THYRISTOR COMMUTATION TECHNIQUES

Introduction

In practice it becomes necessary to turn off a conducting thyristor. (Often thyristors are used as switches to turn on and off power to the load). The process of turning off a conducting thyristor is called commutation. The principle involved is that either the anode should be made negative with respect to cathode (voltage commutation) or the anode current should be reduced below the holding current value (current commutation).

The reverse voltage must be maintained for a time at least equal to the turn-off time of SCR otherwise a reapplication of a positive voltage will cause the thyristor to conduct even without a gate signal. On similar lines the anode current should be held at a value less than the holding current at least for a time equal to turn-off time otherwise the SCR will start conducting if the current in the circuit increases beyond the holding current level even without a gate signal. Commutation circuits have been developed to hasten the turn-off process of Thyristors. The study of commutation techniques helps in understanding the transient phenomena under switching conditions.

The reverse voltage or the small anode current condition must be maintained for a time at least equal to the TURN OFF time of SCR; Otherwise the SCR may again start conducting. The techniques to turn off a SCR can be broadly classified as

- Natural Commutation
- Forced Commutation.

Natural Commutation (CLASS F)

This type of commutation takes place when supply voltage is AC, because a negative voltage will appear across the SCR in the negative half cycle of the supply voltage and the SCR turns off by itself. Hence no special circuits are required to turn off the SCR. That is the reason that this type of commutation is called Natural or Line Commutation. Figure 5.1 shows the circuit where natural commutation takes place and figure 1.2 shows the related waveforms. t_c is the time offered by the circuit within which the SCR should turn off completely. Thus t_c should be greater than t_q, the turn off time of the SCR. Otherwise, the SCR will become forward biased before it has turned off completely and will start conducting even without a gate signal.

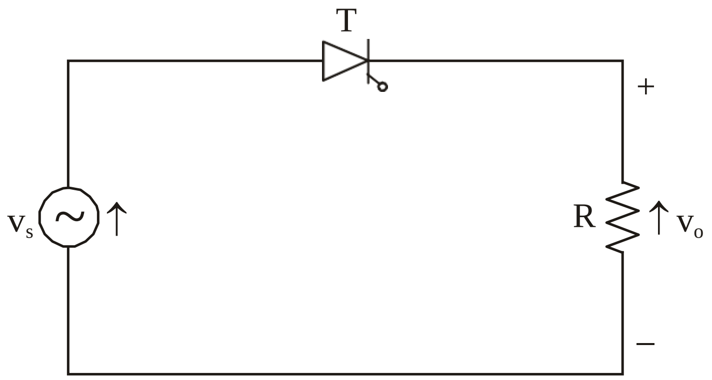


Fig. 5.1: Circuit for Natural Commutation

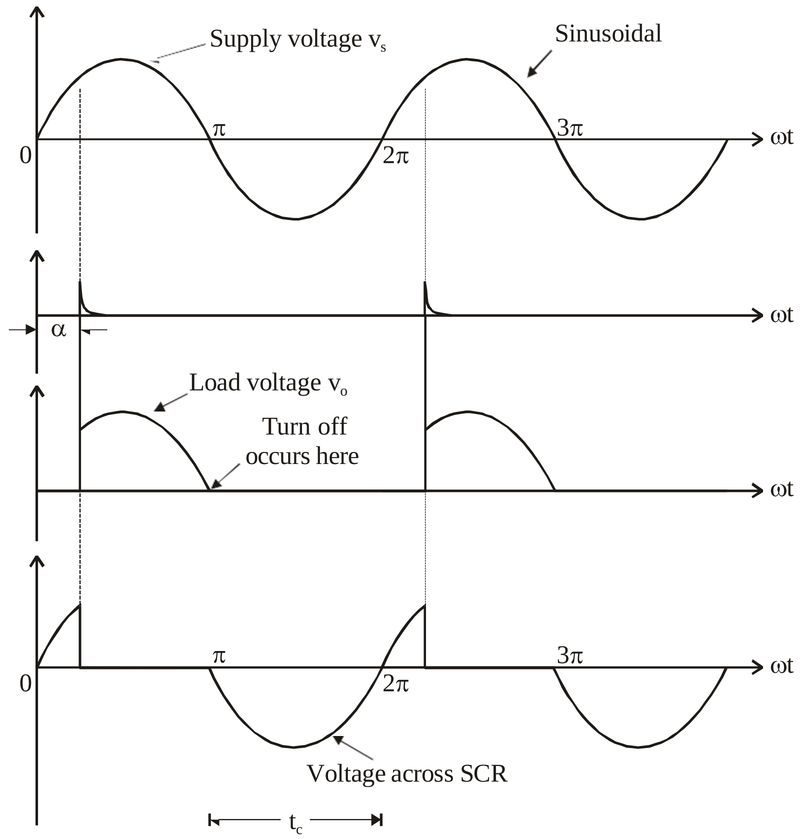


Fig. 5.2: Natural Commutation – Waveforms of Supply and Load Voltages (Resistive Load)

This type of commutation is applied in ac voltage controllers, phase controlled rectifiers and cyclo converters.

Forced Commutation

When supply is DC, natural commutation is not possible because the polarity of the supply remains unchanged. Hence special methods must be used to reduce the SCR current below the holding value or to apply a negative voltage across the SCR for a time interval greater than the turn off time of the SCR. This technique is called FORCED COMMUTATION and is applied in all circuits where the supply voltage is DC - namely, Choppers (fixed DC to variable DC), inverters (DC to AC). Forced commutation techniques are as follows:

- Self Commutation
- Resonant Pulse Commutation
- Complementary Commutation
- Impulse Commutation
- External Pulse Commutation.
- Load Side Commutation.
- Line Side Commutation.

Self Commutation or Load Commutation or Class A Commutation: (Commutation By Resonating The Load)

In this type of commutation the current through the SCR is reduced below the holding current value by resonating the load. i.e., the load circuit is so designed that even though the supply voltage is positive, an oscillating current tends to flow and when the current through the SCR reaches zero, the device turns off. This is done by including an inductance and a capacitor in series with the load and keeping the circuit under-damped. Figure 5.3 shows the circuit.

This type of commutation is used in Series Inverter Circuit.

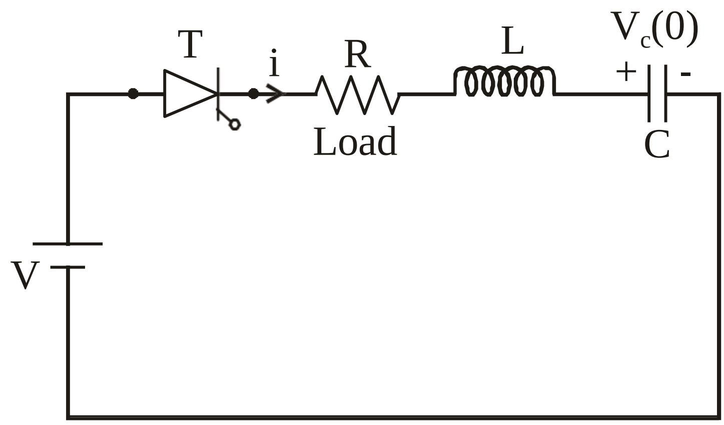


Fig. 5.3: Circuit for Self Commutation

(i) Expression for Current

At $t = 0$, when the SCR turns ON on the application of gate pulse assume the current in the circuit is zero and the capacitor voltage is $V_C\left(0\right)$.

Writing the Laplace Transformation circuit of figure 5.3 the following circuit is obtained when the SCR is conducting.

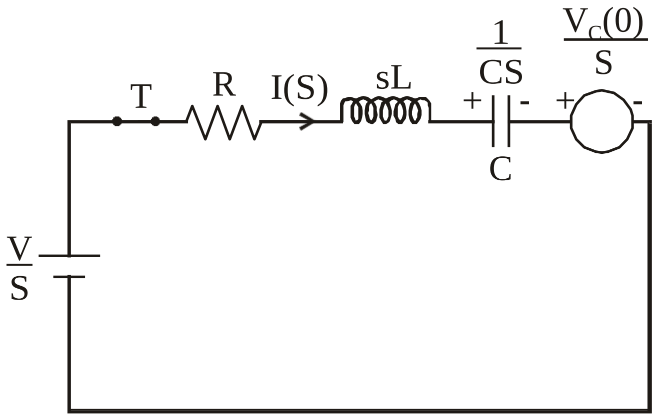


Fig.: 5.4.

$$I(S) = \frac{\frac{\left[V - V_C(0)\right]}{S}}{R + sL + \frac{1}{C_S}}$$

$$= \frac{\frac{C_S\left[V - V_C(0)\right]}{S}}{RCs + s^2 LC + 1}$$

$$= \frac{C\left[V - V_C(0)\right]}{LC\left[s^2 + s\frac{R}{L} + \frac{1}{LC}\right]}$$

$$= \frac{\frac{V - V_C(0)}{L}}{s^2 + s\frac{R}{L} + \frac{1}{LC}}$$

$$= \frac{\frac{\left(V - V_C(0)\right)}{L}}{s^2 + s\frac{R}{L} + \frac{1}{LC} + \left(\frac{R}{2L}\right)^2 - \left(\frac{R}{2L}\right)^2}$$

$$= \frac{\frac{\left(V - V_C(0)\right)}{L}}{\left(s + \frac{R}{2L}\right)^2 + \left[\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\right]^2}$$

$$= \frac{A}{(s+\delta)^2 + \omega^2},$$

Where

$$A = \frac{(V - V_C(0))}{L}, \qquad \delta = \frac{R}{2L}, \qquad \omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

ω is called the natural frequency

$$I(S) = \frac{A}{\omega} \frac{\omega}{(s+\delta)^2 + \omega^2}$$

Taking inverse Laplace transforms

$$i(t) = \frac{A}{\omega} e^{-\delta t} \sin \omega t$$

Therefore expression for current

$$i(t) = \frac{V - V_C(0)}{\omega L} e^{\frac{-R}{2L}t} \sin \omega t$$

$$\text{Peak value of current } = \frac{(V - V_C(0))}{\omega L}$$

(ii) Expression for voltage across capacitor at the time of turn off

Applying KVL to figure 1.3

$$v_c = V - v_R - V_L$$

$$v_c = V - iR - L\frac{di}{dt}$$

Substituting for i,

$$v_c = V - R\frac{A}{\omega} e^{-\delta t} \sin \omega t - L\frac{d}{dt}\left(\frac{A}{\omega} e^{-\delta t} \sin \omega t\right)$$

$$v_c = V - R\frac{A}{\omega} e^{-\delta t} \sin \omega t - L\frac{A}{\omega}\left(e^{-\delta t} \omega \cos \omega t - \delta e^{-\delta t} \sin \omega t\right)$$

$$v_c = V - \frac{A}{\omega} e^{-\delta t}\left[R \sin \omega t + \omega L \cos \omega t - L\delta \sin \omega t\right]$$

$$v_c = V - \frac{A}{\omega} e^{-\delta t}\left[R\sin\omega t + \omega L\cos\omega t - L\frac{R}{2L}\sin\omega t \right]$$

$$v_c = V - \frac{A}{\omega} e^{-\delta t}\left[\frac{R}{2}\sin\omega t + \omega L\cos\omega t \right]$$

Substituting for A,

$$v_c(t) = V - \frac{\left(V - V_C(0)\right)}{\omega L} e^{-\delta t}\left[\frac{R}{2}\sin\omega t + \omega L\cos\omega t \right]$$

$$v_c(t) = V - \frac{\left(V - V_C(0)\right)}{\omega} e^{-\delta t}\left[\frac{R}{2L}\sin\omega t + \omega\cos\omega t \right]$$

SCR turns off when current goes to zero. i.e., at $\omega t = \pi$.

Therefore at turn off

$$v_c = V - \frac{\left(V - V_C(0)\right)}{\omega} e^{\frac{-\delta\pi}{\omega}}\left(0 + \omega\cos\pi\right)$$

$$v_c = V + \left[V - V_C(0)\right] e^{\frac{-\delta\pi}{\omega}}$$

Therefore $$v_c = V + \left[V - V_C(0)\right] e^{\frac{-R\pi}{2L\omega}}$$

Note: For effective commutation the circuit should be under damped.

That is $$\left(\frac{R}{2L}\right)^2 < \frac{1}{LC}$$

- With R = 0, and the capacitor initially uncharged that is $V_C(0) = 0$

$$i = \frac{V}{\omega L}\sin\frac{t}{\sqrt{LC}}$$

But $$\omega = \frac{1}{\sqrt{LC}}$$

Therefore $$i = \frac{V}{L}\sqrt{LC}\sin\frac{t}{\sqrt{LC}} = V\sqrt{\frac{C}{L}}\sin\frac{t}{\sqrt{LC}}$$

and capacitor voltage at turn off is equal to 2V.

- Figure 5.5 shows the waveforms for the above conditions. Once the SCR turns off voltage across it is negative voltage.
- Conduction time of SCR $= \frac{\pi}{\omega}$.

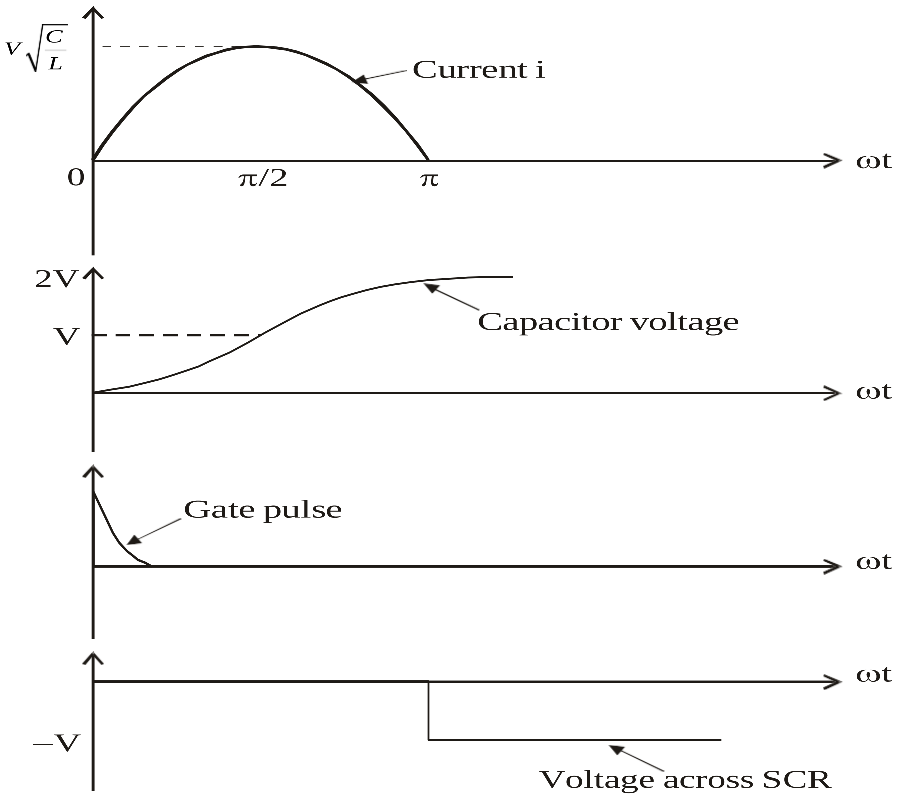


Fig. 5.5: Self Commutation – Wave forms of Current and Capacitors Voltage

Problem 5.1 : Calculate the conduction time of SCR and the peak SCR current that flows in the circuit employing series resonant commutation (self commutation or class A commutation), if the supply voltage is 300 V, C = 1μF, L = 5 mH and R_L = 100 Λ. Assume that the circuit is initially relaxed.

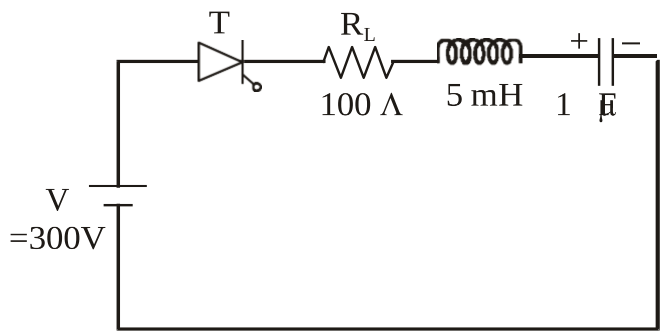


Fig. 5.6

Solution:

$$\omega = \sqrt{\frac{1}{LC} - \left(\frac{R_L}{2L}\right)^2}$$

$$\omega = \sqrt{\frac{1}{5\times10^{-3}\times1\times10^{-6}} - \left(\frac{100}{2\times5\times10^{-3}}\right)^2}$$

$$\omega = 10,000 \text{ rad/sec}$$

Since the circuit is initially relaxed, initial voltage across capacitor is zero as also the initial current through L and the expression for current i is

$$i = \frac{V}{\omega L} e^{-\delta t} \sin\omega t \text{ , where } \delta = \frac{R}{2L},$$

Therefore peak value of $\quad i = \dfrac{V}{\omega L}$

$$i = \frac{300}{10000\times5\times10^{-3}} = 6A$$

Conducting time of SCR $\quad = \dfrac{\pi}{\omega} = \dfrac{\pi}{10000} = 0.314\text{msec}$

Problem 1.2: Figure 1.7 shows a self commutating circuit. The inductance carries an initial current of 200 A and the initial voltage across the capacitor is V, the supply voltage. Determine the conduction time of the SCR and the capacitor voltage at turn off.

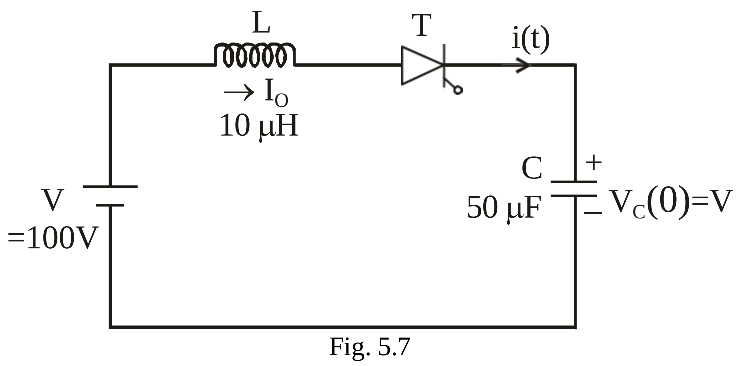


Fig. 5.7

Solution:

The transformed circuit of figure 5.7 is shown in figure 5.8.

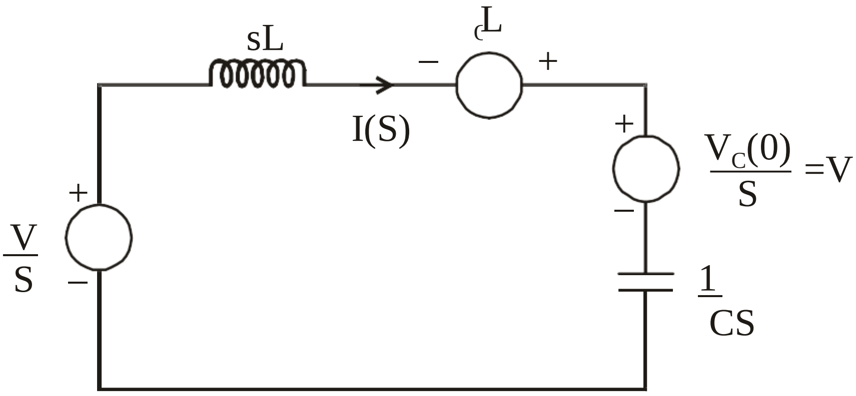


Fig.5.8: Transformed Circuit of Fig. 5.7

The governing equation is

$$\frac{V}{s} = I(S)\,sL - I_O L + \frac{V_C(0)}{s} + I(S)\frac{1}{Cs}$$

Therefore $$I(S) = \frac{\frac{V}{s} - \frac{V_C(0)}{s} + I_O L}{sL + \frac{1}{Cs}}$$

$$I(S) = \frac{\left[\frac{V}{s} - \frac{V_C(0)}{s}\right]Cs}{s^2LC + 1} + \frac{I_O LCs}{s^2LC + 1}$$

$$I(S) = \frac{\left[V - V_C(0)\right]C}{LC\left[s^2 + \frac{1}{LC}\right]} + \frac{I_O LCs}{LC\left[s^2 + \frac{1}{LC}\right]}$$

$$I(S) = \frac{V - V_C(0)}{L\left[s^2 + \omega^2\right]} + \frac{sI_O}{s^2 + \omega^2}$$

$$I(S) = \frac{\left[V - V_C(0)\right]\omega}{\omega L\left[s^2 + \omega^2\right]} + \frac{sI_O}{s^2 + \omega^2} \quad \text{Where } \omega = \frac{1}{\sqrt{LC}}$$

Taking inverse LT

$$i(t) = \left[V - V_C(0)\right]\sqrt{\frac{C}{L}}\sin\omega t + I_O\cos\omega t$$

The capacitor voltage is given by

$$v_c(t) = \frac{1}{C}\int_0^t i(t)\,dt + V_C(0)$$

$$v_c(t) = \frac{1}{C}\int_0^t \left\{\left[V - V_C(0)\right]\sqrt{\frac{C}{L}}\sin\omega t + I_O\cos\omega t\right\} dt + V_C(0)$$

$$v_c(t) = \frac{1}{C}\left[\frac{\left(V - V_C(0)\right)}{\omega}\sqrt{\frac{C}{L}}\left(-\cos\omega t\right)\Big|_o^t + \frac{I_O}{\omega}\left(\sin\omega t\right)\Big|_o^t + V_C(0)\right]$$

$$v_c(t) = \frac{1}{C}\left[\frac{\left(V - V_C(0)\right)}{\omega}\sqrt{\frac{C}{L}}\left(1 - \cos\omega t\right) + \frac{I_O}{\omega}\left(\sin\omega t\right) + V_C(0)\right]$$

$$v_c(t) = \frac{I_O}{C}\times\sqrt{LC}\sin\omega t + \frac{1}{C}\left(V - V_C(0)\right)\sqrt{LC}\sqrt{\frac{C}{L}}\left(1 - \cos\omega t\right) + V_C(0)$$

$$v_c(t) = I_O\sqrt{\frac{L}{C}}\sin\omega t + V - V\cos\omega t - V_C(0) + V_C(0)\cos\omega t + V_C(0)$$

$$v_c(t) = I_O\sqrt{\frac{L}{C}}\sin\omega t - \left(V - V_C(0)\right)\cos\omega t + V$$

In this problem $V_C(0) = V$

Therefore we get, $i(t) = I_O\cos\omega t$ and

$$v_c(t) = I_O\sqrt{\frac{L}{C}}\sin\omega t + V$$

he waveforms are as shown in figure 1.9

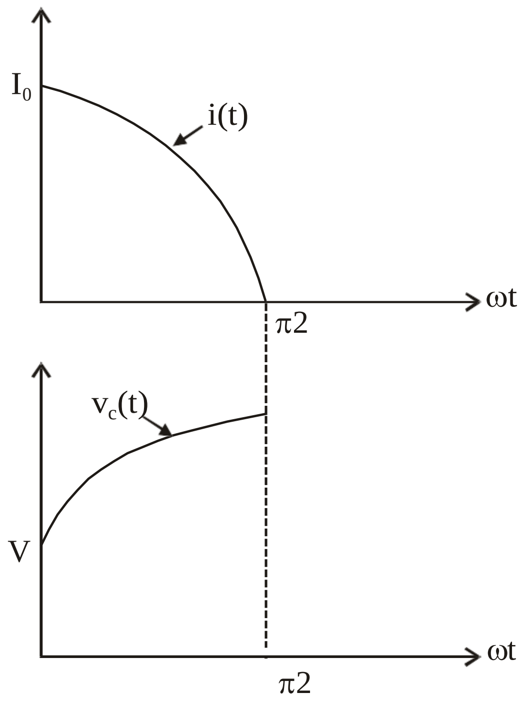


Fig.: 1.9

Turn off occurs at a time to so that $\omega t_O = \frac{\pi}{2}$

Therefore $\quad t_O = \dfrac{0.5\pi}{\omega} = 0.5\pi\sqrt{LC}$

$$t_O = 0.5 \times \pi \sqrt{10 \times 10^{-6} \times 50 \times 10^{-6}}$$

$$t_O = 0.5 \times \pi \times 10^{-6}\sqrt{500} = 35.1\mu\text{seconds}$$

and the capacitor voltage at turn off is given by

$$v_c\left(t_O\right) = I_O\sqrt{\frac{L}{C}}\sin\omega t_O + V$$

$$v_c\left(t_O\right) = 200\sqrt{\frac{10 \times 10^{-6}}{50 \times 10^{-6}}}\sin 90^0 + 100$$

$$v_c\left(t_O\right) = 200 \times 0.447 \times \sin\left(\frac{35.12}{22.36}\right) + 100$$

$$v_c\left(t_O\right) = 89.4 + 100 = 189.4\ V$$

Problem 5.3: In the circuit shown in figure 1.10. V = 600 volts, initial capacitor voltage is zero, L = 20 μH, C = 50μF and the current through the inductance at the time of SCR triggering is I_O = 350 A. Determine (a) the peak values of capacitor voltage and current (b) the conduction time of T_1.

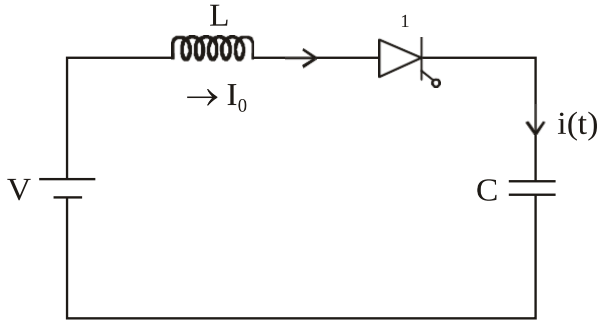


Fig. 5.10

Solution:

(Refer to problem 5.2).

The expression for $i(t)$ is given by

$$i(t) = \left[V - V_C(0)\right]\sqrt{\frac{C}{L}}\sin\omega t + I_O\cos\omega t$$

It is given that the initial voltage across the capacitor $V_C(O)$ is zero.

Therefore $$i(t) = V\sqrt{\frac{C}{L}}\sin\omega t + I_O\cos\omega t$$

$i(t)$ can be written as

$$i(t) = \sqrt{I_O^2 + V^2\frac{C}{L}}\sin(\omega t + \alpha)$$

where $$\alpha = \tan^{-1}\frac{I_O\sqrt{\frac{L}{C}}}{V}$$

and $$\omega = \frac{1}{\sqrt{LC}}$$

The peak capacitor current is

$$\sqrt{I_O^2 + V^2\frac{C}{L}}$$

Substituting the values, the peak capacitor current

$$= \sqrt{350^2 + 600^2 \times \frac{50 \times 10^{-6}}{20 \times 10^{-6}}} = 1011.19\ A$$

The expression for capacitor voltage is

$$v_c(t) = I_O \sqrt{\frac{L}{C}} \sin \omega t - \left(V - V_C(0)\right) \cos \omega t + V$$

with $\quad V_C(0) = 0, \quad v_c(t) = I_O \sqrt{\frac{L}{C}} \sin \omega t - V \cos \omega t + V$

This can be rewritten as

$$v_c(t) = \sqrt{V^2 + I_O^2 \frac{L}{C}} \sin\left(\omega t - \beta\right) + V$$

Where $\quad \beta = \tan^{-1} \frac{V\sqrt{\frac{C}{L}}}{I_O}$

The peak value of capacitor voltage is

$$= \sqrt{V^2 + I_O^2 \frac{L}{C}} + V$$

Substituting the values, the peak value of capacitor voltage

$$= \sqrt{600^2 + 350^2 \times \frac{20 \times 10^{-6}}{50 \times 10^{-6}}} + 600$$

$$= 639.5 + 600 = 1239.5V$$

To calculate conduction time of T_1

The waveform of capacitor current is shown in figure 5.11.When the capacitor current becomes zero the SCR turns off.

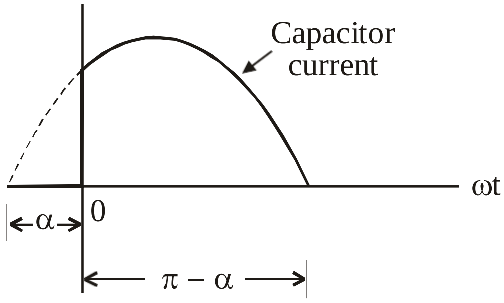


Fig. 5.11

Therefore conduction time of SCR $= \dfrac{\pi - \alpha}{\omega}$

$$= \frac{\pi - \tan^{-1}\left(\dfrac{I_O\sqrt{\dfrac{L}{C}}}{V}\right)}{\dfrac{1}{\sqrt{LC}}}$$

Substituting the values

$$\alpha = \tan^{-1}\left(\frac{I_O\sqrt{\dfrac{L}{C}}}{V}\right)$$

$$\alpha = \tan^{-1}\frac{350}{600}\sqrt{\frac{20\times10^{-6}}{50\times10^{-6}}}$$

$$\alpha = 20.25^0 \text{ i.e., } 0.3534 \text{ radians}$$

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{20\times10^{-6}\times50\times10^{-6}}} = 31622.8 \text{ rad/sec}$$

Therefore conduction time of SCR

$$= \frac{\pi - 0.3534}{31622.8} = 88.17\mu \text{ sec}$$

Resonant Pulse Commutation (Class B Commutation)

The circuit for resonant pulse commutation is shown in figure 5.12.

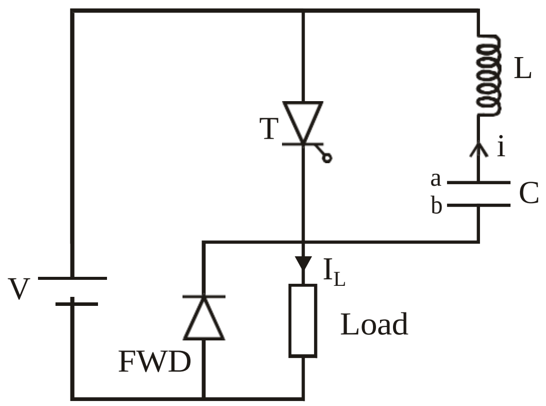


Fig. 5.12: Circuit for Resonant Pulse Commutation

This is a type of commutation in which a LC series circuit is connected across the SCR. Since the commutation circuit has negligible resistance it is always under-damped i.e., the current in LC circuit tends to oscillate whenever the SCR is on.

Initially the SCR is off and the capacitor is charged to V volts with plate ‘a’ being positive. Referring to figure 5.13 at $t = t_1$ the SCR is turned ON by giving a gate pulse. A current I_L flows through the load and this is assumed to be constant. At the same time SCR short circuits the LC combination which starts oscillating. A current ‘i’ starts flowing in the direction shown in figure. As ‘i’ reaches its maximum value, the capacitor voltage reduces to zero and then the polarity of the capacitor voltage reverses ‘b’ becomes positive). When ‘i’ falls to zero this reverse voltage becomes maximum, and then direction of ‘i’ reverses i.e., through SCR the load current I_L and ‘i’ flow in opposite direction. When the instantaneous value of ‘i’ becomes equal to I_L, the SCR current becomes zero and the SCR turns off. Now the capacitor starts charging and its voltage reaches the supply voltage with plate a being positive. The related waveforms are shown in figure 5.13.

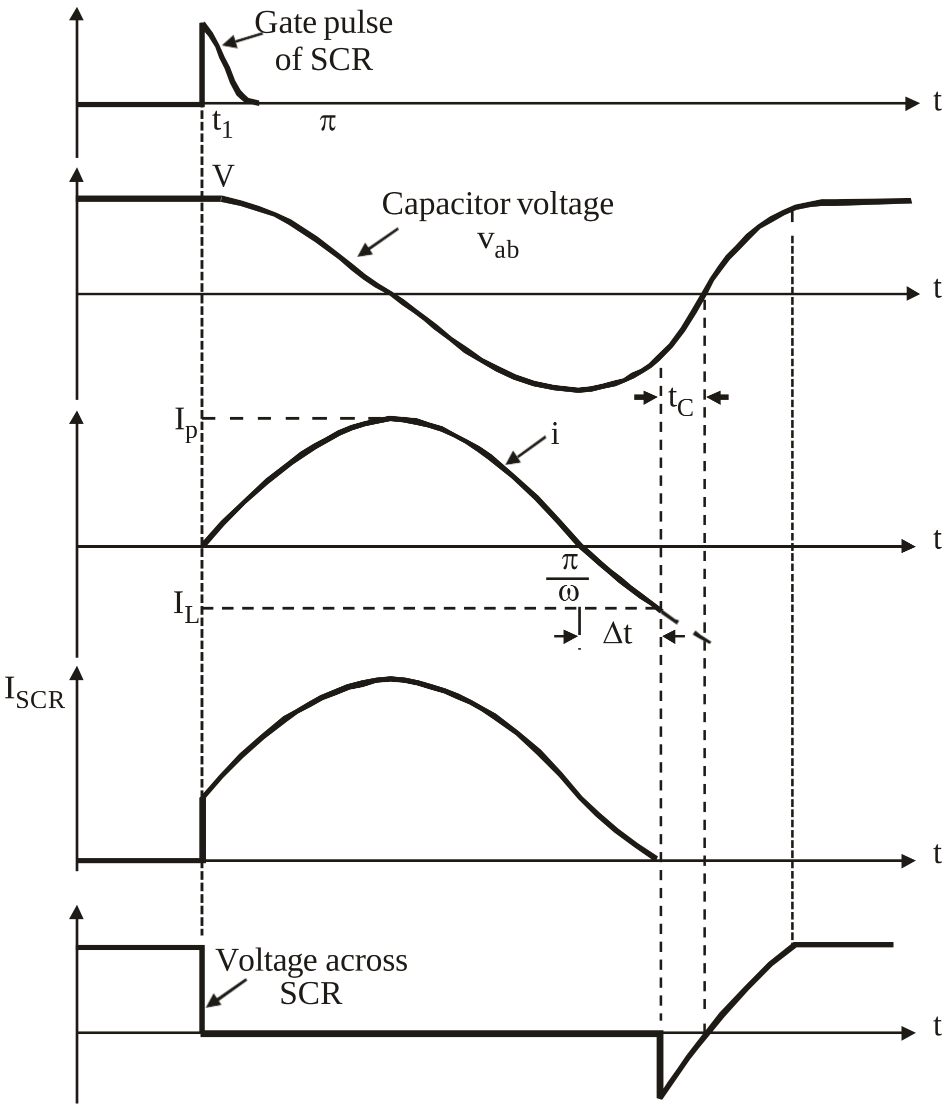


Fig. 1.13: Resonant Pulse Commutation – Various Waveforms

(i) Expression For t_c, The Circuit Turn Off Time

Assume that at the time of turn off of the SCR the capacitor voltage $v_{ab} \approx -V$ and load current I_L is constant. t_c is the time taken for the capacitor voltage to reach 0 volts from – V volts and is derived as follows.

$$V = \frac{1}{C}\int_0^{t_c} I_L dt$$

$$V = \frac{I_L t_c}{C}$$

$$t_c = \frac{VC}{I_L} \text{ seconds}$$

For proper commutation t_c should be greater than t_q, the turn off time of T. Also, the magnitude of I_p, the peak value of i should be greater than the load current I_L and the expression for i is derived as follows

The LC circuit during the commutation period is shown in figure 5.14.

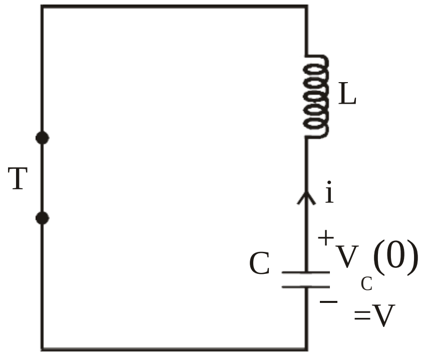


Fig. 5.14

The transformed circuit is shown in figure 5.15.

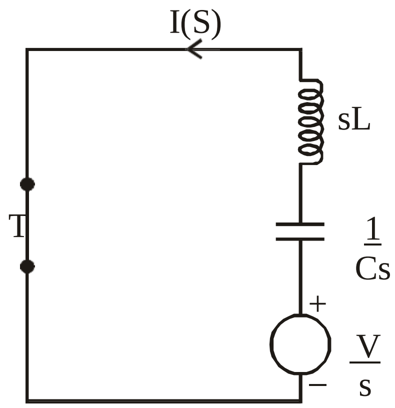


Fig. 5.15

$$I(S) = \frac{\frac{V}{s}}{sL + \frac{1}{Cs}}$$

$$I(S) = \frac{\left(\frac{V}{s}\right)Cs}{s^2LC + 1}$$

$$I(S) = \frac{VC}{LC\left(s^2 + \frac{1}{LC}\right)}$$

$$I(S) = \frac{V}{L} \times \frac{1}{s^2 + \frac{1}{LC}}$$

$$I(S) = \frac{V}{L} \times \frac{\left(\frac{1}{\sqrt{LC}}\right)}{s^2 + \frac{1}{LC}} \times \frac{1}{\left(\frac{1}{\sqrt{LC}}\right)}$$

$$I(S) = V\sqrt{\frac{C}{L}} \times \frac{\left(\frac{1}{\sqrt{LC}}\right)}{s^2 + \frac{1}{LC}}$$

Taking inverse LT

$$i(t) = V\sqrt{\frac{C}{L}} \sin \omega t$$

Where $\omega = \frac{1}{\sqrt{LC}}$

Or $i(t) = \frac{V}{\omega L} \sin \omega t = I_p \sin \omega t$

Therefore $I_p = V\sqrt{\frac{C}{L}}$ amps.

(ii) Expression for Conduction Time of SCR

For figure 5.13 (waveform of i), the conduction time of SCR

$$= \frac{\pi}{\omega} + \Delta t$$

$$= \frac{\pi}{\omega} + \frac{\sin^{-1}\left(\frac{I_L}{I_p}\right)}{\omega}$$

Alternate Circuit for Resonant Pulse Commutation

The working of the circuit can be explained as follows. The capacitor C is assumed to be charged to $V_C(0)$ with polarity as shown, T_1 is conducting and the load current I_L is a constant. To turn off T_1, T_2 is triggered. L, C, T_1 and T_2 forms a resonant circuit. A resonant current $i_c(t)$, flows in the direction shown, i.e., in a direction opposite to that of load current I_L.

$i_c(t) = I_p \sin\omega t$ (refer to the previous circuit description). Where $I_p = V_C(0)\sqrt{\frac{C}{L}}$ & and the capacitor voltage is given by

$$v_c(t) = \frac{1}{C}\int i_C(t).dt$$

$$v_c(t) = \frac{1}{C}\int V_C(0)\sqrt{\frac{C}{L}} \sin\omega t.dt \, .$$

$$v_c(t) = -V_C(0)\cos\omega t$$

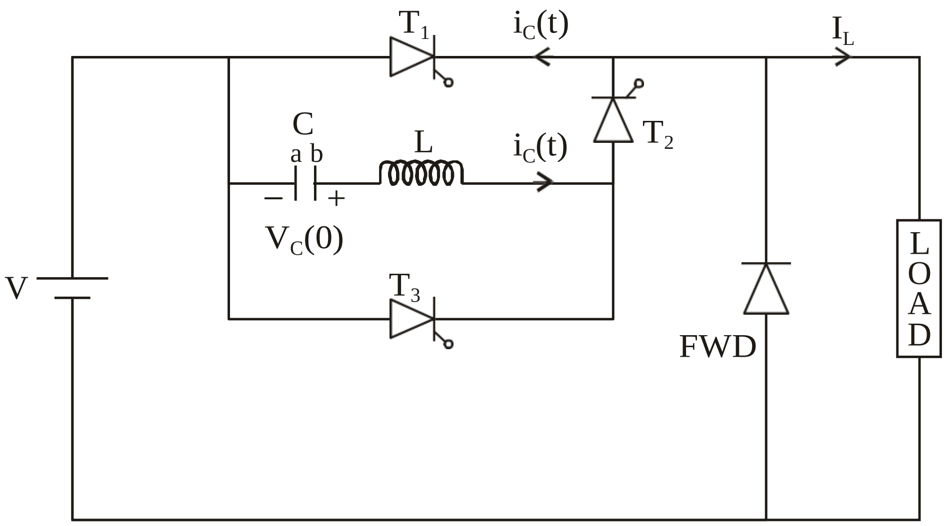


Fig. 5.16: Resonant Pulse Commutation – An Alternate Circuit

When $i_c(t)$ becomes equal to I_L (the load current), the current through T_1 becomes zero and T_1 turns off. This happens at time t_1 such that

$$I_L = I_p \sin\frac{t_1}{\sqrt{LC}}$$

$$I_p = V_C(0)\sqrt{\frac{C}{L}}$$

$$t_1 = \sqrt{LC}\sin^{-1}\left(\frac{I_L}{V_C(0)}\sqrt{\frac{L}{C}}\right)$$

and the corresponding capacitor voltage is

$$v_c(t_1) = -V_1 = -V_C(0)\cos\omega t_1$$

Once the thyristor T_1 turns off, the capacitor starts charging towards the supply voltage through T_2 and load. As the capacitor charges through the load capacitor current is same as load current I_L, which is constant. When the capacitor voltage reaches V, the supply voltage, the FWD starts conducting and the energy stored in L charges C to a still higher voltage. The triggering of T_3 reverses the polarity of the capacitor voltage and the circuit is ready for another triggering of T_1. The waveforms are shown in figure 5.17.

Expression For t_c

Assuming a constant load current I_L which charges the capacitor

$$t_c = \frac{CV_1}{I_L} \text{ seconds}$$

Normally $V_1 \approx V_C(0)$

For reliable commutation t_c should be greater than t_q, the turn off time of SCR T_1. It is to be noted that t_c depends upon I_L and becomes smaller for higher values of load current.

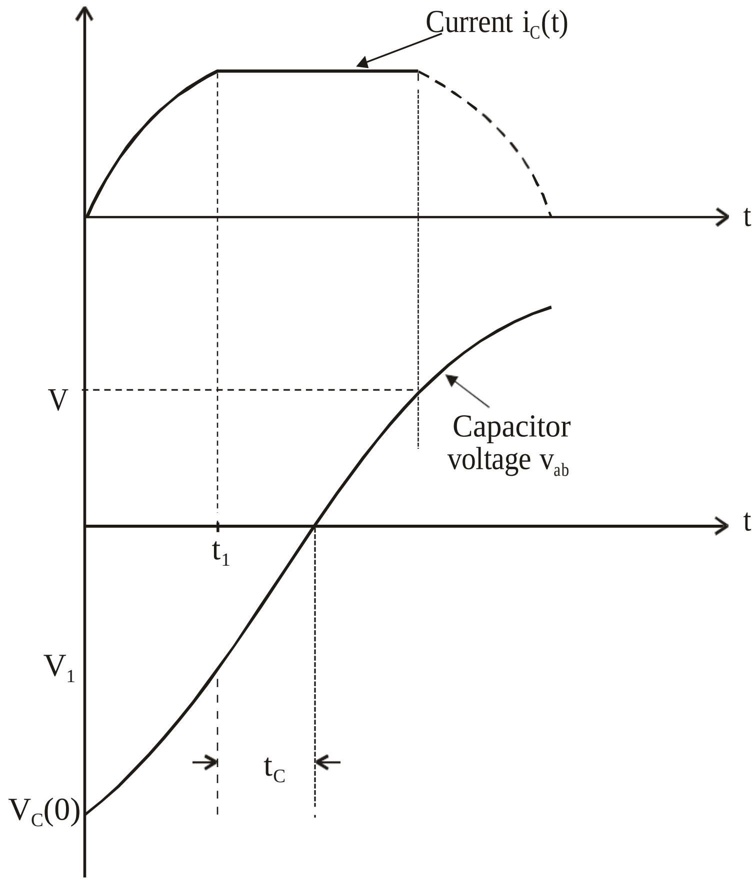


Fig. 5.17: Resonant Pulse Commutation – Alternate Circuit – Various Waveforms

Resonant Pulse Commutation with Accelerating Diode

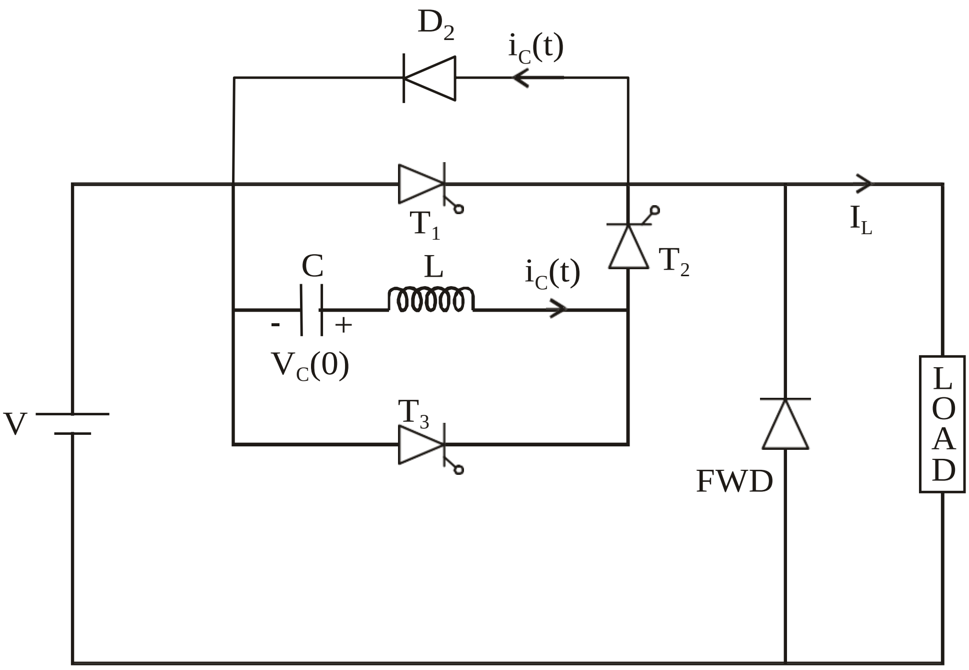


Fig. 5.17(a)

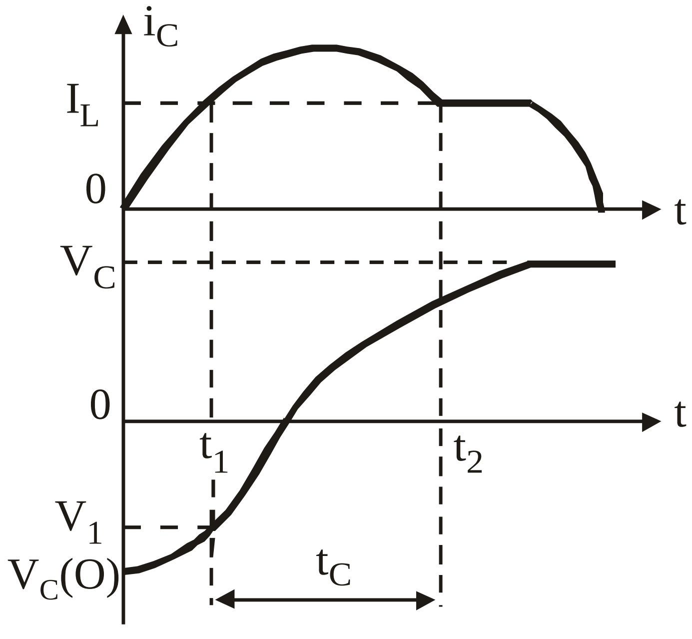


Fig. 5.17(b)

A diode D_2 is connected as shown in the figure 5.17(a) to accelerate the discharging of the capacitor 'C'. When thyristor T_2 is fired a resonant current $i_C(t)$ flows through the capacitor and thyristor T_1. At time $t = t_1$, the capacitor current $i_C(t)$ equals the load current I_L and hence current through T_1 is reduced to zero resulting in turning off of T_1. Now the capacitor current $i_C(t)$ continues to flow through the diode D_2 until it reduces to load current level I_L at time t_2. Thus the presence of D_2 has accelerated the discharge of capacitor ‘C’. Now the capacitor gets charged through the load and the charging current is constant. Once capacitor is fully charged T_2 turns off by itself. But once current of thyristor T_1 reduces to zero the reverse voltage appearing across T_1 is the forward voltage drop of D_2 which is very small. This makes the thyristor recovery process very slow and it becomes necessary to provide longer reverse bias time.

From figure 5.17(b)

$$t_2 = \pi\sqrt{LC} - t_1$$

$$V_C(t_2) = -V_C(O)\cos\omega t_2$$

Circuit turn-off time $t_C = t_2 - t_1$

Problem 5.4: The circuit in figure 5.18 shows a resonant pulse commutation circuit. The initial capacitor voltage $V_{C(O)} = 200V$, C = 30μF and L = 3μH. Determine the circuit turn off time t_c, if the load current I_L is (a) 200 A and (b) 50 A.

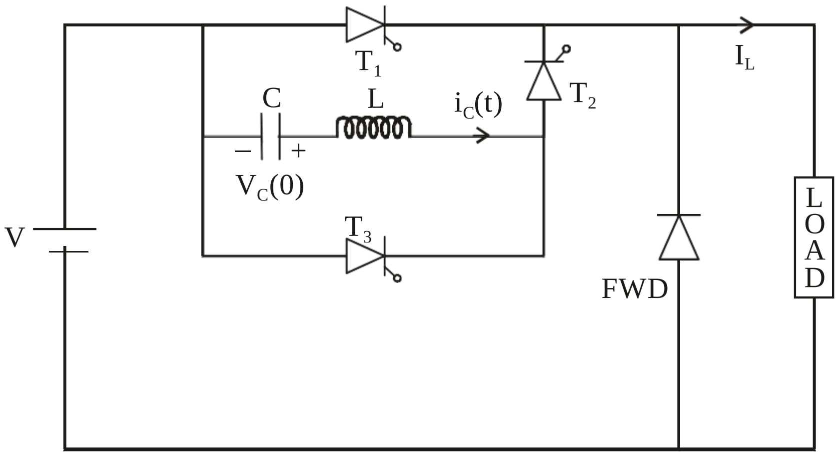


Fig. 5.18

Solution

(a) When $I_L = 200A$

Let T_2 be triggered at $t = 0$.

The capacitor current $i_c(t)$ reaches a value I_L at $t = t_1$, when T_1 turns off

$$t_1 = \sqrt{LC}\sin^{-1}\left(\frac{I_L}{V_C(0)}\sqrt{\frac{L}{C}}\right)$$

$$t_1 = \sqrt{3\times10^{-6}\times30\times10^{-6}}\,\sin^{-1}\left(\frac{200}{200}\sqrt{\frac{3\times10^{-6}}{30\times10^{-6}}}\right)$$

$$t_1 = 3.05\mu \sec .$$

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{3\times10^{-6}\times30\times10^{-6}}}$$

$$\omega = 0.105\times10^{6}\, rad/\sec .$$

At $t = t_1$, the magnitude of capacitor voltage is $V_1 = V_C(0)\cos\omega t_1$

That is $V_1 = 200\cos 0.105\times10^{6}\times3.05\times10^{-6}$

$$V_1 = 200\times0.9487$$

$$V_1 = 189.75 \text{ Volts}$$

and $t_c = \dfrac{CV_1}{I_L}$

$$t_c = \frac{30\times10^{-6}\times189.75}{200} = 28.46\mu \sec .$$

(b) When $I_L = 50A$

$$t_1 = \sqrt{3\times10^{-6}\times30\times10^{-6}}\,\sin^{-1}\left(\frac{50}{200}\sqrt{\frac{3\times10^{-6}}{30\times10^{-6}}}\right)$$

$$t_1 = 0.749\mu \sec .$$

$$V_1 = 200\cos 0.105\times10^{6}\times0.749\times10^{-6}$$

$$V_1 = 200\times1 = 200 \text{ Volts} .$$

$$t_c = \frac{CV_1}{I_L}$$

$$t_c = \frac{30\times10^{-6}\times200}{50} = 120\mu \sec .$$

It is observed that as load current increases the value of t_c reduces.

Problem 5.4a: Repeat the above problem for $I_L = 200A$, if an antiparallel diode D_2 is connected across thyristor T_1 as shown in figure 5.18a.

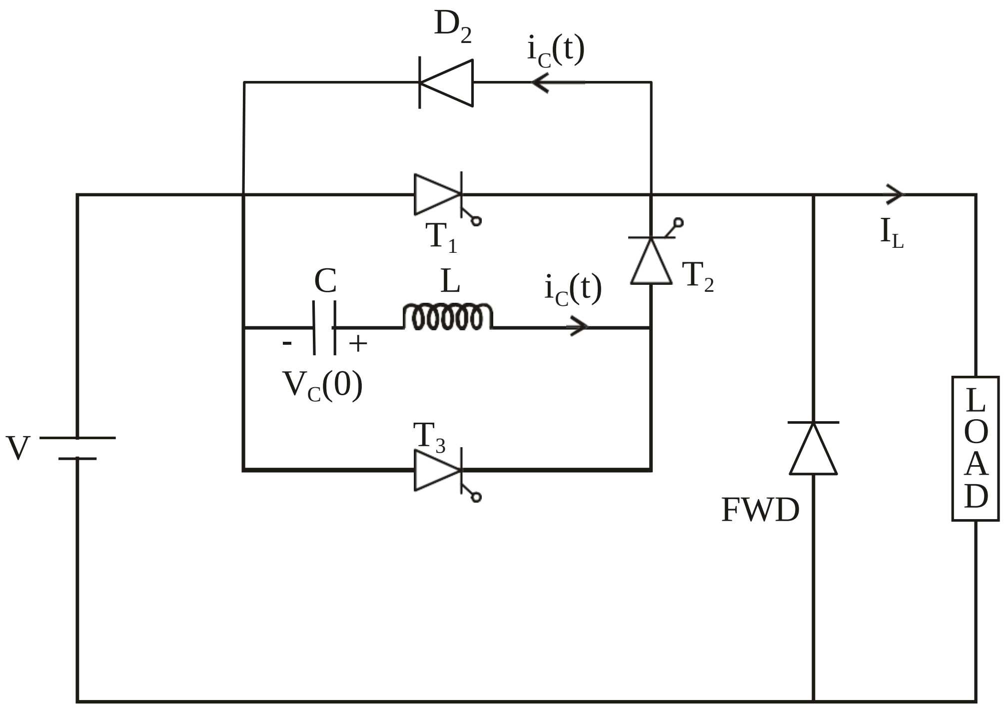


Fig. 5.18(a)

Solution

$$I_L = 200A$$

Let T_2 be triggered at $t = 0$.

Capacitor current $i_C(t)$ reaches the value I_L at $t = t_1$, when T_1 turns off

Therefore $$t_1 = \sqrt{LC}\,\sin^{-1}\left[\frac{I_L}{V_C(O)}\sqrt{\frac{L}{C}}\right]$$

$$t_1 = \sqrt{3\times10^{-6}\times30\times10^{-6}}\,\sin^{-1}\left(\frac{200}{200}\sqrt{\frac{3\times10^{-6}}{30\times10^{-6}}}\right)$$

`

$$t_1 = 3.05\mu\sec.$$

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{3\times10^{-6}\times30\times10^{-6}}}$$

$$\omega = 0.105\times10^{6} \text{ radians/sec}$$

$At\ t = t_1$

$$V_C(t_1) = V_1 = -V_C(O)\cos\omega t_1$$

$$V_C(t_1) = -200\cos\left(0.105\times10^{6}\times3.05\times10^{-6}\right)$$

$$V_C(t_1) = -189.75V$$

$i_C(t)$ flows through diode D_2 after T_1 turns off.
$i_C(t)$ current falls back to I_L at t_2

$$t_2 = \pi\sqrt{LC} - t_1$$

$$t_2 = \pi\sqrt{3\times10^{-6}\times30\times10^{-6}} - 3.05\times10^{-6}$$

$$t_2 = 26.75\mu\text{ sec}.$$

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{3\times10^{-6}\times30\times10^{-6}}}$$

$$\omega = 0.105\times10^{6} \text{ rad/sec.}$$

$At\ t = t_2$

$$V_C(t_2) = V_2 = -200\cos 0.105\times10^{+6}\times26.75\times10^{-6}$$

$$V_C(t_2) = V_2 = 189.02\ V$$

Therefore $\quad t_C = t_2 - t_1 = 26.75\times10^{-6} - 3.05\times10^{-6}$

$$t_C = 23.7\mu\text{secs}$$

Problem 5.5: For the circuit shown in figure 5.19. Calculate the value of L for proper commutation of SCR. Also find the conduction time of SCR.

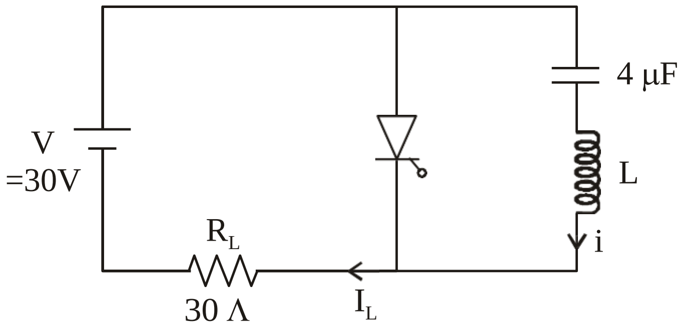


Fig. 5.19

Solution:

The load current $I_L = \frac{V}{R_L} = \frac{30}{30} = 1$ Amp

For proper SCR commutation I_p, the peak value of resonant current i, should be greater than I_L,

Let $I_p = 2I_L$, Therefore $I_p = 2$ Amps .

Also $$I_p = \frac{V}{\omega L} = \frac{V}{\frac{1}{\sqrt{LC}} \times L} = V\sqrt{\frac{C}{L}}$$

Therefore $$2 = 30 \times \sqrt{\frac{4 \times 10^{-6}}{L}}$$

Therefore $L = 0.9mH$.

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.9 \times 10^{-3} \times 4 \times 10^{-6}}} = 16666 \text{ rad/sec}$$

Conduction time of SCR = $$\frac{\pi}{\omega} + \frac{\sin^{-1}\left(\frac{I_L}{I_p}\right)}{\omega}$$

$$= \frac{\pi}{16666} + \frac{\sin^{-1}\left(\frac{1}{2}\right)}{16666}$$

$$= \frac{\pi + 0.523}{16666} \text{ radians}$$

$= 0.00022$ seconds

$= 0.22$ msec

Problem 5.6: For the circuit shown in figure 5.20 given that the load current to be commutated is 10 A, turn off time required is 40μsec and the supply voltage is 100 V. Obtain the proper values of commutating elements.

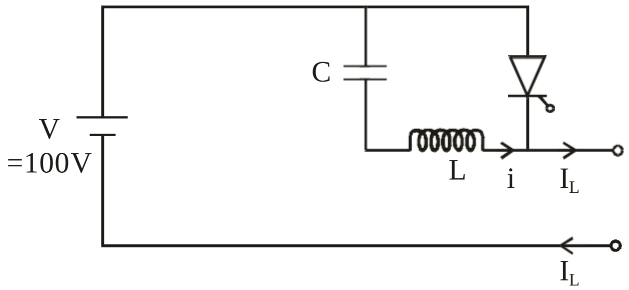


Fig. 5.20

Solution

I_p Peak value of $i = V\sqrt{\dfrac{C}{L}}$ and this should be greater than I_L. Let $I_p = 1.5 I_L$.

Therefore $1.5 \times 10 = 100\sqrt{\dfrac{C}{L}}$ $\quad ...(a)$

Also, assuming that at the time of turn off the capacitor voltage is approximately equal to V (and referring to waveform of capacitor voltage in figure 5.13) and the load current linearly charges the capacitor

$$t_c = \frac{CV}{I_L} \text{ seconds}$$

and this t_c is given to be 40 μsec.

Therefore $\quad 40 \times 10^{-6} = C \times \dfrac{100}{10}$

Therefore $\quad C = 4 \quad F$

Substituting this in equation (a)

$$1.5 \times 10 = 100\sqrt{\frac{4 \times 10^{-6}}{L}}$$

$$1.5^2 \times 10^2 = \frac{10^4 \times 4 \times 10^{-6}}{L}$$

Therefore $\quad L = 1.777 \times 10^{-4}\, H$

$L = 0.177 mH$.

Problem 5.7: In a resonant commutation circuit supply voltage is 200 V. Load current is 10 A and the device turn off time is 20μs. The ratio of peak resonant current to load current is 1.5. Determine the value of L and C of the commutation circuit.

Solution

Given $\frac{I_p}{I_L} = 1.5$

Therefore $I_p = 1.5 I_L = 1.5 \times 10 = 15A$.

That is $I_p = V\sqrt{\frac{C}{L}} = 15A \qquad ...(a)$

It is given that the device turn off time is 20 μsec. Therefore t_c, the circuit turn off time should be greater than this,

Let $t_c = 30\mu \sec$.

And $t_c = \frac{CV}{I_L}$

Therefore $30 \times 10^{-6} = \frac{200 \times C}{10}$

Therefore $C = 1.5 \quad F$.

Substituting in (a)

$$15 = 200\sqrt{\frac{1.5 \times 10^{-6}}{L}}$$

$$15^2 = 200^2 \times \frac{1.5 \times 10^{-6}}{L}$$

Therefore $L = 0.2666$ mH

Complementary Commutation (Class C Commutation, Parallel Capacitor Commutation)

In complementary commutation the current can be transferred between two loads. Two SCRs are used and firing of one SCR turns off the other. The circuit is shown in figure 5.21.

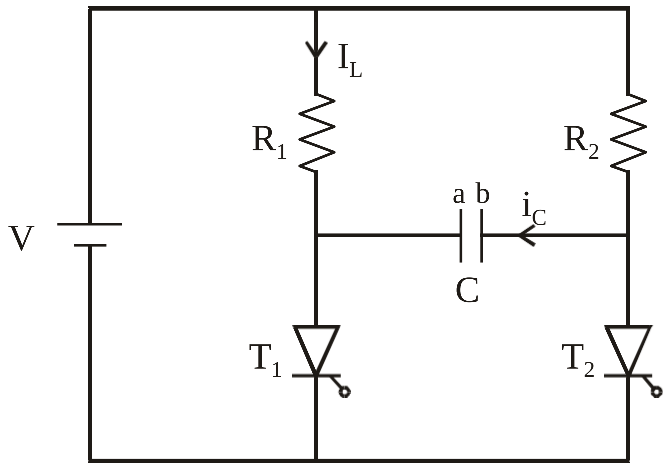


Fig. 5.21: Complementary Commutation

The working of the circuit can be explained as follows.

Initially both T_1 and T_2 are off; now, T_1 is fired. Load current I_L flows through R_1. At the same time, the capacitor C gets charged to V volts through R_2 and T_1 ('b' becomes positive with respect to 'a'). When the capacitor gets fully charged, the capacitor current i_c becomes zero.

To turn off T_1, T_2 is fired; the voltage across C comes across T_1 and reverse biases it, hence T_1 turns off. At the same time, the load current flows through R_2 and T_2. The capacitor 'C' charges towards V through R_1 and T_2 and is finally charged to V volts with 'a' plate positive. When the capacitor is fully charged, the capacitor current becomes zero. To turn off T_2, T_1 is triggered, the capacitor voltage (with 'a' positive) comes across T_2 and T_2 turns off. The related waveforms are shown in figure 5.22.

(i) Expression for Circuit Turn Off Time t_c

From the waveforms of the voltages across T_1 and capacitor, it is obvious that t_c is the time taken by the capacitor voltage to reach 0 volts from – V volts, the time constant being RC and the final voltage reached by the capacitor being V volts. The equation for capacitor voltage $v_c(t)$ can be written as

$$v_c(t) = V_f + (V_i - V_f)e^{-t/\tau}$$

Where V_f is the final voltage, V_i is the initial voltage and τ is the time constant.

At $t = t_c$, $v_c(t) = 0$,

$= R_1 C$, $V_f = V$, $V_i = -V$,

Therefore $0 = V + (-V - V)e^{\frac{-t_c}{R_1 C}}$

$$0 = V - 2Ve^{\frac{-t_c}{R_1 C}}$$

Therefore $V = 2Ve^{\frac{-t_c}{R_1 C}}$

$$0.5 = e^{\frac{-t_c}{R_1 C}}$$

Taking natural logarithms on both sides

$$\ln 0.5 = \frac{-t_c}{R_1 C}$$

$$t_c = 0.693 R_1 C$$

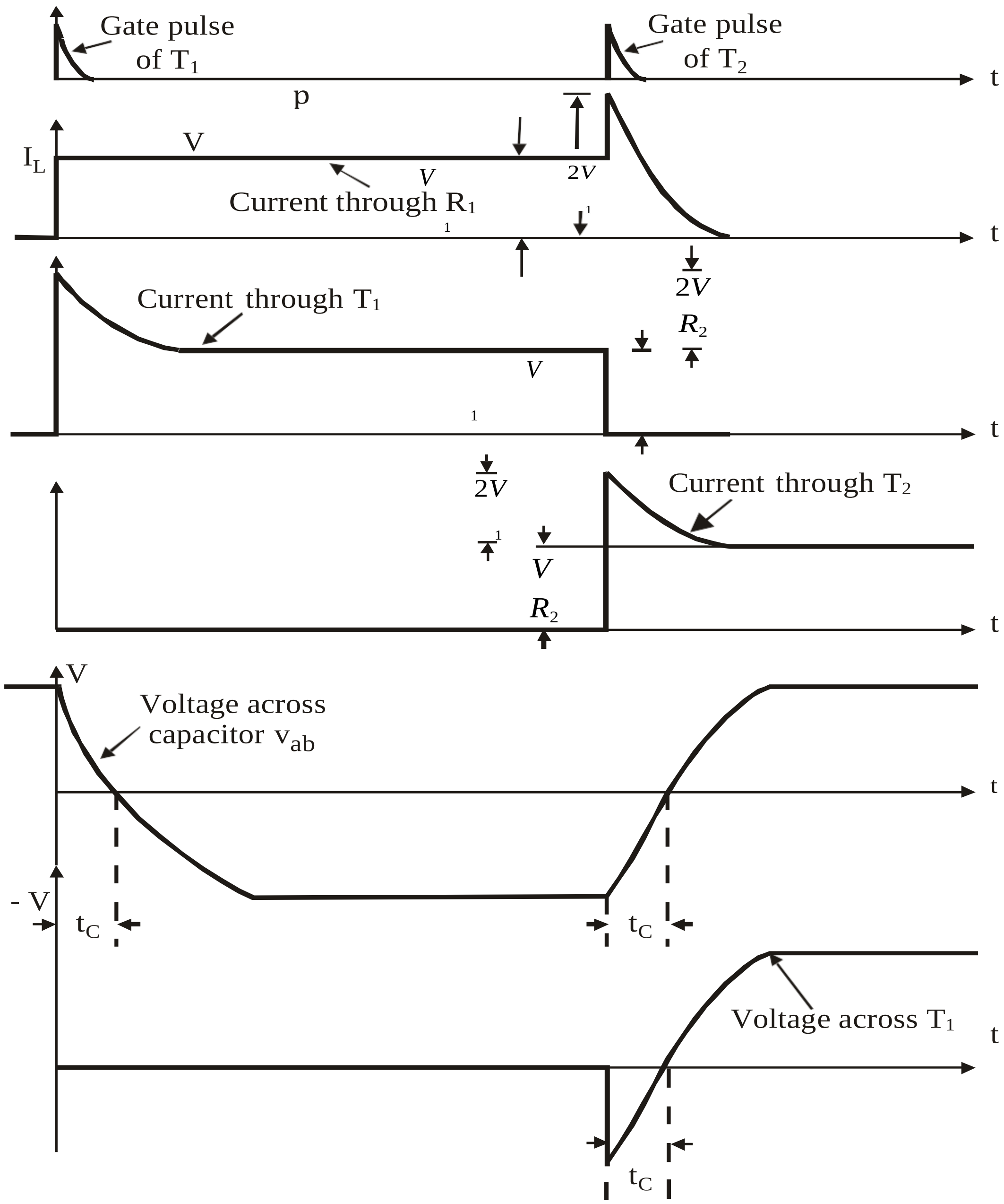
This time should be greater than the turn off time t_q of T_1.

Similarly when T_2 is commutated

$$t_c = 0.693 R_2 C$$

And this time should be greater than t_q of T_2.

Usually $R_1 = R_2 = R$



Gate pulse
of T_1
Gate pulse
of T_2
t
p
I_L
V
V
2V
Current through R_1
1
1
2V
R_2
Current through T_1
V
1
2V
Current through T_2
V
R_2
V
Voltage across
capacitor v_{ab}
- V
t_C
t_C
Voltage across T_1
t_C

Fig. 5.22

Problem 5.8: In the circuit shown in figure 1.23 the load resistances $R_1 = R_2 = R = 5\Lambda$ and the capacitance C = 7.5 μF, V = 100 volts. Determine the circuits turn off time t_c.

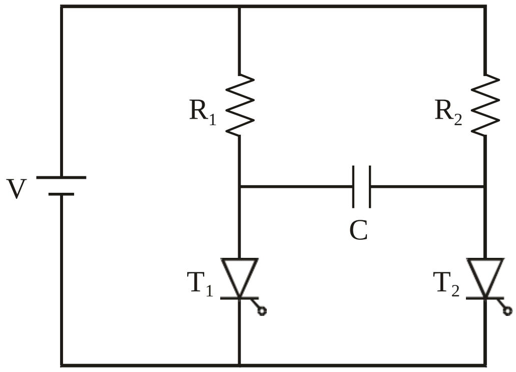


Fig. 5.23

Solution

The circuit turn-off time $t_c = 0.693$ RC seconds

$$t_c = 0.693 \times 5 \times 7.5 \times 10^{-6}$$

$$t_c = 26\mu \text{ sec}.$$

Problem 5.9: Calculate the values of R_L and C to be used for commutating the main SCR in the circuit shown in figure 1.24. When it is conducting a full load current of 25 A flows. The minimum time for which the SCR has to be reverse biased for proper commutation is 40μsec. Also find R_1, given that the auxiliary SCR will undergo natural commutation when its forward current falls below the holding current value of 2 mA.

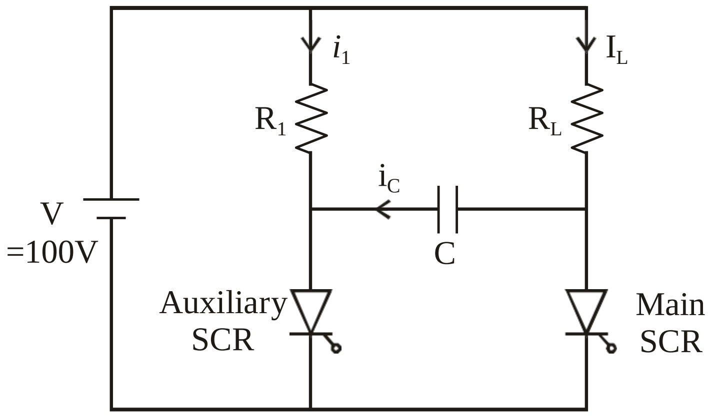


Fig. 5.24

Solution

In this circuit only the main SCR carries the load and the auxiliary SCR is used to turn off the main SCR. Once the main SCR turns off the current through the auxiliary SCR is the sum of the capacitor charging current i_c and the current i_1 through R_1, i_c reduces to zero after a time t_c and hence the auxiliary SCR turns off automatically after a time t_c, i_1 should be less than the holding current.

Given $\quad I_L = 25A$

That is $\quad 25A = \dfrac{V}{R_L} = \dfrac{100}{R_L}$

Therefore $\quad R_L = 4\Lambda$

$$t_c = 40\mu \text{ sec} = 0.693 R_L C$$

That is $\quad 40 \times 10^{-6} = 0.693 \times 4 \times C$

Therefore $\quad C = \dfrac{40 \times 10^{-6}}{4 \times 0.693}$

$$C = 14.43 \;\; F$$

$i_1 = \dfrac{V}{R_1}$ should be less than the holding current of auxiliary SCR.

Therefore $\quad \dfrac{100}{R_1}$ should be < 2mA.

Therefore $\quad R_1 > \dfrac{100}{2 \times 10^{-3}}$

That is $\quad R_1 > 50K\Lambda$

Impulse Commutation (CLASS D Commutation)

The circuit for impulse commutation is as shown in figure 5.25.

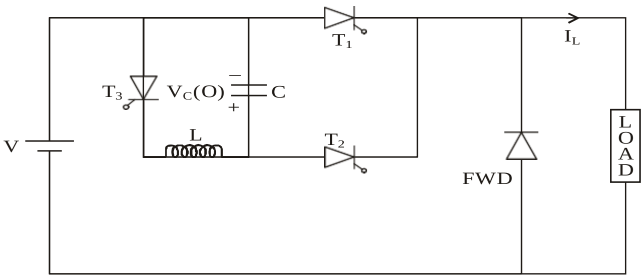


Fig. 5.25: Circuit for Impulse Commutation

The working of the circuit can be explained as follows. It is assumed that initially the capacitor C is charged to a voltage $V_C(O)$ with polarity as shown. Let the thyristor T_1 be conducting and carry a load current I_L. If the thyristor T_1 is to be turned off, T_2 is fired. The capacitor voltage comes across T_1, T_1 is reverse biased and it turns off. Now the capacitor starts charging through T_2 and the load. The capacitor voltage reaches V with top plate being positive. By this time the capacitor charging current (current through T_2) would have reduced to zero and T_2 automatically turns off. Now T_1 and T_2 are both off. Before firing T_1 again, the capacitor voltage should be reversed. This is done by turning on T_3, C discharges through T_3 and L and the capacitor voltage reverses. The waveforms are shown in figure 5.26.

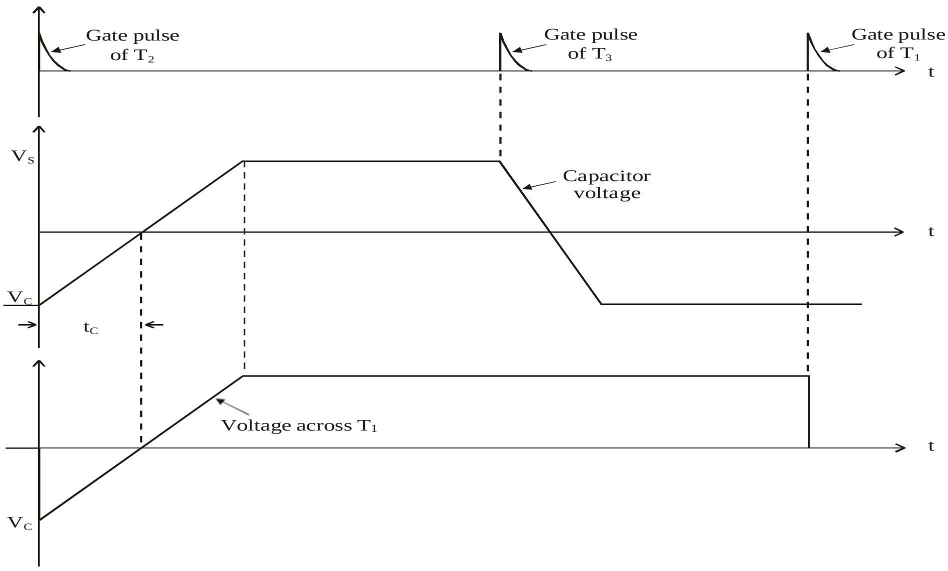


Fig. 5.26: Impulse Commutation – Waveforms of Capacitor Voltage, Voltage across T_1.

(i) Expression for Circuit Turn Off Time (Available Turn Off Time) t_c

t_c depends on the load current I_L and is given by the expression

$$V_C = \frac{1}{C}\int_0^{t_c} I_L dt$$

(assuming the load current to be constant)

$$V_C = \frac{I_L t_c}{C}$$

$$t_c = \frac{V_C C}{I_L} \text{ seconds}$$

For proper commutation t_c should be $> t_q$, turn off time of T_1.

Note:

- T_1 is turned off by applying a negative voltage across its terminals. Hence this is voltage commutation.
- t_c depends on load current. For higher load currents t_c is small. This is a disadvantage of this circuit.
- When T_2 is fired, voltage across the load is $V + V_C$; hence the current through load shoots up and then decays as the capacitor starts charging.

An Alternative Circuit for Impulse Commutation

Is shown in figure 5.27.

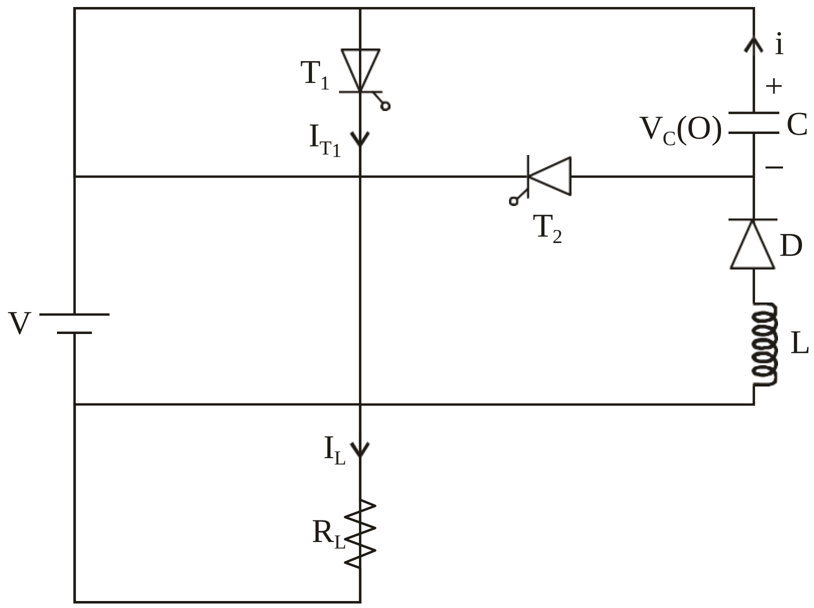


Fig. 5.27: Impulse Commutation – An Alternate Circuit

The working of the circuit can be explained as follows:

Initially let the voltage across the capacitor be $V_C(O)$ with the top plate positive. Now T_1 is triggered. Load current flows through T_1 and load. At the same time, C discharges through T_1, L and D (the current is 'i') and the voltage across C reverses i.e., the bottom plate becomes positive. The diode D ensures that the bottom plate of the capacitor remains positive.

To turn off T_1, T_2 is triggered; the voltage across the capacitor comes across T_1. T_1 is reverse biased and it turns off (voltage commutation). The capacitor now starts charging through T_2 and load. When it charges to V volts (with the top plate positive), the current through T_2 becomes zero and T_2 automatically turns off.

The related waveforms are shown in figure 5.28.

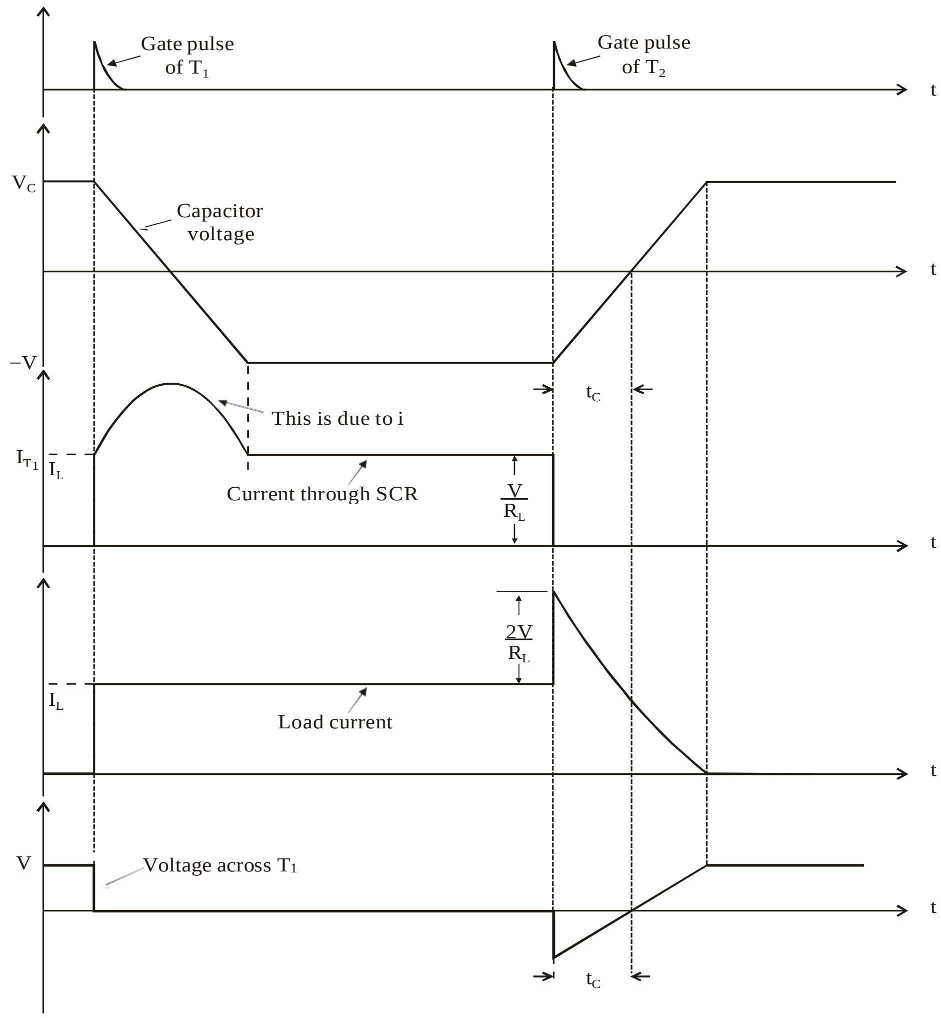


Fig. 5.28: Impulse Commutation – (Alternate Circuit) – Various Waveforms

Problem 5.10: An impulse commutated thyristor circuit is shown in figure 5.29. Determine the available turn off time of the circuit if V = 100 V, R = 10 Λ and C = 10 μF. Voltage across capacitor before T_2 is fired is V volts with polarity as shown.

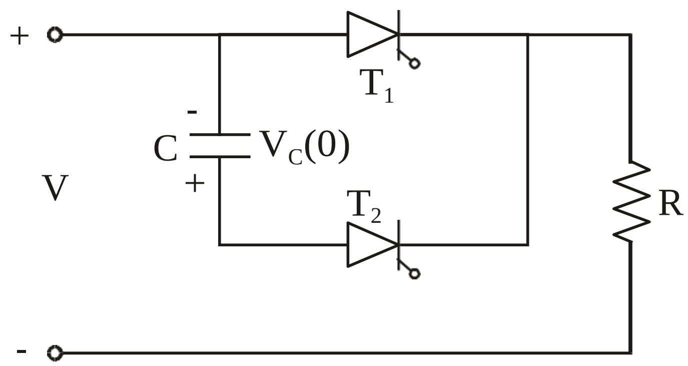


Fig. 5.29

Solution

When T_2 is triggered the circuit is as shown in figure 5.30.

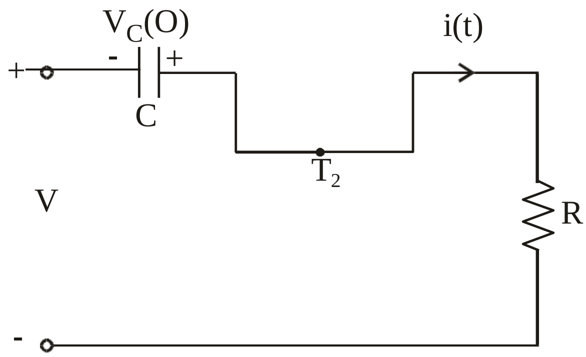


Fig. 5.30

Writing the transform circuit, we obtain

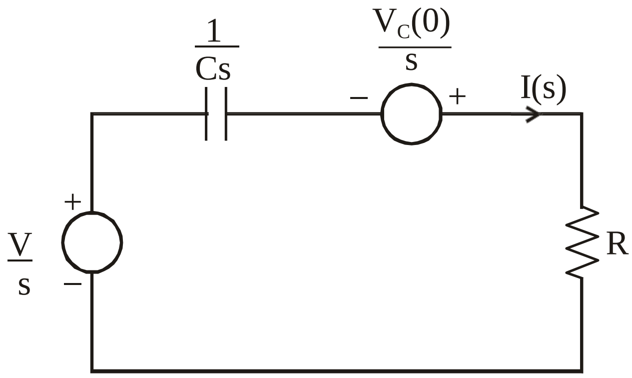


Fig. 5.31

We have to obtain an expression for capacitor voltage. It is done as follows:

$$I(S)=\frac{\frac{1}{s}\left(V+V_C(0)\right)}{R+\frac{1}{Cs}}$$

$$I(S)=\frac{C\left(V+V_C(0)\right)}{1+RCs}$$

$$I(S)=\frac{\left(V+V_C(0)\right)}{R\left(s+\frac{1}{RC}\right)}$$

Voltage across capacitor $\quad V_C(s)=I(s)\frac{1}{Cs}-\frac{V_C(0)}{s}$

$$V_C(s) = \frac{1}{RCs}\frac{V + V_C(0)}{\left(s + \frac{1}{RC}\right)} - \frac{V_C(0)}{s}$$

$$V_C(s) = \frac{V + V_C(0)}{s} - \frac{V + V_C(0)}{\left(s + \frac{1}{RC}\right)} - \frac{V_C(0)}{s}$$

$$V_C(s) = \frac{V}{s} - \frac{V}{s + \frac{1}{RC}} - \frac{V_C(0)}{s + \frac{1}{RC}}$$

$$v_c(t) = V\left(1 - e^{-t/RC}\right) - V_C(0)e^{-t/RC}$$

In the given problem $V_C(0) = V$

Therefore $v_c(t) = V\left(1 - 2e^{-t/RC}\right)$

The waveform of $v_c(t)$ is shown in figure 5.32.

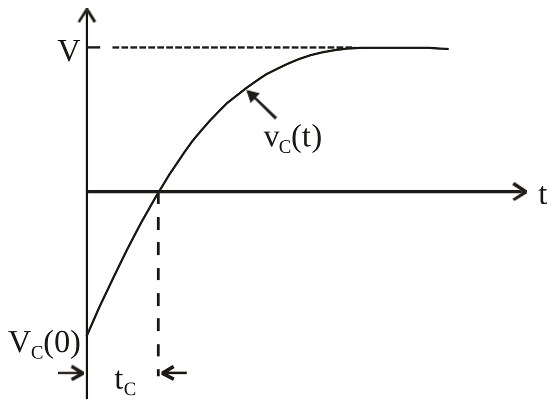


Fig. 5.32

At $t = t_c$, $v_c(t) = 0$

Therefore $0 = V\left(1 - 2e^{-t_c/RC}\right)$

$$1 = 2e^{-t_c/RC}$$

$$\frac{1}{2} = e^{-t_c/RC}$$

Taking natural logarithms

$$\log_e\left(\frac{1}{2}\right) = \frac{-t_c}{RC}$$

$$t_c = RC\ln(2)$$

$$t_c = 10\times10\times10^{-6}\ln(2)$$

$$t_c = 69.3\mu\ \text{sec}\ .$$

Problem 5.11: In the commutation circuit shown in figure 5.33. C = 20 μF, the input voltage V varies between 180 and 220 V and the load current varies between 50 and 200 A. Determine the minimum and maximum values of available turn off time t_c.

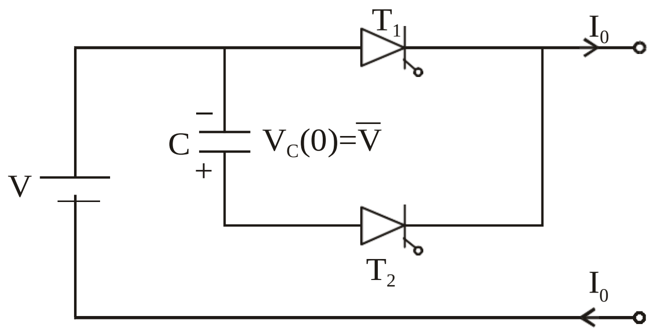


Fig. 5.33

Solution

It is given that V varies between 180 and 220 V and I_O varies between 50 and 200 A. The expression for available turn off time t_c is given by

$$t_c = \frac{CV}{I_O}$$

t_c is maximum when V is maximum and I_O is minimum.

Therefore $$t_{c\max} = \frac{CV_{\max}}{I_{O\min}}$$

$$t_{c\max} = 20\times10^{-6}\times\frac{220}{50} = 88\mu\ \text{sec}$$

and $$t_{c\min} = \frac{CV_{\min}}{I_{O\max}}$$

$$t_{c\min} = 20\times10^{-6}\times\frac{180}{200} = 18\mu\ \text{sec}$$

External Pulse Commutation (Class E Commutation)

Fig. 5.34: External Pulse Commutation

In this type of commutation an additional source is required to turn-off the conducting thyristor. Figure 5.34 shows a circuit for external pulse commutation. V_S is the main voltage source and V_{AUX} is the auxiliary supply. Assume thyristor T_1 is conducting and load R_L is connected across supply V_S. When thyristor T_3 is turned ON at $t=0$, V_{AUX}, T_3, L and C from an oscillatory circuit. Assuming capacitor is initially uncharged, capacitor C is now charged to a voltage $2V_{AUX}$ with upper plate positive at $t=\pi\sqrt{LC}$. When current through T_3 falls to zero, T_3 gets commutated. To turn-off the main thyristor T_1, thyristor T_2 is turned ON. Then T_1 is subjected to a reverse voltage equal to $V_S - 2V_{AUX}$. This results in thyristor T_1 being turned-off. Once T_1 is off capacitor 'C' discharges through the load R_L

Load Side Commutation

In load side commutation the discharging and recharging of capacitor takes place through the load. Hence to test the commutation circuit the load has to be connected. Examples of load side commutation are Resonant Pulse Commutation and Impulse Commutation.

Line Side Commutation

In this type of commutation the discharging and recharging of capacitor takes place through the supply.

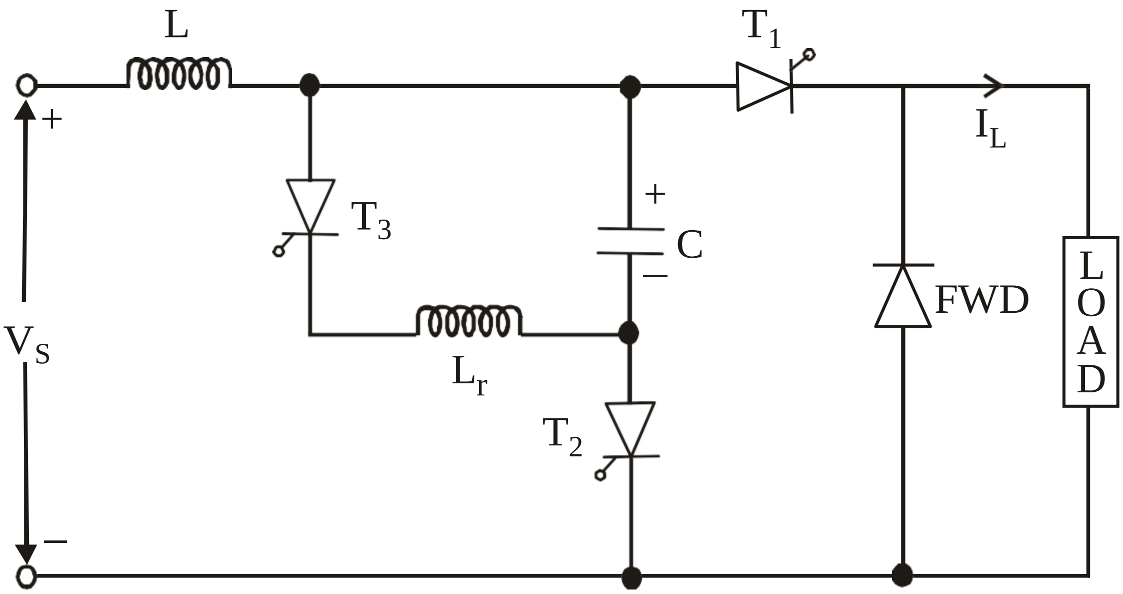


Fig.: 5.35 Line Side Commutation Circuit

Figure 5.35 shows line side commutation circuit. Thyristor T_2 is fired to charge the capacitor 'C'. When 'C' charges to a voltage of 2V, T_2 is self commutated. To reverse the voltage of capacitor to -2V, thyristor T_3 is fired and T_3 commutates by itself. Assuming that T_1 is conducting and carries a load current I_L thyristor T_2 is fired to turn off T_1. The turning ON of T_2 will result in forward biasing the diode (FWD) and applying a reverse voltage of 2V across T_1. This turns off T_1, thus the discharging and recharging of capacitor is done through the supply and the commutation circuit can be tested without load.

Recommended questions:

1. What are the two general types of commutation?
2. What is forced commutation and what are the types of forced commutation?
3. Explain in detail the difference between self and natural commutation.
4. What are the conditions to be satisfied for successful commutation of a thyristor
5. Explain the dynamic turn off characteristics of a thyristor clearly explaining the components of the turn off time.
6. What is the principle of self commutation?
7. What is the principle of impulse commutation?
8. What is the principle of resonant pulse commutation?
9. What is the principle of external pulse commutation?
10. What are the differences between voltage and current commutation?
11. What are the purposes of a commutation circuit?
12. Why should the available reverse bias time be greater than the turn off time of the Thyristor