CHAPTER #4#

THYRISTORS

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Introduction

- The thyristor is one of the most important power semiconductor devices.
- They are operated as bistable switches, operating from non-conducting to conducting state.

Thyristor Characteristics

- A thyristor is a four layer pnpn semiconductor device consisting of three pn junctions.
- It has three terminals: an anode, a junction, cathode, and a gate.
- Fig below shows the thyristor symbol and a sectional view of the three pn junctions.
- When the anode voltage is made positive, $J_1$ and $J_3$ are forward biased and $J_2$ is reverse biased.
- The thyristor is said to be in the *off-state condition*. A small leakage current flows from anode to cathode and is called the *off-state current*.
- If the anode voltage $V_{AK}$ is increased to a sufficiently large value, the reverse biased junction $J_2$ would breakdown. This is known as *avalanche breakdown* and the corresponding voltage is called the *forward breakdown voltage* $V_{BO}$.
- Since the other two junctions $J_1$ and $J_3$ are already forward biased, there will be free movement of carriers across all three junctions. This results in a large forward current. The device is now (*on-state*). The voltage drop in the on-state is due to the (ohmic drop) in the four layers and is very small (in the region of 1 V).
**Latching Current** $I_L$: This is the minimum anode current required to maintain the thyristor in the on-state immediately after a thyristor has been turned on and the gate signal has been removed.

**Holding Current** $I_H$: This is the minimum anode current required to maintain the thyristor in the on-state.

To turn off a thyristor,

**Reverse Current** $I_R$: When the cathode voltage is positive with respect to the anode, the junction $J_2$ is forward biased but junctions $J_1$ and $J_3$ are reverse biased.

**Forward Breakover Voltage** $V_{BO}$: If the forward voltage $V_{AK}$ is increased beyond $V_{BO}$, the thyristor can be turned on. But such a turn-on could be critical. In practice, the forward voltage is maintained below $V_{BO}$ and the thyristors is turned on by applying a positive gate signal between gate and cathode.
Two - Transistor Model of Thyristor

- A thyristor is two complementary transistors. One being pnp and the other npn. As shown in

\[ I_C = \alpha_1 I_E + I_{CBO} \]

**General equation**

\[ I_{C1} = \alpha_1 I_A + I_{CBO1} \]  

**For Q1**

- where \( \alpha_1 \) and \( I_{CBO1} \) are the current gain and leakage current respectively for transistor \( Q_1 \).

- Similarly, the collector current for transistor \( Q_2 \) is \( I_{C2} \) where

\[ I_{C2} = \alpha_2 I_k + I_{CBO2} \]

\[ I_A = I_{C1} + I_{C2} \]

\[ I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \]

- When a gate current \( I_G \) is applied to the thyristor

\[ I_k = I_A + I_G \]

\[ I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \]

- The current gain \( \alpha_1 \) varies with emitter current \( I_{E1} \) which is equal to \( I_A \);
- \( \alpha_2 \) varies with emitter current \( I_{E2} \) which is equal to \( I_k \).
The increase in values of both $\alpha_1$ and $\alpha_2$ would added increase the value of anode current $I_A$ which is a regenerative or positive feedback effect.

The capacitance of the pn junctions are shown in figure below.

- If a thyristor is in the blocking state
- and a rapidly rising voltage is applied to the device, then
- high currents would flow through the junction capacitors.

The current through capacitor $C_{j2}$ can be expressed as

$$i_{j2} = \frac{d(q_{j2})}{dt} = \frac{d(C_{j2}V_{j2})}{dt} = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt}$$

- If the rate of rise of voltage $dv/dt$ is large,
- then $i_{j2}$ would be large,
- increased leakage currents $I_{CBO1}$ and $I_{CBO2}$.
- High enough values of $I_{CBO1}$ and $I_{CBO2}$ may cause $\alpha_1$ and $\alpha_2$ to approach unity,
- resulting in undesirable turn on of the thyristor.
- It must be noted that a large current through the junction capacitors may cause damage to the device.
Thyristor Turn-on

- A thyristor is turned on by increasing the anode current. This can be accomplished in the following ways.

  **Thermals**
  - If the temperature of a thyristor is high,
  - increase in the number of electron-hole pairs.
  - increase the leakage current.
  - This will cause the anode current to increase and as a result causes $a_1$ and $a_2$ to increase.
  - Due to the regenerative action, the sum $a_1 + a_2$ may tend to unity and the thyristor may be turned on.
  - This type of turn-on may cause thermal runaway and should be avoided.

  **Light**
  - If light is allowed to strike the junction of a thyristor the electron-hole pairs will increase and this may cause the thyristor to be turned on.

  **High Voltage**
  - If the voltage $V_{AK}$ is increased beyond the forward breakdown voltage $V_{BO}$, leakage currents will flow, causing regenerative turn-on.
  - This type of turn-on is critical and should be avoided.

  **$dv/dt$**
  - If the $VAK$ is high.
  - the charging current of the capacitive junctions ($icj$) may be high enough to turn on the thyristor.
  - That may cause damage to the thyristor and must be avoided.
  - Hence, thyristors must be protected against high $dv/dt$ and must be operated within the manufacturer's $dv/dt$ specifications.
Gate Current

**Turn-on Time** $t_{on}$
The turn-on time $t_{on}$ is defined as the time interval between 10% of steady-state gate current and 90% of steady-state thyristor on-state current.

**Delay Time** $t_d$
The delay time $t_d$ is defined as the time interval between 10% of gate current and 10% of thyristor on-state current.

**Rise Time** $t_r$
The rise time is defined as the time required for the anode current to rise from 10% of the on-state current to 90% of the on-state current.

**EXAMPL 4.1**

$$t_{on} = t_d + t_r$$
di/dt Protection

- A minimum time is required for the thyristor to spread the current conduction uniformly throughout the junctions.
- If this time is not allotted and the rate of rise of anode current is very high compared to the spreading velocity at turn-on, then this could lead to localised "hot-spot" heating and the device may fail as a result of excessive heating.
- When thyristor T1 is turned off, free-wheeling diode Dm conducts load current. If thyristor T1 is fired when diode Dm is still conducting, di/dt can be very high. In order to reduce the high di/dt a series inductor Ls is added to the circuit as shown. The forward di/dt is given as \( \frac{di}{dt} = \frac{V_S}{L_s} \).

dv/dt Protection

- A high dv/dt may cause damage to a thyristor.
- To protect a thyristor from high dv/dt, we can use the circuits shown in figure below.

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If the switch $S_1$ is closed at time $t = 0$, a step voltage will be applied across thyristor $T_1$ and $dv/dt$ may be high enough to turn on the thyristor. In fig (a) $dv/dt$ can be limited by connecting capacitor $C_s$ across the thyristor as shown in figure (b).

Since $v_C = \frac{1}{C} \int i(t) dt$ then $\frac{dv_C}{dt} = \frac{i(t)}{C}$

and the rate of rise of voltage is limited by the value of the capacitor used.

In order to limit the capacitor discharge current when the thyristor is turned on, a resistor $R_s$ is inserted in series with the capacitor as shown in figure (c). This resistor capacitor is known as a snubber circuit. For figure (c), when switch $S_1$ is closed at time $t = 0$, the voltage across the capacitor is given by

$$v_C = V_S \left[ 1 - e^{-t/R_s C_s} \right]$$

and this charging capacitor voltage is seen by the thyristor anode to cathode terminals as $V_{AK}$. This is depicted by the waveform of figure (d). The rate of rise of voltage across the thyristor can be represented by

$$\frac{dv}{dt} = \frac{0.632 V_S}{R_s C_s} \text{ where } 0.632V_S \text{ is one time constant.}$$

The value of the snubber time constant $R_s C_s$ can be found for a known $dv/dt$. And for a known discharge current $I_{TD}$, the value of resistor $R_s$ can be found using

$$R_s = \frac{V_S}{I_{TD}}$$

We can use one resistor for $dv/dt$ and another for limiting the discharge current of the snubber capacitor. As shown in figure (e). In this circuit, $R_1$ and $C_S$ are used for $dv/dt$ protection, while $R_1 + R_2$ is used for limiting the capacitor discharge current.

The load can also be placed in series with the snubber components as shown in figure (f).
EXAMPLE 4.2
The input voltage to the circuit shown below is $V_s = 200$ V with load resistance $R = 5$ ohms. The load and stray inductances are negligible and the thyristor is operated at a frequency of 2 kHz. If the required $dv/dt$ is 100 V/µs and the discharge current is to be limited to 100 A, determine
1. the values of $R_s$ and $C_s$
2. the snubber losses and
3. the power rating if the snubber resistor.

Thyristor Turn-Off
- A thyristor can be turned off by reducing the (IA) to a level below the (IH) and keeping the (IA) below this level for a sufficiently long time so that the excess carriers in the four layers are swept out or recombinated. Thyristors can either be line commutated or forced commutated

$$I_{RR} = t_a \frac{di}{dt}$$

- For this line commutated thyristor, $V$ reverse appears across the thyristor immediately after the IFWR goes through the zero value.
**Turn-off Time** $t_q$
It is defined as the time interval between the instant when the on-state current has decreased to zero and the instant when the thyristor is capable of withstanding forward voltage without turning on. It depends on the peak value of on-state current and the instantaneous on-state voltage.

**Reverse Recovery Charge** $Q_{RR}$
This is defined as the amount of charge which has to be recovered during the turn-off process. Its magnitude is determined by the area enclosed by the path of the reverse recovery current and depends on:
1. The rate of fall of on-state current and
2. The peak value of on-state current before turn-off

**Thyristor Types**
1. Phase Control Thyristors (SCRs)
2. Fast Switching Thyristors (SCRs)
3. Gate Turn-off Thyristors (GTOs)
4. Bidirectional Triode Thyristors (TRIACs)
5. Reverse Conducting Thyristors (RCTs)
6. Static Induction Thyristors (SITHs)
7. Light Activated Silicon Controlled Rectifiers (LASCRs)
8. FET Controlled Thyristors (FET-CTHs)
9. MOS Controlled Thyristors (MCTs)
Series Operation of Thyristors

Thyristors are connected in series to improve their overall voltage rating.

There are auxiliary components must be added to thyristors connected in series to ensure proper operation.

In the curve it is clearly seen that for the same off-state current the off-state voltages differ.

Voltage sharing networks are required for both reverse and off-state conditions.

Resistors placed in parallel with the thyristors are used to accomplish voltage sharing between thyristors placed in series.

The voltage sharing resistors for n thyristors in series are shown in figure below.

For equal voltage sharing, the off-state currents differ as shown in figure below.
the off-state current of thyristor T1 be represented by ID1. For \( ns \) thyristors in the string, and the other \((ns - 1)\) thyristors having the same off-state current, then
\[
ID_2 = ID_3 = Idn \quad \text{and} \quad ID_1 < ID_2
\]
\( IP_1 \) is the current through resistor \( R \) which is connected across thyristor T1, then the current through the other resistors are equal and given by
\[
I_2 = I_3 = In
\]
The off-state current spread is given by \( \Delta ID \) where
\[
\Delta ID = ID_1 - ID_2
\]
\[
\Delta ID = (IT - I_2) - (IT - I_1)
\]
\[
\Delta ID = I_1 - I_2
\]
Therefore or
\[
I_2 = I_1 - \Delta ID
\]
The voltage drop across thyristor T1 is given by
\[
VD_1 \quad \text{where,} \quad VD_1 = RI_1
\]
Using Kirchhoff's voltage law where supply voltage is given by \( V_s \) yields
\[
V_s = VD_1 + (ns - 1)I_2R = VD_1 + (ns - 1)(I_1 - \Delta ID)R
\]
\[
V_s = VD_1 + (ns - 1)I_1R - (ns - 1) \Delta IDR
\]
\[
V_s = nsVD_1 - (ns - 1) \Delta IDR
\]
\[
V_{D1} = \frac{V_s + (n_s - 1)R \Delta ID}{n_s}
\]

\( V_{D1} \) will be a maximum when the \( \Delta ID \) is maximum, \( ID_1 = 0 \) and
\[
\Delta ID = ID_2
\]
The voltage across thyristor T1 is now given as \( V_{D_S}(\text{max}) \), where
\[
V_{DS(\text{max})} = \frac{V_s + (n_s - 1)R ID_2}{n_s}
\]
The differences in forward leakage currents causes differences in stored charge which in turn causes differences in reverse voltage sharing.

The thyristor with the lowest reverse recovery time will see the highest transient voltage.

The same components R1 and C1 are used for both transient voltage sharing and dv/dt protection.

The voltage difference between thyristors T1 and the other thyristors is given by

\[ \Delta V = R \Delta I_D = \frac{Q_2 - Q_1}{C_1} = \frac{\Delta Q}{C_1} \]

where \( Q_1 \) is the charge stored by thyristor T1 and \( Q_2 \) is the charge stored by the other thyristors such that \( Q_2 = Q_3 = Q_n \) and \( Q_1 < Q_2 \)

The transient voltage across thyristor T1 is given by

\[ V_{D1} = \frac{1}{n_s} \left[ V_s + \frac{(n_s-1)\Delta Q}{C_1} \right] \]

The worse case transient voltage occurs when \( Q_1 = 0 \), hence \( DQ = Q_2 \) and is given by

\[ V_{DT(max)} = \frac{1}{n_s} \left[ V_s + \frac{(n_s-1)\Delta Q}{C_1} \right] \]

The transient voltage derating factor which is normally used to increase the reliability of the string is given by

\[ DRF = 1 - \frac{V_s}{n_s V_{DS(max)}} \]
Parallel Operation of Thyristors

When thyristors are connected in parallel the load current is not shared equally between the thyristors,

- The thyristor carrying the higher current would dissipate more power which in turn will increase the junction temperature and hence decrease the internal resistance.
- This in turn will increase its current sharing capacity and maybe damage the thyristor.
- Equal current sharing could be accomplished with the use of a small resistor or inductor in series with each thyristor as shown in figure below.

When a resistor is used to produce equal current sharing, the losses in the series resistor is very high and may be unacceptable.
- When magnetically coupled inductors are used for the purpose of current sharing,
- if thyristor $T_1$ current increases, a voltage of opposite polarity to that of the coil in series with $T_1$ will be induced in the coil in series with thyristor $T_2$.
- The polarity of this voltage is as such to increase the anode potential of thyristor $T_2$, so increasing the current flow through this thyristor.
**Thyristor Firing Circuits**

- In thyristor converters, high ac voltages exist between anode and cathode of the thyristor, while low voltage level pulses are placed between gate and cathode.
- Isolation is necessary between the gate-cathode circuit and the anode-cathode circuit. This isolation is accomplished with the use of:
  1. Optocouplers and
  2. Pulse transformers.
- In the case of optocoupler isolation, the low voltage gate drive circuit is optically isolated from the high voltage anode-cathode circuit as shown in figure below.

- In the circuit, the gate drive circuit is connected to the light emitting diode $D_1$ via a current limiting resistor $R_1$.
- Pulses sent to the light emitting diode $D_1$ turn on the photo SCR $T_1$ which in turn triggers the power thyristor $T_L$.
- Hence the gate drive circuit is optically isolated from the output circuit.
2-Pulse transformers.
Gate protection circuits

(a) 

(b) 

(c) 

(d)
REFERENCES

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