Multiple connections of SCRs:

- SCRs are now available in higher voltage & current ratings (6KV, 4KA) and development stage of 10KV, 6KA in future.

- But in applications demanding opern. at h.v. and h.c. (HVDC Tx systems), many such Thyristors need to be connected in series and parallel for h.v. & h.c. operations.

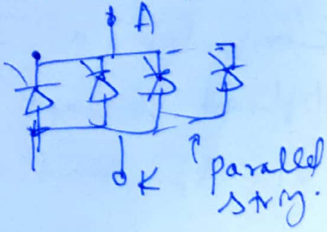
- For h.v. opern., many SCRs need to be connected in series & for h.c. opern., SCRs need to be connected in parallel.

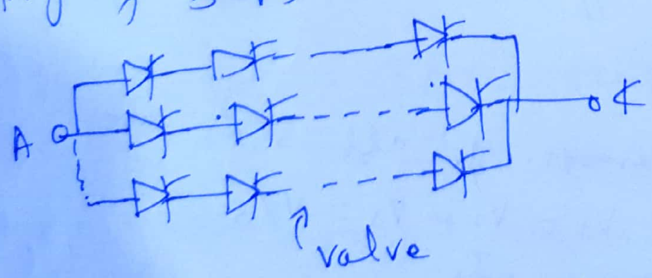
- In some other power control applications, SCRs of lower l.v. and l.c. than above are involved and SCRs of this voltage & current rating can be used. But for the reasons of availability and economy, SCRs of lower voltage & current ratings are connected in series/parallel.

- For applications requiring h.v. and l.c. operation, SCRs of lower ratings are used in series and for l.v. and h.c. operation, they are used in parallel.

- When SCRs are connected in series/parallel, they form a series/parallel string of SCRs.

- In HVDC systems, the series/parallel string of SCRs is called the valve.





- The efficiency of string of SCRs is called the string efficiency and is defined as the ratio of total voltage/current rating of string to individual voltage/current rating of SCR multiplied by the no. of SCRs in series/parallel.

$$\%\eta_{series} = \frac{\text{Total voltage rating of string}}{n_s \times \text{voltage rating of each unit}}$$

where n_s = no. of units in series

$$\eta_{parallel} = \frac{\text{Total current rating of string}}{n_p \times \text{current rating of each unit}}$$

where n_p = no. of units in parallel.

- Ideally, $\eta_{string} = 1.0$ but the SCRs don't share voltage/current equally due to spread in their characteristics and these characts. need to be matched as much as possible.

Series connection of SCRs:-

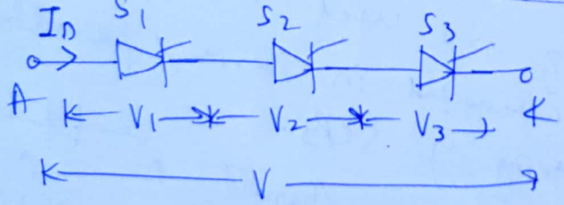
Problem: Unequal voltage sharing among the thyristors in series string due to:

i) Difference in Static V-I characts., → Difference in forward blocking resistances

ii) Difference in Dynamic characts.,

iii) ~~Difference Due to pulse appli~~ Due to firing at different instants.

i) Difference in Static V-I characts.:-

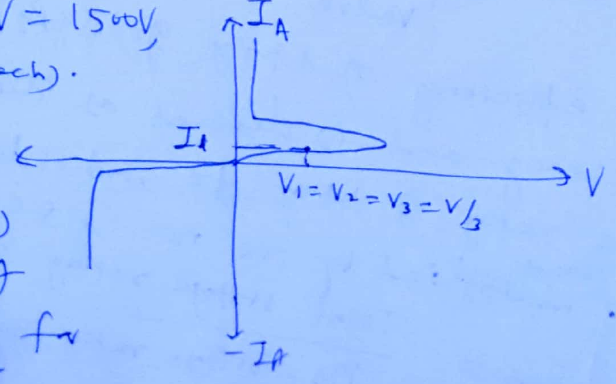


Consider a series string of three SCRs with total applied voltage of V and voltage shared by devices as V_1, V_2 and V_3, respectively.

Ideally, the V-I characts. of all SCRs are identical as shown so that $V_1 = V_2 = V_3 = V/3$.

~~but practically~~ If $V = 1500V$,

then $V_1 = V_2 = V_3 = 500V$ (each).



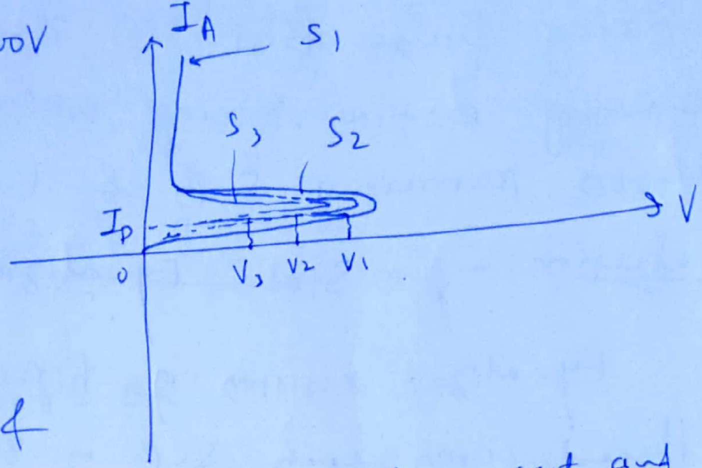
practically, there production spread (shift) in V-I static characts. of SCRs in series string (even for same batch of SCRs).

for same voltage, they have different leakage currents and since they are connected series, they carry same amount of leakage current. Thus share voltage differently as shown in the I characts. The SCR with lowest leakage current will share highest voltage & the SCR with highest leakage current will share ~~high~~ lowest voltage.

Now, $V_1 + V_2 + V_3 = V = 1500V$

But $V_1 \neq V_2 \neq V_3$.

Let $V_{BO} = 700V$



Let $V_3 = 300V < V_{BO}$

$V_2 = 400V < V_{BO}$ &

$V_1 = 800V > V_{BO}$ & hence S_1 shorts out and $V_1 = 0$. So, the entire 1500V has to be shared bet. ~~S_1 &~~ S_2 & S_3 and they get damaged, resulting in the damage of entire string.

ii) <u>Difference in Dynamic characts.</u>: Due to the shift in dynamic characts. of SCRs, they have different t_{ON} & t_{OFF}.

Let $t_{ON1} = 3\mu s$, $t_{ON2} = 5\mu s$ and $t_{ON3} = 6\mu s$

So, S_1 is the first to ~~turn~~ turn on, causing the entire voltage to get applied across remaining SCRs and hence damage to the series string. This is called transient turn-on voltage sharing.

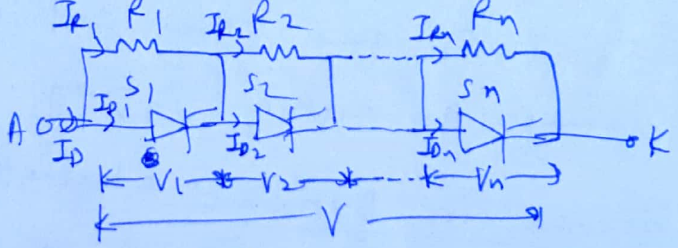
In a similar way, the SCRs have differences in reverse recovery times and hence t_{OFF}. The fastest SCR is the first to turn-off and hence share entire voltage and get damaged, followed by damage of other SCRs in the string. This is called transient turn-off voltage sharing.

iii) ~~Diff~~ Application of firing pulses at different time instants

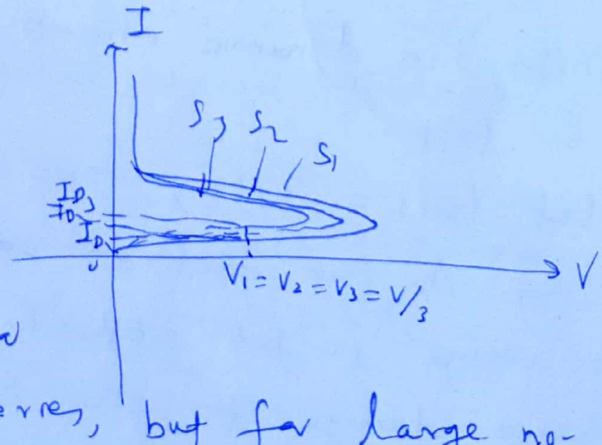
- It is quite possible that firing pulses get ~~are~~ issued to SCRs in the string at different time instants, causing damage to the string. The SCR to get firing pulse first is the one to conduct, causing entire string voltage to get applied across remaining SCRs & hence causing damage to them.

Solution:— a) Static Equalizing circuit:

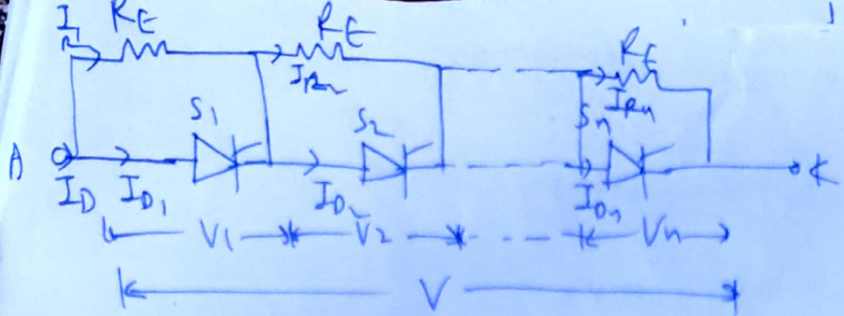
Equalizer resistors of higher ohmic values are placed across each SCR as shown to equalize the forward blocking resistances of SCRs and cause different leakage current in them so that they share voltages equally.



As shown in V-I static characts., diff. leakage currents cause equal voltage sharing among SCRs in the series string.



The above method is economical & realizable for small no. of SCRs in series, but for large no. of SCRs in series, this method is uneconomical and unrealistic. Instead, it is preferred to connect same value resistance (as shown) across each SCR so that they share different but fixed voltages within permissible limits. The difference is shared voltage is reduced.



This is called Static Equalizing circuit.

Now,
$$I_D = I_{D1} + I_{R1} = I_{D2} + I_{R2} \cdots$$

$$\Rightarrow I_D = I_{D1} + \frac{V_1}{R_E} = I_{D2} + \frac{V_2}{R_E} = \cdots = I_{Dn} + \frac{V_n}{R_E}$$

Now,
$$\frac{V_1}{R_E} + I_{D1} = \frac{V_2}{R_E} + I_{D2}$$

$$\frac{V_1 - V_2}{R_E} = I_{D2} - I_{D1}$$

$$\frac{\Delta V}{R_E} = \Delta I \Rightarrow \boxed{R_E = \frac{\Delta V}{\Delta I}}$$

Let $\Delta V = 200V$ & $\Delta I = 15mA$

$$\therefore \boxed{R_E \simeq 13K\Omega}$$

For $R_E > 13K\Omega$, better equalization can be achieved.

In fact, R_E will not perfectly equalize the voltages but will tend to do so so that $V_1, V_2, V_3 < V_{BO}$.

If forward blocking resistances of two SCRs are $13K\Omega$ and $15K\Omega$ and $R_E = 30K\Omega$, then equiv. forward blocking resistances are:

$13K \parallel 30K$ & $15K \parallel 30K$

$= 9.06K$ & $10K$

So, net forward dynamic resistances are more close to each other and

~~Let $R_E = 100K$~~

~~$\therefore 13K \parallel 100K$ & $15K \parallel 100K$~~

~~$= 11.5K$ & $13.04K$~~

tend to equalize the voltages.

Now, let voltage across each SCR be of the order of 1000V.

$$\therefore P_E \approx \frac{(V)^2}{R_E} \approx \frac{(1000)^2}{13\times10^3} \approx 77W$$

So, for proper heat dissipation, heat sinks are required.

⇒ Requirements of equalizing resistance are:

- R_E should be of higher ohmic value
- R_E should be non-inductive in nature
- R_E should have higher power dissipation capability.

Also,
$$R_E = \frac{n_s V_s - V}{(n_s - 1) I_D},$$
where

n_s = no. of units in series, V_s = voltage across each unit, V = Total string voltage &

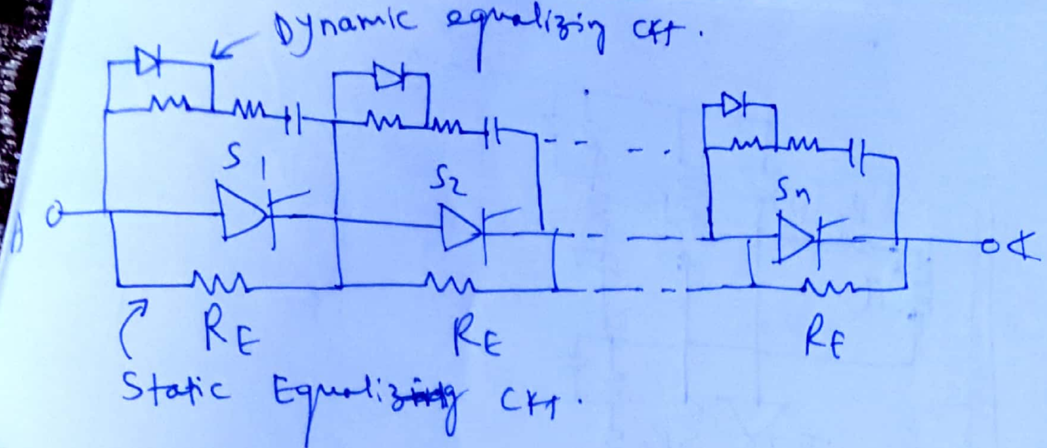
I_D = max. leakage current at rated voltage.

---

b) **Dynamic Equalizing circuit:** It takes care of turn-on & turn-off transient voltage sharing of SCRs.

An R-C n/w (snubber ckt.) is placed across each SCR which, apart from providing protection against high dv/dt signals, also causes transient voltage sharing among SCRs.

RC causes slowing down of voltages across each SCR so that by the time voltage reaches max. rated value, all SCRs are triggered.



Let $t_{on1} = 3.5\mu s$, $t_{on2} = 5\mu sec.$ & $t_{on3} = 6\mu s$

& let V reaches rated value

in 10 μsec. So, by the time, 'V' reaches rated value, all SCRs are triggered without causing higher stress across an SCR due to it's earlier turn on.

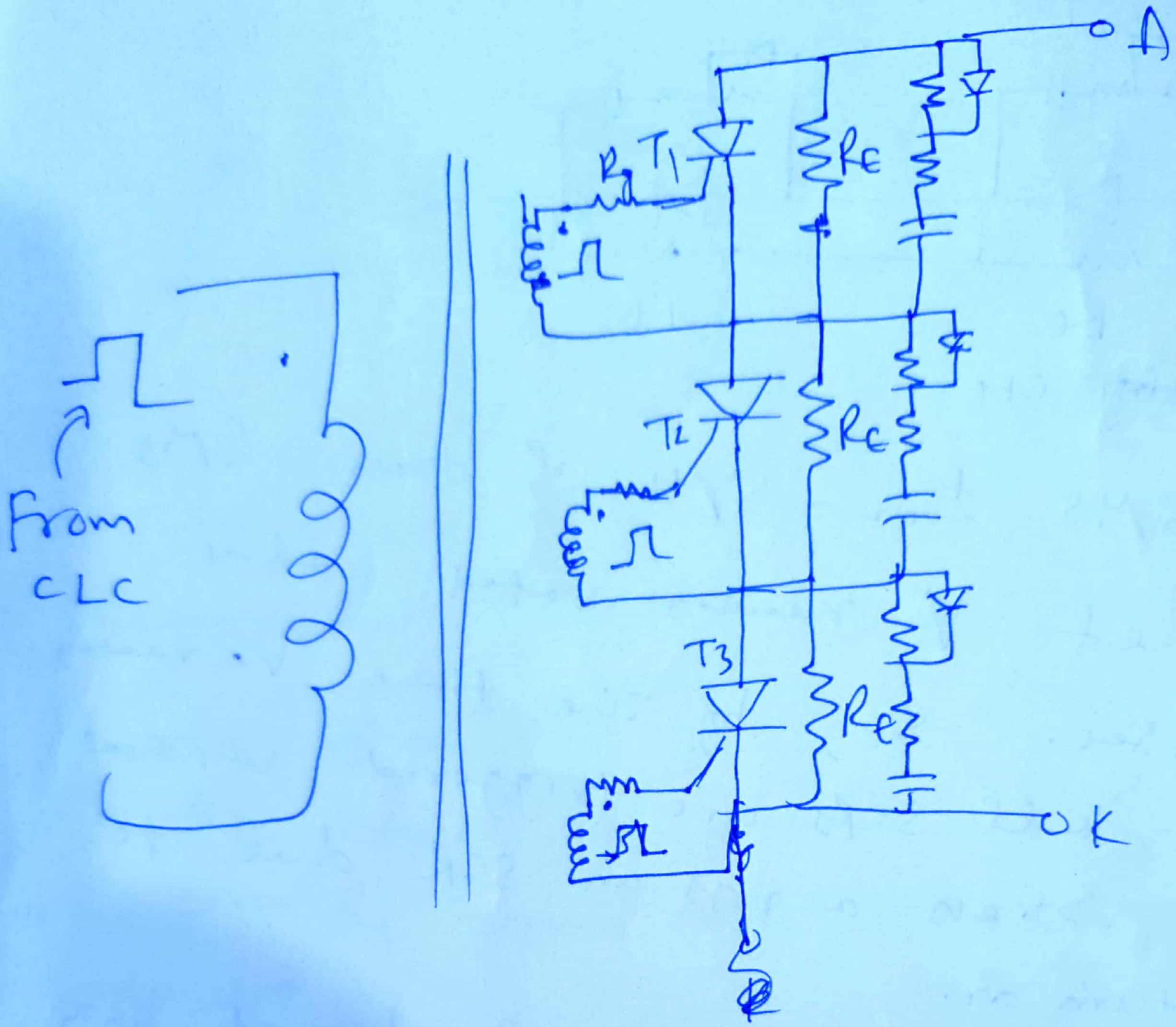
Also, when an SCR turns off, R_E provides path for reverse recovery current of other SCR.

$$\boxed{C = \frac{(n_s - 1)\Delta Q}{n_s V_s - V}}$$, where

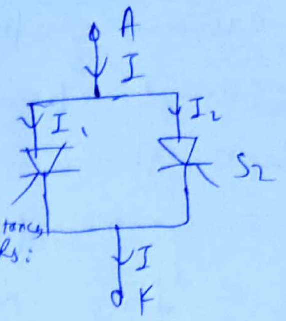
ΔQ = max. difference in recovery charge of SCRs in the string. It can be obtained from data sheets, application notes of manufacturers or from handbooks.

c) Independent Triggering Scheme:

Drive circuit with pulse transformer having single primary and multiple secondaries results in simultaneous application of firing pulses to all SCRs.


A
R
T1
Re
T2
Re
T3
Re
From
CLC
K

...llel connection of SCRs: – This is also called high current operation of Thyristors. Ideally, the thyristors in the parallel string should share currents equally as shown in fig(a) below.



For two SCRs in parallel,

$$I_1 = I_2 = I/2.$$

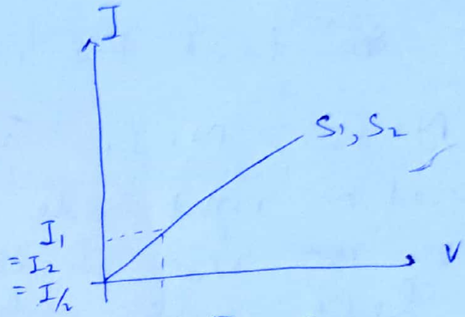
Problem: i) Due to diff. in forward dynamic resistance of SCRs:

But due to the difference in forward dynamic resistances of two SCRs, they don't share currents equally as shown in fig(b).

$$\therefore I_1 \neq I_2$$

$$I_2 > I_1$$

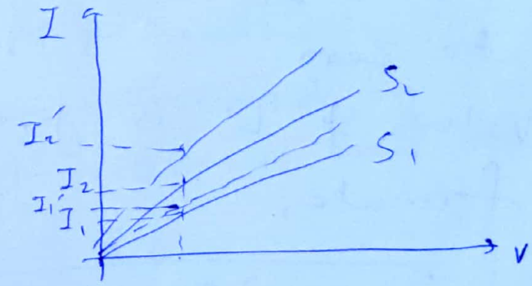
$$I_1 + I_2 = I$$



Fig(a).

Due to this, $I_2^2 R_2 > I_1^2 R_1$

So, Jxn. temp. rise of S_2 will be higher than that of S_1. This further reduces the forward dynamic resistances of both S_1 & S_2 and characts. shift more towards y-axis. But shift is more in S_2 than S_1 as shown in fig(b). So, this leads to $I_2' \gg I_1'$ and this is a regenerative process and I_2' will go on increasing much more than I_1' leading to what is known as thermal runaway in which S_2 gets damaged followed by damage of other SCRs in the string.

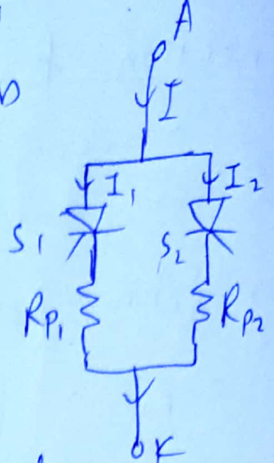


Fig(b).

Solution: The method to equalize currents is to connect external resistances in series with each branch as shown.

Now, $R_{P1} + R_1 = R_{P2} + R_2$

Hence, S_1 & S_2 share currents equally. But this method is less efficient due to power losses in R_{P1} and R_{P2} and is suitable only for low-current operation. For high-current operation, balancing reactors, as shown, are used. The losses are now negligible.

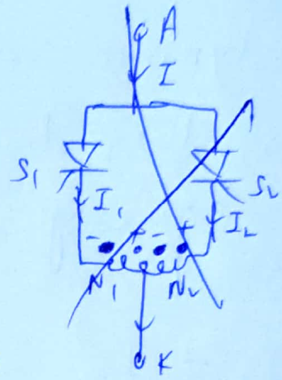


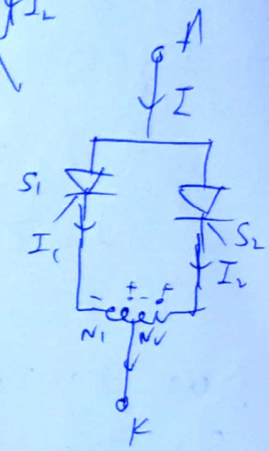
It is a centre-tapped reactor with $N_1 = N_2$.

If $I_1 = I_2$, $N_1 I_1 = N_2 I_2$.

Let I_2 tend to increase.

$\therefore$ $N_2 I_2 > N_1 I_1$ and emf induced on right side tends to oppose rise in current and on left side aids current till $I_1 = I_2$ and inductor voltage falls to zero.





Value of 'L' is given by the empirical formula,

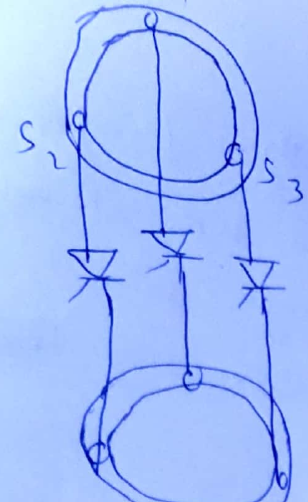
$$L = \frac{20,000}{\omega_s \times I_{FRM}} \rightarrow mH$$, where

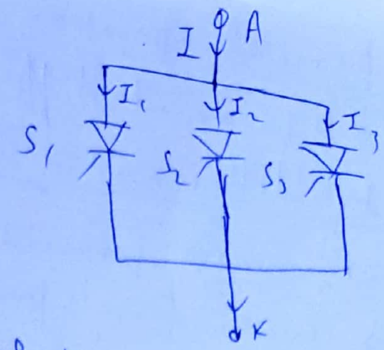
$\omega_s = 2\pi f_s \rightarrow$ rad/sec. & I_{FRM} = max. repetitive forward current.

Other factors affecting distribution of currents in a parallel string are:

~~ii) Difference in the manufacturing process of~~

ii) Difference in the manner of mounting: If the three SCRs are mounted as shown, the flux linkage of middle SCR is higher, resulting in higher current sharing by external SCRs, and, hence, unequal current sharing.



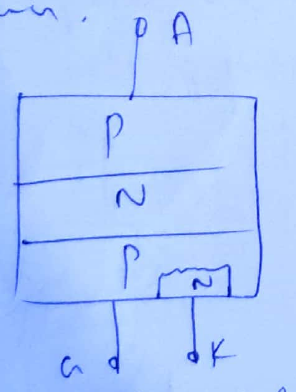


The solution to this problem is to have symmetrical arrangement of SCRs as shown. The SCRs are mounted on same heat sink.

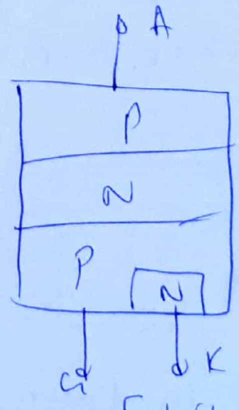
iii) Difference in the manufacturing process of SCRs:— Based on the manufacturing process, two types of SCRs are available.

a) Epit-axial type SCR b) Alloy-diffused type SCR

In ~~epit-axial~~ alloy-diffused type SCR, the gate-to-cathode Jxn. is formed by alloying at high temperature. The Jxn, thus, formed is not well-defined as shown. On the other hand, in epit-axial type SCR, PNP sandwich is formed as before and p-n Jxn. is formed by photo-litho-graphic process and find p-n Jxn. is well-defined, as shown.

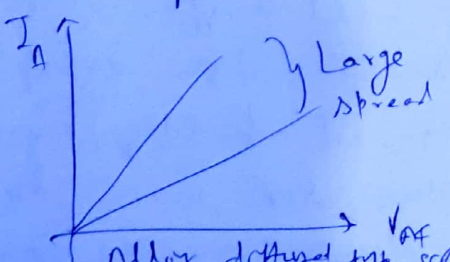


Alloy-diffused SCR

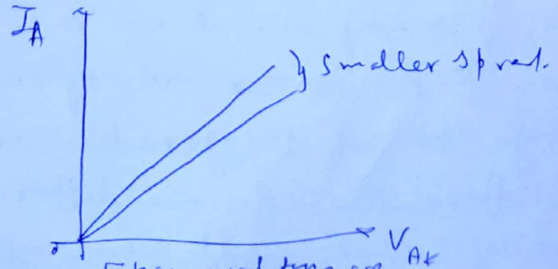


Epit-axial SCR

The spread in V-I static characts. is more in alloy-diffused type SCR, as shown, than epit-axial type SCR.



Alloy-diffused type SCR

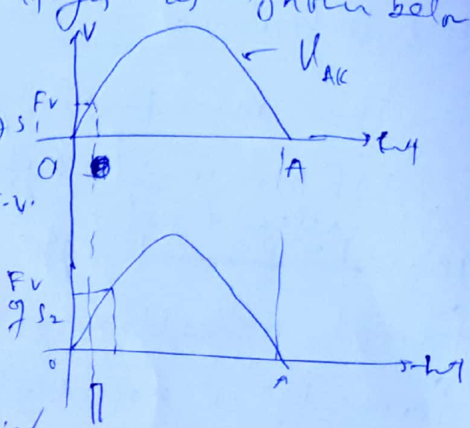


Epit-axial type SCR

Solution:
Thus, for parallel operation of SCRs, it is recommended to use epit-axial type SCRs.

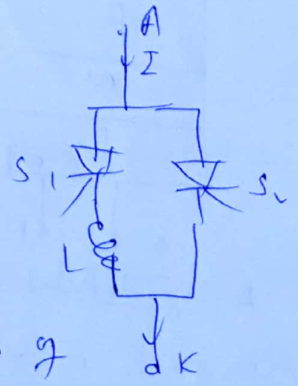
iv) Due to difference in finger voltages:- Finger voltage is the minimum forward-bias across an SCR at which the SCR fires with firing pulse. Any voltage below this voltage will not cause conduction of SCR, no matter how strong the firing pulse may be.

Now, in the parallel string of SCRs, different SCRs may have different finger voltages as shown below. This leads to a Sorrious Situation, especially at lower firing angles. The SCR with smaller F.V. will fire and the other SCRs with higher F.V. will never see a voltage high-enough to trigger.



Solution: The solution lies in choosing SCRs having FV as close as practically possible.

Other solution is to connect an inductance in series with SCR having lower FV to delay it's firing till other SCRs in the string also fire.



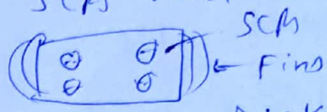
v) Difference in Latching & Holding currents:- If the latching currents of different SCRs are different, the SCR with lower latching current in the string will trigger first, with other SCRs in the string never seeing a high enough voltage to get triggered. Similarly, if holding currents of different SCRs are different, the SCR with higher holding current will turn-off first during turn-off process

The SCRs with lower holding currents will have carry bulk of load current, causing damage to them.

Solution: choose SCRs with same I_L & I_H for parallel operation.

vi) Difference in Thermal resistances of SCRs :-

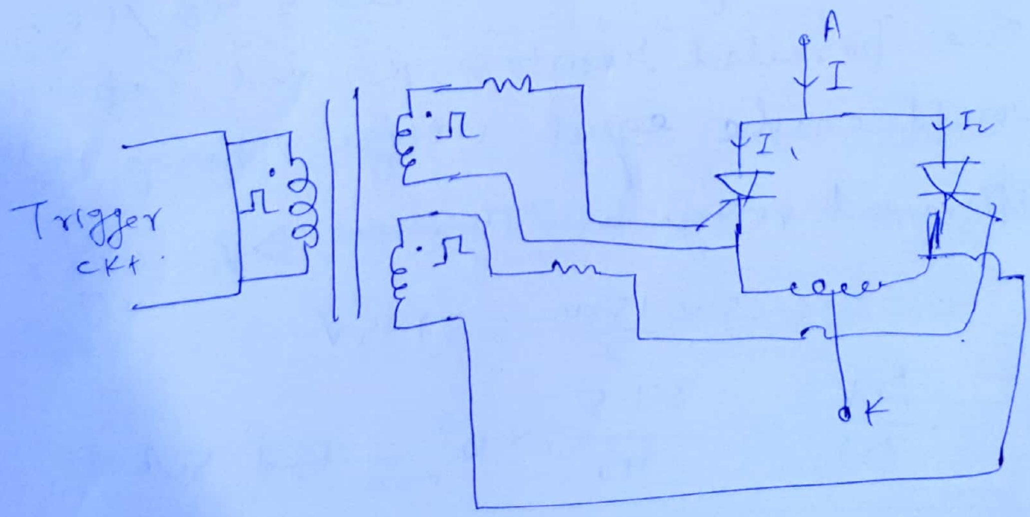
If SCRs are mounted on different heat sinks, due to different amount of pressure applied on SCRs, The thermal resistances between device body and heat sinks may vary, leading to different temp. rises of SCRs and non-uniform distribution of current.



Solution: Mount all SCRs on common heat sink.

vii) Difference in application of firing pulses at different times: The SCRs getting firing pulses earlier will trigger, sharing bulk of current and getting instantly damaged.

Solution: Independent firing scheme:



Derating:- Even with all above measures, it is preferable to derate the devices during series/parallel connection for their reliable operation. Another reason for derating is poor cooling and heat dissipation.

Normal recommended derating factors are :-

$$\% \text{ Series derating} = \left(1 - \frac{V}{n_s V_T}\right) \times 100$$

Where n_s = no. of series SCRs, V_T = unit voltage & V = Total string voltage.

$$\% \text{ Parallel derating} = \left(1 - \frac{I}{n_p \times I_T}\right) \times 100$$

Where n_p = no. of units in parallel,
I_T = unit current & I = Total string current.

Ex. No. 1 Two Thyristors (International Rectifier S30EF8A), 800V, 480A and 520A are connected in series to share 1500V. The Thyristor specifications are;
Max. reverse leakage current difference, $\Delta I_D = 40mA$,
Max. stored charge difference, $\Delta Q = 48 \mu C$.
Find the parallel resistance, R and capacitance, C that would enable equal voltage sharing within 5%.

Soln.:- Differential voltage on Thyristors, $\Delta V = 0.05 \times V/2$

$$= 0.05 \times \frac{1500}{2} = 37.5V$$

$$\therefore R = \frac{\Delta V}{\Delta I_D} = \frac{37.5}{40} \times 10^3 = 937.5\Omega$$

$$R \approx 1000\Omega \ (1K)$$

$$C = \frac{\Delta Q}{\Delta V} = \frac{48 \times 10^{-6}}{37.5}$$

$$C = 1.28 \mu F$$

---

calculate the values of R and C that will [d]ivide the static and dynamic voltage equally [betw]een series-connected SCRs in above example. [Th]e SCRs have the max. difference in their off-state [l]eakage current, $\Delta I_D = 1mA$ and max. diff. in their reverse-recovery charge, $\Delta Q = 30\mu C$.

Sol:-

$$C = \frac{(n_s-1)\Delta Q}{n_s V_T - V} = \frac{(18-1)\times 30}{18\times 500 - 7500} = \boxed{0.34\mu F}$$

$$R = \frac{n_s V_T - V}{(n_s-1)\times \Delta I_D} = \frac{18\times 500 - 7500}{17\times 1\times 10^{-3}} = \boxed{88.24K}$$

Ex. 3 A Thyristor string is formed by the series and parallel connections of Thyristors. The voltage and current ratings of the string are 6KV and 4KA, respectively. Available Thyristors have the voltage and current ratings of 1.2KV and 1KA, respectively. The string efficiency is 90% for both the series and parallel connections. calculate the no. of SCRs to be connected in series and parallel.

If max. blocking current is 15mA and $\Delta Q_{max} = 25\mu C$, calculate the values of R and C.

Sol:

$$n_s = \frac{6000}{0.9\times 1200} \Rightarrow \boxed{n_s = 5.56 \approx 6}$$

$$n_p = \frac{4000}{0.9\times 1000} = 4.45 \Rightarrow \boxed{n_p \approx 5}$$

$$R = \frac{n_s V_T - V}{(n_s-1)\times \Delta I_D} = \frac{6\times 1200 - 6000}{5\times 15\times 10^{-3}} \Rightarrow \boxed{R = 16K}$$

$$C = \frac{(n_s-1)\Delta Q}{n_s V_T - V} = \frac{5\times 25\times 10^{-6}}{6\times 1200 - 6000} \Rightarrow \boxed{C = 0.104}$$

Ex. 4 The voltage and current ratings in a particular circuit are 3KV and 750A. SCRs with a rating of 800V and 175A (GEC designation C350) are available. The recommended min. derating factor is 15%.
Calculate the no. of series and parallel units required. Also obtain the required values of R & C to be used in the static & dynamic equalizing ckts if max. forward leakage current of SCR is 10mA and $\Delta Q = 20 \mu C$.

Sol:-

$$\% \text{ Parallel derating} = \left(1 - \frac{I}{n_p \times I_T}\right) \times 100$$

$$0.15 = 1 - \frac{750}{n_p \times 175} \Rightarrow n_p = 5.05$$

$$\Rightarrow \boxed{n_p \cong 5}$$

$$\% \text{ Series derating} = \left(1 - \frac{V}{n_s \times V_T}\right) \times 100$$

$$0.15 = \left(1 - \frac{3000}{n_s \times 800}\right) \Rightarrow n_s = 4.3 \approx 5$$

$$\therefore \boxed{n_s = 5}$$

Now,

$$R = \frac{n_s V_T - V}{(n_s - 1) \times I_D} = \frac{5 \times 800 - 3000}{(5-1) \times 10} \times 10^{3} = 25 K\Omega$$

$$C = \frac{(n_s - 1) \Delta Q}{n_s V_T - V} = \frac{4 \times 20 \times 10^{-6}}{5 \times 800 - 3000} = 0.08 \mu F$$

$$\therefore \boxed{\begin{aligned} R &= 25 K\Omega \\ C &= 0.08 \mu F \end{aligned}}$$