CHAPTER 5

Thyristor Commutation Techniques

5.1 Introduction

- The turn-off of a thyristor means bringing the device from forward conduction state to forward blocking state.
- The thyristor turn-off requires that
  (*i*) its anode current falls below the holding current and
  (*ii*) a reverse voltage is applied to thyristor for a sufficient time to enable it to recover to blocking state.
- Commutation is defined as the process of turning off a thyristor. Once thyristor starts conducting, gate losses control over the device, therefore, external means may have to be adopted to commutate the thyristor.
- Several commutation techniques have been developed with the sole objective of reducing their turn-off (or commutation) time.

Class-A commutation: Load commutation
Class-B commutation: Resonant-pulse commutation
Class-C commutation: Complementary commutation
Class-D commutation: Impulse commutation
Class-E commutation: External pulse commutation
Class-F commutation: Line commutation

Class-A Commutation: Load Commutation

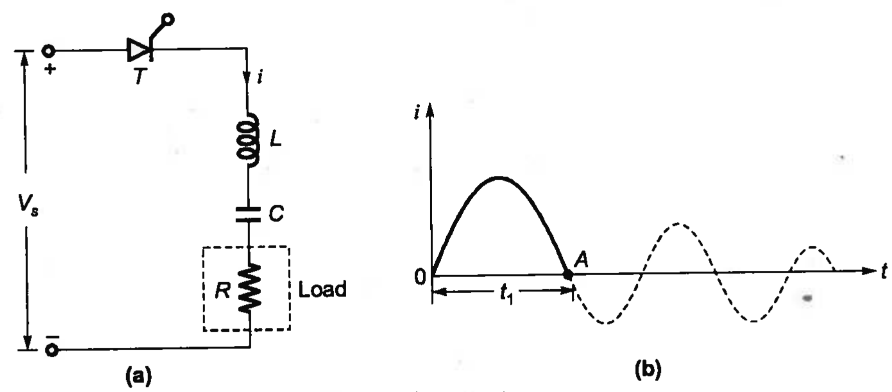


***Figure*-5.1**

For achieving load commutation of a thyristor, the commutating components L and C are connected as shown above. Here R is the load resistance. For low values of R, L and C are connected in series with R, and for high values of R, load R is connected across C.

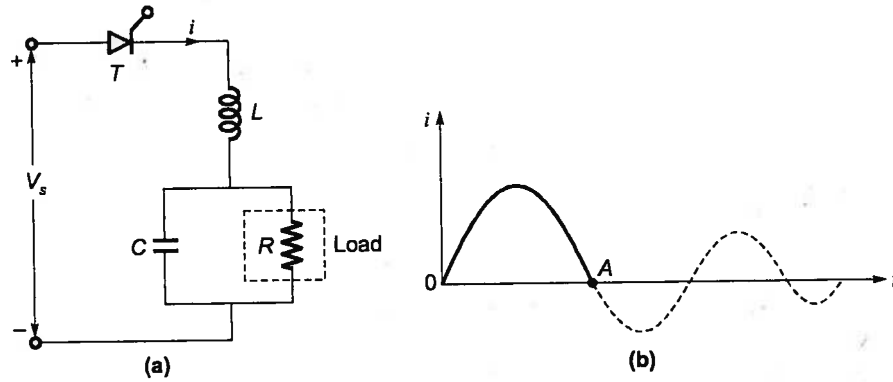


Figure-5.2

- The essential requirement for both the circuits is that the overall circuit must be underdamped.
- It is seen that current 'i' first rises to maximum value and then begins to fall. When current decays to zero and tends to reverse, thyristor T turns-off on its own at instant A.
- Class-A or load commutation is also called resonant commutation or self commutation.
- The conduction time of the thyristor is = $\pi\sqrt{LC}$.

  i.e. at $\omega t = \pi$ current becomes zero.

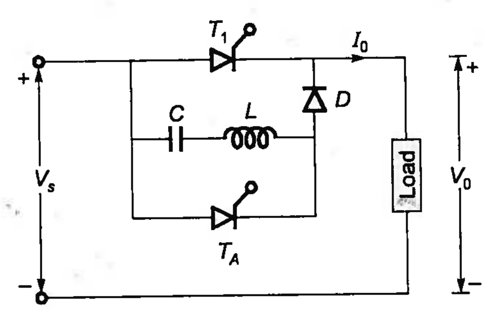
$$\omega_0 t_0 = \pi$$

$$t_0 = \frac{\pi}{\omega_0}$$

$$\boxed{t_0 = \pi\sqrt{LC}}$$

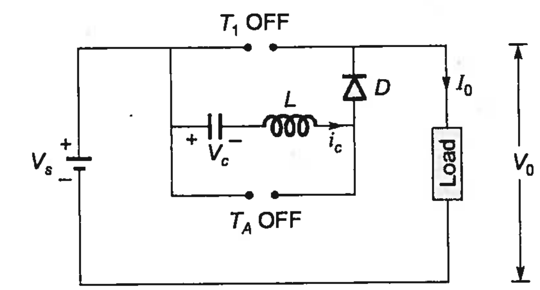
Here, $\omega_0 = \frac{1}{\sqrt{LC}}$ is called the resonant frequency.

Class-B Commutation: Resonant Pulse Commutation



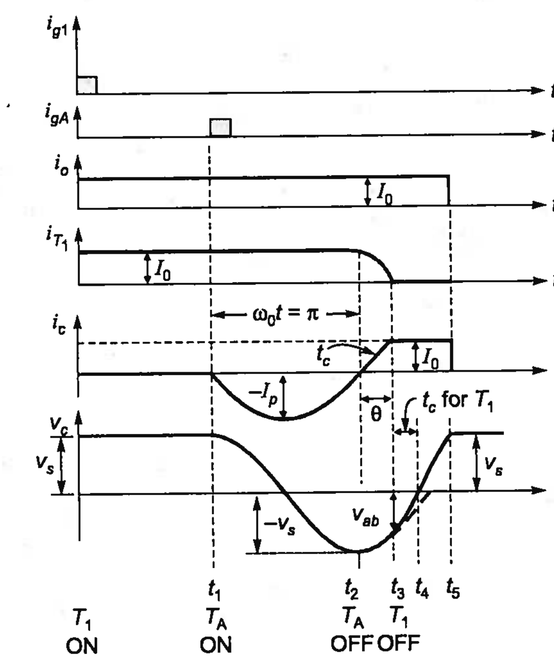
(a)

The source voltage V_s charges capacitor C to V_s with left hand plate positive. Main thyristor T_1 and auxiliary thyristor T_A are off.



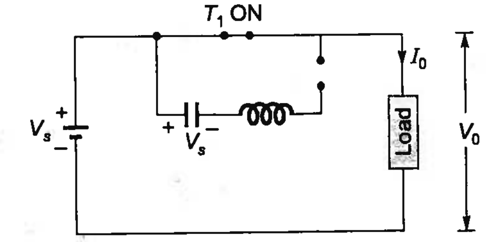
(b)

Output Waveforms



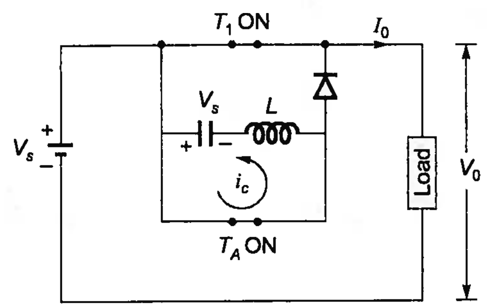
(c)

When T_1 is turned on at $t = 0$, a constant current I_0 is established in the load circuit.



(d)

Here in this circuit $V_c = V_s$ and $i_c = 0$.
For initiating the commutation of main thyristor T_1, auxiliary thyristor T_A is gated at $t = t_1$.
With T_A on, a resonant current i_c begins to flow from C through T_A, L and back to C.



(e)

This resonant current, with time measured from instant t_1, is given by

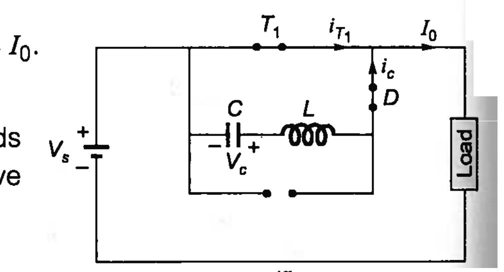
$$i_c = -V_s\sqrt{\frac{C}{L}}\sin\omega_0 t = -I_P\sin\omega_0 t$$

Minus sign before $I_P \sin\omega_0 t$ is due to the fact that this current flows opposite to the reference positive direction chosen for i_c.

Capacitor voltage, $$V_c(t) = \frac{1}{C}\int i_c\,dt = \frac{1}{\omega_0 C}\int\left(-V_s\sqrt{\frac{C}{L}}\right)\sin\omega_0 t\,d(\omega_0 t)$$

$$V_c(t) = V_s\cos\omega_0 t$$

After half a cycle of i_c from instant t_1; $i_c = 0$, $V_c = -V_s$ and $i_{T_1} = I_0$.



(f)

After π radians from instant t_1, i.e. just after instant t_2, as i_c tends to reverse, T_A is turned off at t_2. With $V_c = -V_s$ right hand plate has positive polarity. Resonant current i_c now builds up through C, L, D and T_1.

$$i_{T_1} + i_c = I_0$$

$$i_{T_1} = I_0 - i_c$$

Finally, when i_c in the reversed direction attains the value of I_0, forward current in $T_1 (i_{T_1} = I_0 - I_0 = 0)$ is reduced to zero and the device T_1 is turned-off at t_3.

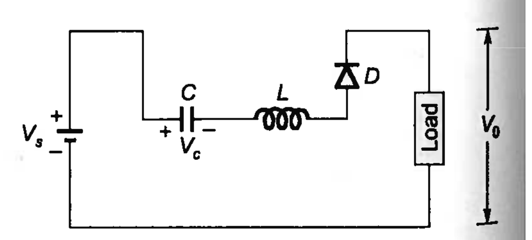
For reliable commutation, peak resonant current I_P must be greater than load current I_0.

As thyristor is commutated by the gradual build up of resonant current in the reversed direction, this method of commutation is called current commutation, class *B* commutation or resonant pulse commutation.

After T_1 is turned-off at t_3, constant current I_0 flows from V_s to load through C, L and D. Capacitor begins charging linearly from $-V_{ab}$ to zero at t_4 and then to V_s at t_5.

As a result, at instant t_5, when $V_c = V_s$, load current $i_0 = i_c = I_0$ reduces to zero as shown.

It is seen from the waveform of i_c that main thyristor T_1 is turned-off when.



(g)

Figure-5.3 : (a), (b), (c), (d), (e), (f) and (g)

$$V_s\sqrt{\frac{C}{L}}\sin\omega_0(t_3 - t_2) = I_0$$

$$\omega_0(t_3 - t_2) = \sin^{-1}\left(\frac{I_0}{I_P}\right)$$

where, $$I_P = V_s\sqrt{\frac{C}{L}} = \text{peak resonant current}$$

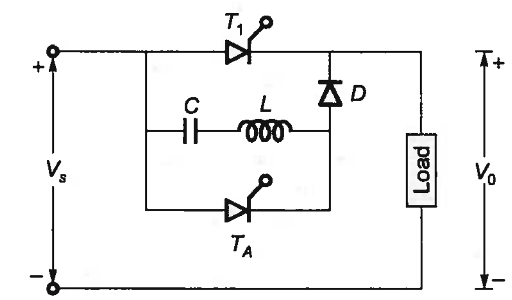
$\therefore$ Circuit turn-off time for main thyristor, $$t_c = t_4 - t_3 = C\frac{V_{ab}}{I_0}$$

Main thyristor T_1 is commutated at t_3. As constant load current I_0 charges C linearly from $-V_{ab}$ at t_3 to zero at t_4, SCR T_1 is reverse biased by voltage V_c for a period $(t_4 - t_3) = t_c$.

The above equation shows that t_c is dependent on the load current. Waveform of capacitor voltage V_c reveals that the magnitude of reverse voltage V_{ab} across main thyristor T_1, when it gets commutated, is given by

$$V_{ab} = V_s\cos\omega_0(t_3 - t_2)$$

Example - 5.1 **The circuit shown below employing resonant pulse commutation (or class *B* commutation) has $C = 20\ \mu F$ and $L = 5\ \mu H$. Initial voltage across capacitor is $V_s = 230$ V. For a constant load current of 300 A. Calculate:**



(*i*) Conduction time for the auxiliary thyristor,
(*ii*) Voltage across the main thyristor when it gets commuted and
(*iii*) The circuit turn-off time for the main thyristor.

Solution:

Peak value of resonant current, $$I_p = V_s\sqrt{\frac{C}{L}} = 230\sqrt{\frac{20}{5}} = 460\ \text{A}$$

Resonant frequency, $$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{10^6}{\sqrt{100}} = 0.1\times10^6\ \text{rad/s}$$

(*i*) Conduction time for auxiliary thyristor $= \frac{\pi}{\omega_0} = \frac{\pi}{0.1\times10^6} = 31.416\ \mu s$

(*ii*) $$\phi = \sin^{-1}\left(\frac{I_0}{I_p}\right) = \sin^{-1}\left(\frac{300}{460}\right) = 40.706° \text{ or } 0.71045\ \text{rad}$$

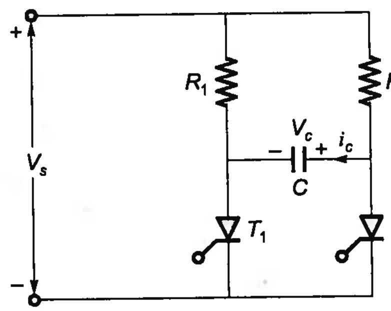
Voltage across main thyristor, when it gets turned-off, is

$\therefore$ $$V_{ab} = V_s\cos\phi = 230\cos(40.706°) = 174.355\ \text{V}$$

(*iii*) Circuit turn-off time for main thyristor,

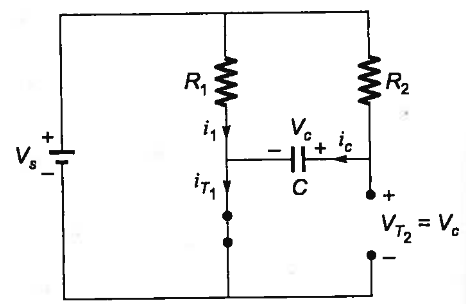
$$t_c = C\frac{V_{ab}}{I_0} = 20\times10^{-6}\,\frac{174.355}{300} = 11.624\ \mu s \text{ or } 11.6236\ \mu s$$

Class-C Commutation: Complementary Commutation



(a)

In this circuit, firing of SCR T_1 commutates T_2 and subsequently, firing of SCR T_2 would turn-off T_1. Capacitor is supposed to be initially uncharged.



(b)

When T_1 is turned-on at $t = 0$, current through R_1 is $i_1 = \frac{V_s}{R_1}$ and through R_2 is $i_c = \frac{V_s}{R_2}$.

So thyristor T_1 current is,

$$i_{T_1} = i_1 + i_c = V_s\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \text{ begins to flow}$$

Capacitor begins to charge through R_2 from $V_c = 0$.

The charging current through the circuit V_s, R_2 and C is given by $\boxed{i_c(t) = \frac{V_s}{R_2} \cdot e^{-t/R_2C}}$

and voltage across capacitor C is given by $\boxed{V_c(t) = V_s(1 - e^{-t/R_2C})}$

Voltage across thyristor T_2 is $V_{T_2} = V_c(t)$. After sometime, when transients are over, $V_c = V_{T_2} = V_s$ and i_c decays to zero.

$$i_{T_1} = \frac{V_s}{R_1}$$

When T_1 is to be turned-off, T_2 is triggered. If T_2 is turned on at t_1, then capacitor voltage V_c applies a reverse potential V_s across SCR T_1 and turns it off.

At the instant t_1,

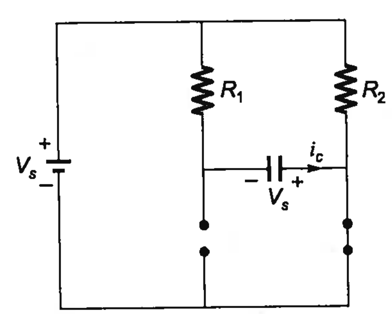
$$V_{T_2} = 0$$

$$V_{T_1} = -V_s$$

$$i_c = -\frac{2V_s}{R_1}$$

and

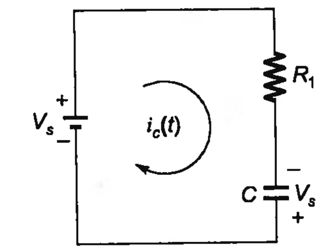
$$i_{T_2} = V_s\left(\frac{2}{R_1} + \frac{1}{R_2}\right)$$



(c)

In the circuit consisting of V_s, R_1, C and T_2, the capacitor voltage changes from V_s to $-V_s$.

$$\boxed{i_c(t) = \frac{2V_s}{R_1} \cdot e^{-t/R_1C}}$$



(d)

as this current $i_c(t)$ flows opposite to the positive direction indicated

$$i_c(t) = -\frac{2V_s}{R_1} \cdot e^{-t/R_1C}$$

Voltage across capacitor is, $V_c(t) = \left[\frac{1}{C}\int_0^t i_c\, dt + V_s\right] = \left[\frac{1}{C}\int_0^t\left(-\frac{2V_s}{R_1} \cdot e^{-t/R_1C}\right)dt + V_s\right]$

$$\boxed{V_c(t) = V_s\left[2e^{-t/R_1C} - 1\right]}$$

Voltage across SCR T_1 is, $V_{T_1} = -V_c = V_s\left[1 - 2e^{-t/R_1C}\right]$

Current i_{T_2} falls from its value $V_s\left(\frac{2}{R_1} + \frac{1}{R_2}\right)$ to $\frac{V_s}{R_2}$ with time constant R_1C. When transients are over after t_1,

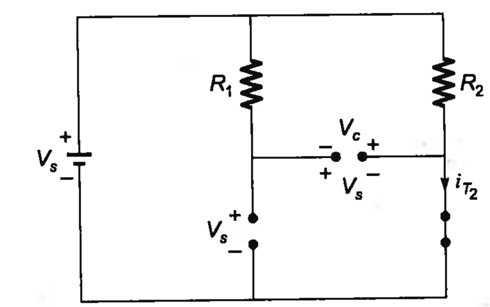
$$V_{T_1} = V_s$$

$$V_c = -V_s$$

$$i_c = 0$$

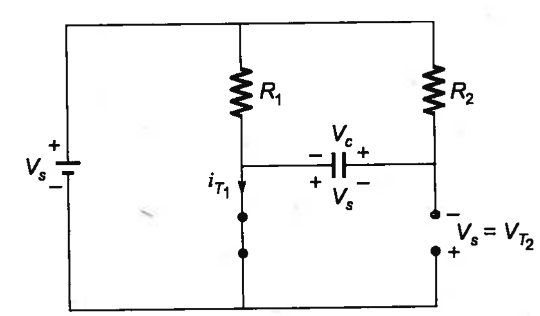
$$V_{T_2} = 0$$

$$i_{T_2} = \frac{V_s}{R_2} \text{ and } i_{T_1} = 0$$



(e)

when T_1 is turned-on to cummutate T_2 at instant t_3, $i_{T_2} = 0$, $i_{T_1} = V_s\left(\frac{2}{R_2} + \frac{1}{R_1}\right)$, $V_{T_2} = -V_s$, $V_{T_1} = 0$ and $i_c = \frac{2V_s}{R_2}$.



(f)

Figure-5.4 : (a), (b), (c),(d), (e) and (f)

With the turn-on of T_2 at t_1, capacitor voltage V_s suddenly appears as reverse bias across T_1 to turn it off. Similarly, at t_3, capacitor voltage V_s applies a sudden reverse bias across T_2 to turn it off.

Class 'C' commutation is called as voltage commutation or complementary impulse commutation.

Waveform of V_{T_1} indicates that a reverse voltage $-V_s$ to zero appears across thyristor T_1 for a certain period. This period is called circuit turn-off time t_{c_1}. For T_1 is

$$V_{T_1} = 0 = V_s\left[1 - 2e^{-t_{c_1}/R_1C}\right]$$

$$\boxed{t_{c_1} = R_1 C\, ln(2)}$$

Similarly, circuit turn-off time for T_2 is $\boxed{t_{c_2} = R_2 C\, ln(2)}$

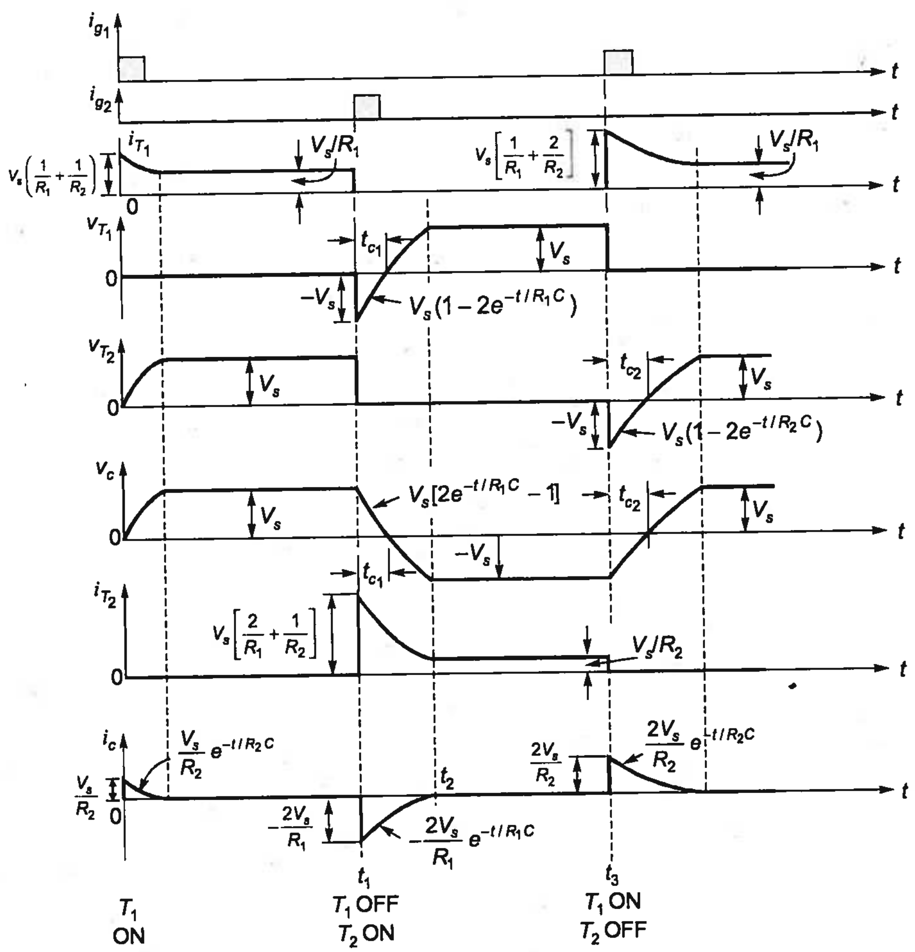
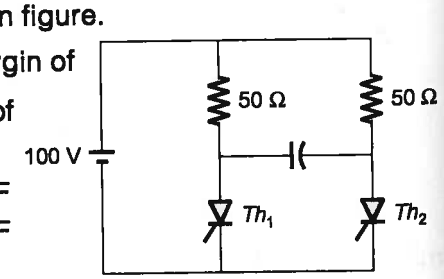


Figure-5.5

Example - 5.2 A voltage commutation circuit is shown in figure. If the turn off time of the SCRs is 50 m sec and a safety margin of 2 is considered, what will be the approximate minimum value of capacitor required for proper commutation?

(a) 2.88 μF
(b) 1.44 μF
(c) 0.91 μF
(d) 0.72 μF



Solution: (a)

In this type of commutation, a thyristor carrying load current is commutated by transferring its load current to another incoming thyristor.

Firing of SCR Th_1 commutates Th_2 and subsequently, firing of SCR Th_2 would turn-off Th_1.

Circuit turn-off time t_{c1} for Th_1

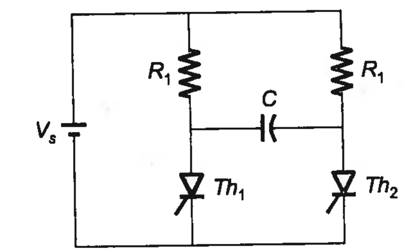
$$t_{c1} = R_1 C\, ln\, 2$$

and circuit turn-off time tc_2 for Th_2

$$t_{c2} = R_2 C\, ln\, 2$$

as

$$R_1 = R_2 = 50\ \Omega$$
$$t_{c2} = t_{c1} = R_1 C\, ln\, 2$$

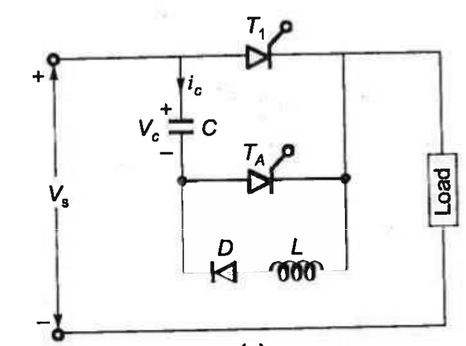


Safety margin = 2

So, $R_1 C\, ln\, 2 = 2t_{c1}$

$$C = \frac{2 \times 50 \times 10^{-6}}{50 \times ln 2} = 2.88 \mu F$$

Class-D Commutation: Impulse Commutation



(a)

T_1 and T_A are called main and auxiliary thyristor respectively.

Initially, main thyristor T_1 and auxiliary thyristor T_A are off and capacitor is assumed charged to voltage V_s with upper plate positive.

When T_1 is turned-on at $t = 0$. Source voltage V_s is applied across load and load current I_0 begins to flow which is assumed to remain constant.

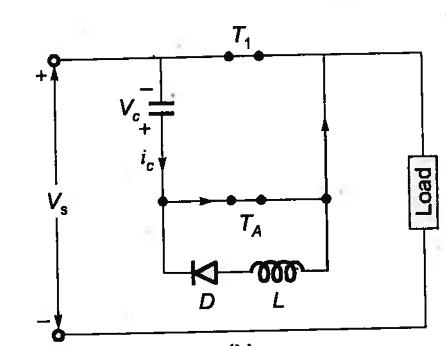
With T_1 on at $t = 0$, another oscillatory circuit consisting of C, T_1, L and D is formed where the capacitor current is given by

$$\boxed{i_c = V_s\sqrt{\frac{C}{L}}\sin\omega_0 t = I_p \sin\omega_0 t}$$

When $\omega_0 t = \pi$; $i_c = 0$. Between $0 < t < \left(\frac{\pi}{\omega_0}\right)$, $i_{T_1} = I_0 + I_p \sin\omega_0 t$.

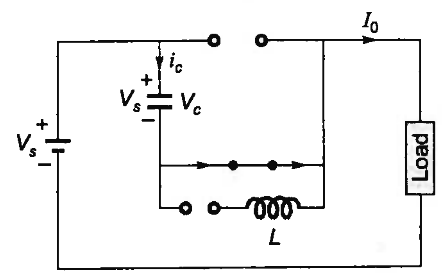
Capacitor voltage changes from $+V_s$ to $-V_s$ co-sinusoidally and the lower plate becomes positive. At $\omega_0 t = \pi$, $i_c = 0$, $i_{T_1} = I_0$ and $V_c = -V_s$.

At t_1, auxiliary thyristor T_A is turned-on.



(b)

Immediately after T_A is on. Capacitor voltage V_s applies a reverse voltage across main thyristor T_1 so that $V_{T_1} = -V_s$ at t_1 and SCR T_1 is turned-off and $i_{T_1} = 0$.



(c)

***Figure-5.6 :** (a), (b) and (c)*

The load current is now carried by C and T_A. Capacitor gets charged from $-V_s$ to $+V_s$ as shown.

When $V_c = V_s$, $i_c = 0$ at t_2, thyristor T_A is turned-off.

With the firing of thyristor T_A, a reverse voltage V_s is suddenly applied across T_1. This method of commutation is therefore called as voltage commutation.

As an auxiliary thyristor T_A is used for turning off the main thyristor T_1, this type of commutation is also known as auxiliary commutation.

When thyristor T_A is turned-on. Capacitor gets connected across T_1 to turn it off, this type of commutation is, also called parallel capacitor commutation.

Output Wave Forms

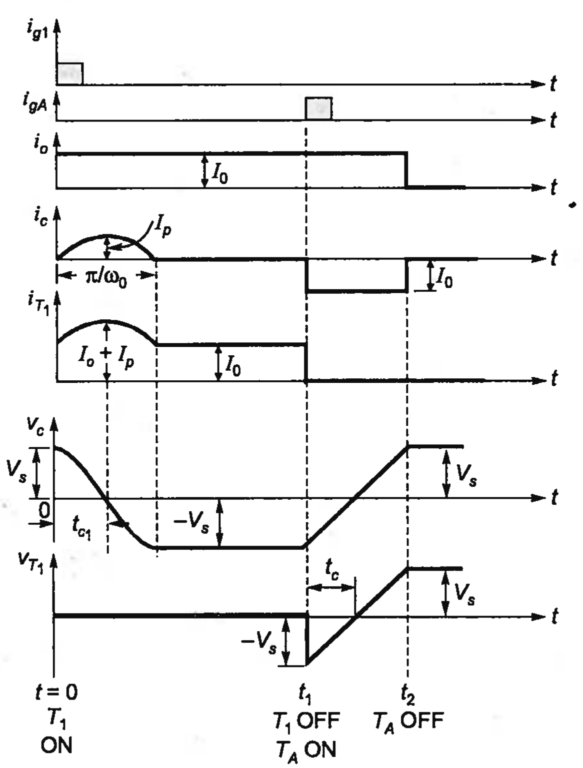
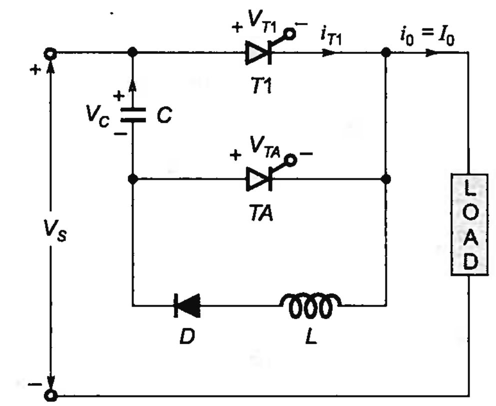


Figure-5.7

Example - 5.3 In the circuit shown below, V_s = 230 V, L = 20 μH and C = 40 μF. For a constant load current of 120 A. Calculate:



(*i*) **Peak value of current through capacitance and also through main and auxiliary thyristors.**

(*ii*) **Circuit turn-off times for main and auxiliary thyristors.**

Solution:

(*i*) When main thyristor T_1 is turned-on, an oscillatory current in the circuit C, T_1, L and D is set up and it is given by

$$i_c(t) = V_s \cdot \sqrt{\frac{C}{L}} \sin \omega_0 t$$

∴ Peak value of current through capacitor

$$I_p = V_s \cdot \sqrt{\frac{C}{L}} = 230\sqrt{\frac{40}{20}} = 325.269 \text{ A}$$

Peak value of current through main thyristor

$$T_1 = I_p + I_0 = 325.269 + 120 = 445.269 \text{ A}$$

Peak value of current through auxiliary thyristor $TA = I_0$ = 120 A

(*ii*)
$$I_0 = C\frac{V_s}{t_c}$$

∴ Circuit turn-off time for main thyristor

$$t_c = C\frac{V_s}{I_0} = 40 \times 10^{-6}\frac{230}{120} = 76.67 \ \mu\text{s}$$

An examination of figure reveals that when T_1 conducts and during the time upper plate of C is posiitve, $v_{TA} = -v_c$ i.e. auxiliary thyristors TA is reverse biased by v_c. This gives circuit turn-off time t_{c1} for $TA = \dfrac{\pi}{2\omega_0}$

Here,
$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{10^6}{\sqrt{20 \times 40}} = \frac{10^6}{\sqrt{800}}$$

Circuit turn-off time for auxiliary thyristor,

$$t_{c1} = \frac{\pi}{2\omega_0} = \frac{\pi\sqrt{800}}{2 \times 10^6} = 44.43 \ \mu\text{s} \ \text{ or } 44.428 \ \mu\text{s}$$

Class-E Commutation: External Pulse Commutation

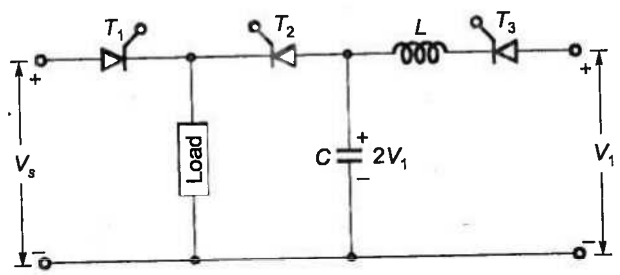


Figure-5.8

In this type of commutation, a pulse of current is obtained from a separate voltage source to turn-off the conducting SCR. The peak value of this current pulse must be more than the load current.

In the circuit shown above, V_s is the voltage of main source and V_1 is the voltage of the auxiliary supply.

Thyristor T_1 is conducting and load is connected to source voltage V_s. When thyristor T_3 is turned-on at $t = 0$, V_1, T_3, L and C form an oscillatory circuit. Therefore, C is charged to a voltage $+2V_1$ with upper plate positive at $t = \pi\sqrt{LC}$, oscillatory current falls to zero and thyristor T_3 gets commutated.

For turning off the main thyristor T_1, thyristor T_2 is turned-on. With T_2 on, T_1 is subjected to a reverse voltage equal to $V_s - 2V_1$ and T_1 is therefore turned-off. After T_1 is off, capacitor discharges through the load.

Class-F Commutation: Line Commutation

This type of commutation is known as natural commutation.

This can occur only when converter circuits are fed from ac source.

During positive half cycle of single phase ac voltage, SCR, when triggered will conduct current. The ac voltage after positive half cycle becomes zero at $\omega t = \pi$ and anode current also becomes zero at $\omega t = \pi$ for R load and at $\omega t > \pi$ for RL load. After anode current has reduced to zero, ac source applies a negative voltage across SCR for sometime to turn it off naturally.

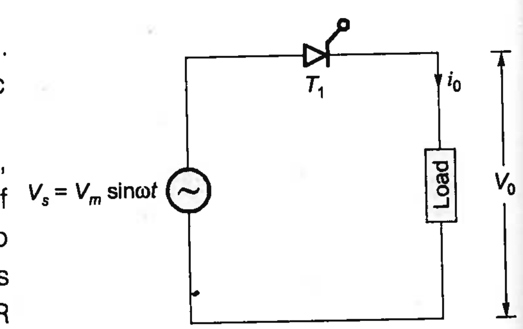


Figure-5.9

NOTE

The essential condition for natural commutation is that

- anode current must decay to zero and
- ac source must apply a negative voltage (or reverse bias) across SCR for bringing it to forward blocking capability.

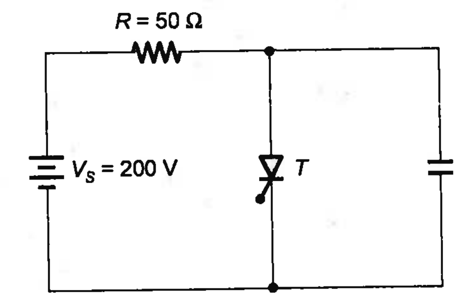
Example - 5.4 In a commutation circuit employed to turn-off an SCR, satisfactory turn-off is obtained when

(a) Circuit turn-off time < device turn-off time
(b) Circuit turn-off time > device turn-off time
(c) Circuit time constant > device turn-off time
(d) Circuit time constant < device turn-off time

Solution: (b)

The circuit should not turn-off before making off the thyristor.

Example - 5.5 In the circuit shown below, *SCR* is forced commulated by circuitry not shown in the figure. Compute the minimum value of C so that *SCR* does not get turned-on due to re-applied dv/dt. This SCR has minimum charging current current of 5 mA to turn it on and its junction capacitance is 25 pF.



Solution:

Under steady state, *SCR* conducts a current $= \dfrac{V_s}{R} = \dfrac{200}{50} = 4$ A and voltage across ideal *SCR* = voltage v_c across $C = 0$.

When *SCR* is force commutated, capacitor C begins charging from source V_s through R so that capacitor voltage $v_c (= v_T)$ is given by

$$v_c = V_s[1 - e^{-t/RC}]$$

$$\left[\frac{dv_c}{dt}\right] = V_s \cdot e^{-t/RC} \cdot \frac{1}{RC} \quad \text{or} \quad \left[\frac{dv_c}{dt}\right]_{t=0} = \frac{V_s}{RC}$$

The rate of rise of capacitor voltage v_c across *SCR* may be large. In case *SCR* charging current $C_j \cdot \left(\dfrac{dv_c}{dt}\right)_{t=0}$ happens to be equal to 5 mA, *SCR* will get turned-on. Here C_j is the junction capacitance of *SCR*.

$$\therefore \qquad C_j \cdot \left(\frac{dv_c}{dt}\right)_{t=0} = 5 \text{ mA}$$

Substuting the value of $\left(\dfrac{dv_c}{dt}\right)_{t=0}$,

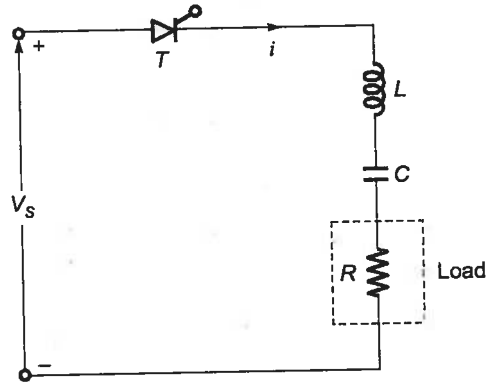
$$C_j \frac{V_s}{RC} = 5 \times 10^{-3} \quad \text{or} \quad 25 \times 10^{-12} \frac{200}{50 \times C} = 5 \times 10^{-3}$$

or,

$$C = \frac{25 \times 10^{-12} \times 200}{250 \times 10^{-3}} = 0.02\ \mu\text{F}$$

In order to obviate turning-on of *SCR*, the value of capacitance C should be less than 0.02 μF.

Example - 5.6 For the circuit shown in figure, commutating elements $L = 20$ μH and $C = 40$ μH are connected in series with load resistance $R = 1\ \Omega$. Check whether self-commutation, or load commutation, would occur or not. Find the conduction time of the thyristor.



Solution:

The ringing frequency ω_r in rad/sec, from equation is given by

$$\omega_r = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} = \text{damped frequency of oscillation, } \omega_d$$

The condition for underdamping is that $\omega_d > 0$

or, $$\frac{1}{LC} - \left(\frac{R}{2L}\right)^2 > 0 \quad \text{or} \quad R < \sqrt{\frac{4L}{C}}$$

Here, $$\frac{4L}{C} = \frac{4 \times 20 \times 10^{-6}}{40 \times 10^{-6}} = 2$$

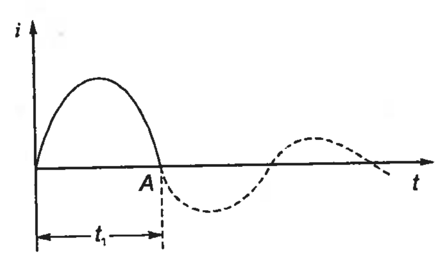
Therefore, $$\sqrt{\frac{4L}{C}} = \sqrt{2} = 1.414$$

and $$R = 1\ \Omega$$

As $$R < \sqrt{\frac{4L}{C}};$$

The circuit is underdamped.

Figure shows that thyristor stops conducting when $\omega_r t_1 = \pi$.



Here, $$\omega_r = \left[\frac{10^{12}}{20 \times 40} - \left(\frac{1 \times 10^6}{2 \times 20}\right)^2\right]^{1/2} = 25000 \text{ rad/sec}$$

∴ Conduction time of thyristor,

$$t_1 = \frac{\pi}{\omega_r} = \frac{\pi \times 10^6}{25000}\ \mu s = 125.664\ \mu s$$

Student's Assignments 1

Q.1 Which one of the following is correct?
In a switched capacitor network for VAR compensation the SCRs are commutated by
(a) forced commutation
(b) resonant commutation
(c) natural commutation
(d) delayed commutation

Q.2 An SCR is in conducting state, a reverse voltage is applied between anode and cathode, but is fails to turn off. What could be the reason.
(a) Positive voltage is applied to the gate
(b) The reverse voltage is small
(c) The anode current is more than the holding current
(d) Turn off time of SCR is large

Q.3 A thyristor can be switched from a non-conducting state to a conducting state by applying:
1. Voltage more than forward break over voltage.
2. A voltage with high dv/dt.
3. Positive gate current with positive anode voltage.
4. Negative gate current with positive anode voltage.

(a) 1, 2, 3 and 4 are correct
(b) 1, 2 and 4 are correct
(c) 1, 2 and 3 are correct
(d) 2, 3 and 4 are correct

Q.4 An SCR triggered by a current pulse applied to the gate-cathode can be turned off
(a) by applying a pulse to the cathode.
(b) by applying a pulse to the anode.
(c) by applying another pulse of opposite polarity to the gate-cathode.
(d) by reversing the polarity of the anode and cathode voltage.

Q.5 Consider the following statements regarding Thyristor:
1. It conducts when forward biased and positive current flows through the gate.
2. It conducts when forward biased and negative current flows through the gate.
3. It commutates when reverse biased and negative current flows through the gate.
4. It commutates when the gate current is withdrawn.

Which of these statement(s) is/are correct?
(a) 1, 2 and 3 (b) 1 and 2 only
(c) 2 and 3 only (d) 1 only

Answer Key:

1. (b) **2.** (c) **3.** (c) **4.** (d)
5. (d)