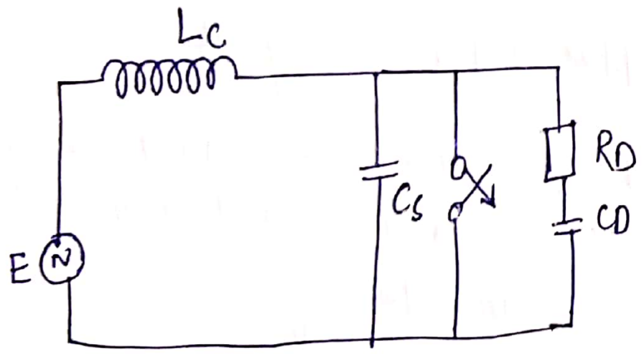
→



(fig. Effect of Mismatch of reverse recovery charges during turn off)

Q_{rrA} = Reverse recovery charge at A.
Q_{rrB} = Reverse recovery charge at B
Q_{rr} = Reverse recovery charge
C = Stray capacitance

→



RD =
CD =
Cs = stray capacitance
Ls = source inductance

(fig. simplified equivalent circuit during turn off)

→ The recovery voltage across the valve that has turned-off shows an overshoot that is due to the charging of the stray capacitance through the source inductance. As shown in figure below.

→ The reduction in short ckt Ratio (SCR) tends to reduce the max^m value of fault current in a valve.

→ and not necessary to reduce stress, as the device failures occur due to over voltage.

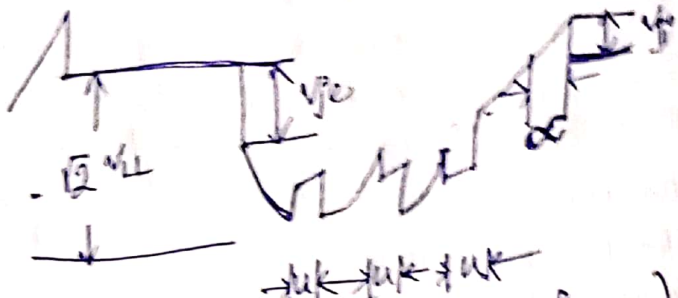
→ The low SCR can be give nonsinusoidal voltage at converter bus which can cause commutation failures.

→ The control of electrostatic and electromagnetic fields surroundings a valve is essential to avoid corona discharges and inference with sensitive electronic ckts.

→ The below figure shows the valve voltage waveform

→ The damper ckt is the significant component of overall losses.

→ The damper loss is due to discontinuity in the valve voltage wave form.



→ 8 voltage jumps in a cycle. (fig. valve voltage waveform)

Suspended valve:-

→ Quadri-valve configuration is a compact valve hall & it is a tall in structures (upto 16meter tall).

→ The suspension arrangement has spring and damper mechanism for mechanical isolation of the valve from the building vibrations.

→ The valve structure is flexible.

Water cooling:-

→ In place of air, water is replaced for cooling the valves from heat.

→ Water has several excellent qualities as a coolant :- high specific heat, high thermal conductivity, high heat transfer capability, low viscosity and low density.

→ It also electrolytic conductor.

→ in an HVDC valve, more than 95% of the heat losses are produced in thyristors, snubber ckt resistors & the valve reactors.

→ Water cooling is used to remove heat from components.

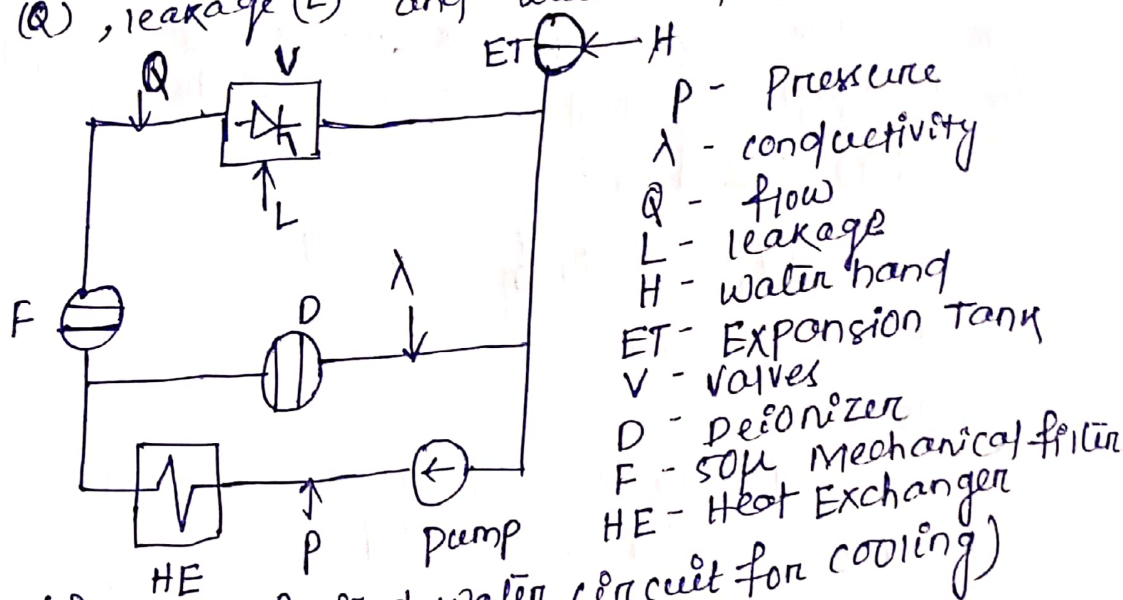
→ The cooling ckt needs to be optimized w.r.t

1. Thermal / hydraulic
2. Electrical performance.

→ conductivity of the water, the piping of the cooling ckt forms as a resistive n/w shunting thyristor, snubber etc.

→ A ||el cooling ckt configuration of a module, avoiding any flow of electrolytic current to metal parts.

→ The basic configuration of the cooling ckt for a HVDC thyristor valve group is as shown in below figure.
→ The quantities monitored are pressure (P), conductivity (λ), flow (Q), leakage (L) and water head (H).



(fig. De-ionized water circuit for cooling)

Valve protection :- (L.q.)

overvoltage protection | over temperature protection.

Overvoltage protection :-

→ A HVDC valve must be designed with (i) internal & (ii) external over voltages.
→ The external sources for overvoltage is (i) lighting & switching surges
(ii) dynamic overvoltages caused by load rejection.
(iii) low order harmonic resonance in the AC system &
(iv) injection of AC voltage on the DC line due to converter faults.
→ valves can be protected by zinc oxide, gap less DC arresters from the over voltage.
→ The over voltage in the forward dirn can be controlled by protective firing of the thyristors in a valve.
→ The over voltages in the f/d dirn can also arise from partial recovery of a valve following turn-off process (in inverters).
→ forward dv/dt protection is also required by sensing dv/dt measured across a level and turning on the device if the threshold is exceeded.

Over temperature protection :-

→ The current ratings of a valve is determined by the ability of thyristors to withstand the recovery voltages following a worst case, credible fault current.

→ This is normally determined by junⁿ. Temp.
→ An accurate prediction of junⁿ Temp. can be Made, if pre-fault and post-fault current waveforms are specified.
→ The thermal model of a thyristor is characterized by its transient thermal impedance R_{TH} & following is the eqⁿ

$$T(t) = \sum A_n \phi_n(t)$$

$$d\phi_n/dt + B_n\phi_n = B_n W(t)$$

Where T is the Temp. rise.

$W = VI$

A_n, B_n = parameters determined from tests.

V = On-state voltage drop

$$= V_0(1+\alpha T+\beta T^2) + R_0(1+\delta t+\epsilon T^2)I + E_0(273+T)\ln I + F_0(1+\gamma T+\theta T^2)\sqrt{I}$$

where $V_0, R_0, E_0, F_0, \alpha, \beta, \gamma, \epsilon, \delta$ and θ are constants.

When W(t) is a unit step funⁿ.

$$T(t) = R_{TH}(t)$$

$$= \sum A_n[1-\exp(-B_nT)]$$

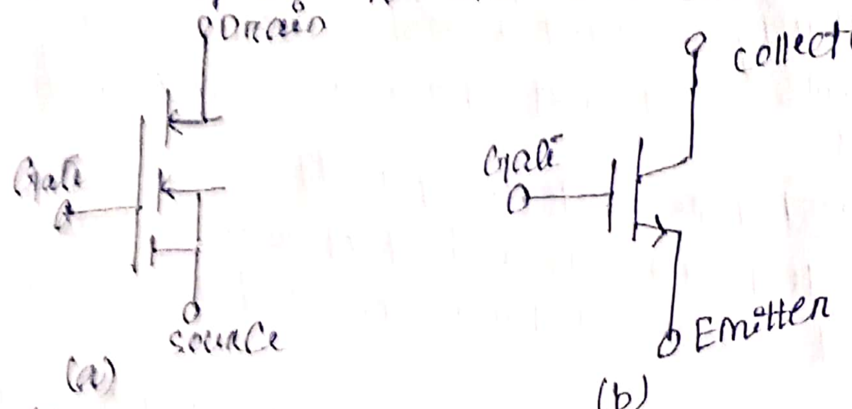
→ When the junⁿ Temp. exceeds a critical level, the optical firing pulses to all the thyristors in a valve are inhibited.
→ If two or more thyristors are connected in parallel, current sharing protection is provided to ensure that in case of a transient disturbance, one of the ∥el thyristors does not extinguish.

Recent trends of HVDC valves :-

IGBT valve :- (L.q)

BJT & MOSFET have complement each other.
→ BJTs have lower conduction losses in the on state but longer switching times. ~~on the other~~
→ MOSFETs can be turned on or off much faster, but their on state conduction losses are much longer.
→ Combine BJT and MOSFET monolithically in the same silicon wafer have led to the development of insulated gate Bipolar transistor (IGBT).

→ The ckt symbols for IGBT are shown in fig. below.



(fig. circuit symbol of IGBT)

→ IGBT combines a high impedance, low-power gate input with the power handling capacity of bipolar transistors.

→ And control is achived by using a pattern of MOS transistors.

→ The bipolar effect of the IGBT gives a self-limiting current.

→ The device is protected by turning it off within a few μ seconds.

→ IGBT is the linear control through the gate.

→ $\frac{dI}{dt}$ and $\frac{dv}{dt}$ can be controlled during commutations.

→ IGBT valves are invariably used in VSC-HVDC converter station.

→ To obtain rated current capability, the IGBT is made of a number of chips connected in ||el in the same housing.

→ The IGBT chip is designed to have only forward blocking capability, since the anti ||el diode protects against voltage in the reverse dirn. (free wheeling diode)

→ The IGBT is preferred choice for VSC based HVDC converters due to the following reasons:

1. It allows active voltage sharing.
2. Low power control which is advantageous at very high voltage levels.
3. Transistor action that enables the converter to be turned off even in short ckt conditions.
4. High switching speeds, thus making high switching frequency feasible.

→ Valve design considerations:- (LQ)

To ensure reliability, an IGBT have few redundant devices to enable confirmed operation of the valve in case of failures.

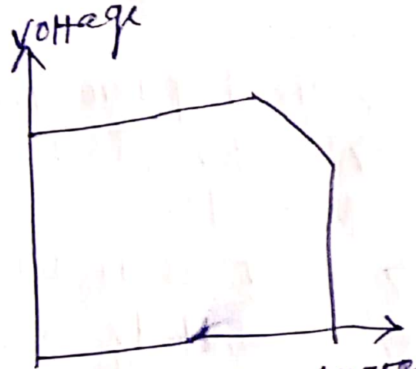
→ A faulty device cannot create an open ckt.

→ A faulty device must enter into a short ckt mode and carry current until it is replaced during the scheduled maintance period.

→ Short ckt failure mode (S.C.F.M) operation is very critical for series connected IGBT devices.

→ IGBT is their capability to turn off current.

→ This capability is defined in the switching safe operating Area (SSOA) as shown in below figure.



(fig. A typical SSOA of IGBT)

→ Each valve may have 100 or more IGBT devices connected in series to provide the required voltage rating.

→ Design an IGBT valve that maintains voltage sharing during switching & blocked states by gate control.

→ power losses can be reduced by the selection of 3-level converters that operate at lower switching speeds.

→ The design of cooling system for IGBT and FWD is similar to that of thyristor valves.

→ The only difference is the increased losses in the IGBT valves.

→ The losses in IGBT consists of on state conduction losses, and turn on and turn off lose.

→ The losses in diode is negligible turn-on loss.

→ As with thyristor valves, IGBT valves must be installed in especially designed valves halls or separate valve enclosures.