(iv) ***Turn-on Time*** **(t_{on}):** This is the sum of the delay time, rise-time and spread time. This is typically of the order of 1 to 4 μs, depends upon the anode circuit parameters and the gate signal waveshapes.

The width of the firing pulse should, therefore, be more than 10 μs, preferably in the range of 20 to 100 μs. The amplitude of the gate-pulse should be 3 to 5 times the minimum gate current required to trigger the SCR.

From Fig. 2.10, it is noted that during rise-time, the SCR carries a large forward current and supports an appreciable forward voltage. This may result in high-instantaneous power dissipation creating local internal hot-spots which could destroy the device. It is, therefore, necessary to limit the rate of rise of current. Normally, a small inductor, called *di*/*dt* inductor is inserted in the anode circuit to limit the *di*/*dt* of the anode current.

The shadow area under the power-curve in Fig. 2.10 represents the switching loss of the device. This loss may be significant in high-frequency applications.

2.9 TURN-OFF MECHANISM (TURN-OFF CHARACTERISTIC)

Once the SCR starts conducting an appreciable forward current, the gate has no control on it and the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current. Process of turn-off is also called as commutation. Various methods used for turning off thyristors will be discussed in Section 2.10. However, if a forward voltage is applied immediately after reducing the anode current to zero, it will not block the forward voltage and will start conducting again, although it is not triggered by a gate pulse. It is, therefore, necessary to keep the device reverse biased for a finite period before a forward anode voltage can be reapplied.

The turn-off time of the thyristor is defined as the minimum time interval between the instant at which the anode current becomes zero, and the instant at which the device is capable of blocking the forward voltage. The turn-off time is illustrated by the waveforms shown in Fig. 2.11. The total turn-off time t_{off} is divided into two time intervals the reverse, recovery time t_{rr} and the gate recovery time t_{gr}.

At the instant t_1, the anode forward current becomes zero. During the reverse recovery time, t_1 to t_3, the anode current flows in the reverse direction. At the instant t_2, a reverse anode voltage is developed and the reverse recovery current continues to decrease. At t_3, junction J_1 and J_3 are able to block a reverse voltage. However, the thyristor is not yet able to block a forward voltage because carriers, called *trapped charges*, are still present at the junction J_2. During the interval t_3 to t_4, these carriers recombine. At t_4, the recombination is complete and therefore, a forward voltage can be reapplied at this instant. The SCR turn-off time is the interval between t_4 and t_1. In an SCR, this time varies in the range 10 to 100 μs. Thus, the total turn-off time (t_q) required for the device is the sum of the duration for which the reverse recovery current flows after the application of reverse voltage, and the time required for the recombination of all excess carriers in the

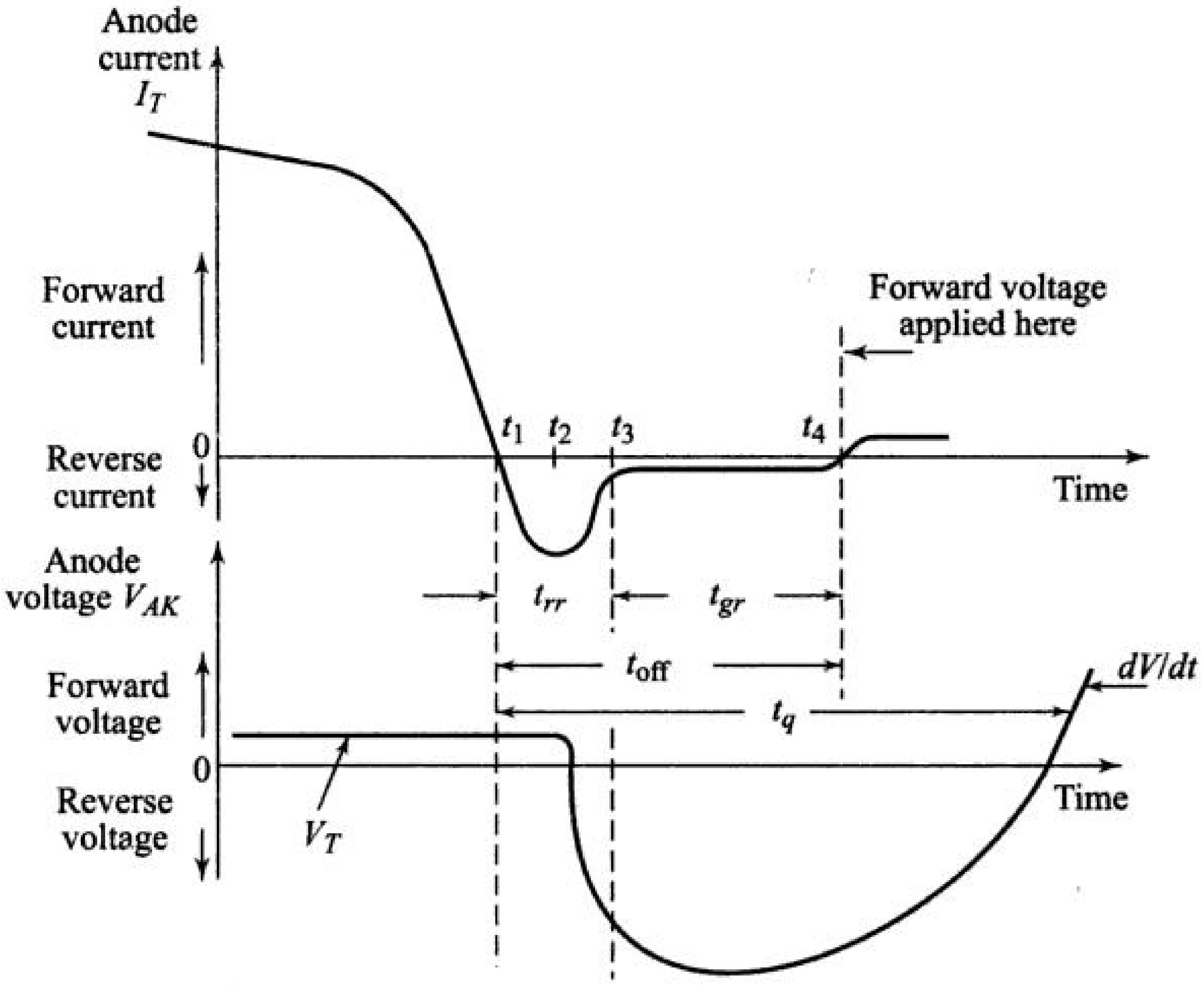


Fig. 2.11 *Waveforms during SCR turn-off*

inner two layers of the device. This may be noted that in case of highly inductive load circuit, the current cannot change abruptly at t_1. Also, the fast change in current at t_2 may give rise to high voltage surges in the inductance, which will then appears across the terminals of the thyristor.

In practical applications, the turn-off time required to the SCR by the circuit, called the circuit turn-off time t_q, must be greater than the device turn-off time t_{off} by a suitably safe margin, otherwise the device will turn-on at an undesired instant a process known as *commutation failure.* Thyristor having large turn-off time (50–100 μs) are called as slow switching or phase control type thyristors (or converter grade thyristors), and those having low turn-off time (10–50 μs) are called fast switching or inverter type thyristors. In high frequency applications, the required circuit turn-off time consumes an appreciable portion of the total cycle time and therefore, inverter grade thyristors must be used.

2.10 TURN-OFF METHODS

The term *commutation* basically means the transfer of current from one path to another. In thyristor circuits, this term is used to describe process of transferring current from one thyristor to another. As explained earlier, it is not possible for a thyristor to turn itself OFF; the circuit in which it is connected must reduce the thyristor current to zero to enable it to turn-off. 'Commutation' is the term to describe the methods of achieving this.

Commutation is one of the fundamental principles the use of thyristors for control purposes. A thyristor can only operate in two modes: it is either in the OFF state, i.e., open circuit, or in the ON state, i.e., short circuit. By itself it cannot control the level of current or voltage in a circuit. Control can only be achieved by variation in the time thyristors when switched ON and OFF, and commutation is central to this switching process. All thyristor circuits, therefore, involve the cyclic or sequential switching of thyristors. The two methods by which a thyristor can be commutated are as follows.

2.10.1 Natural Commutation

The simplest and most widely used method of commutation makes use of the alternating, reversing nature of a.c. voltages to effect the current transfer. We know that in a.c. circuits, the current always passes through zero every half cycle. As the current passes through natural zero, a reverse voltage will simultaneously appear across the device. This immediately turns-off the device. This process is called as *natural commutation* since no external circuit is required for this purpose. This method may use a.c. mains supply voltages or the a.c. voltages generated by local rotating machines or resonant circuits. The line commutated converters and inverters comes under this category.

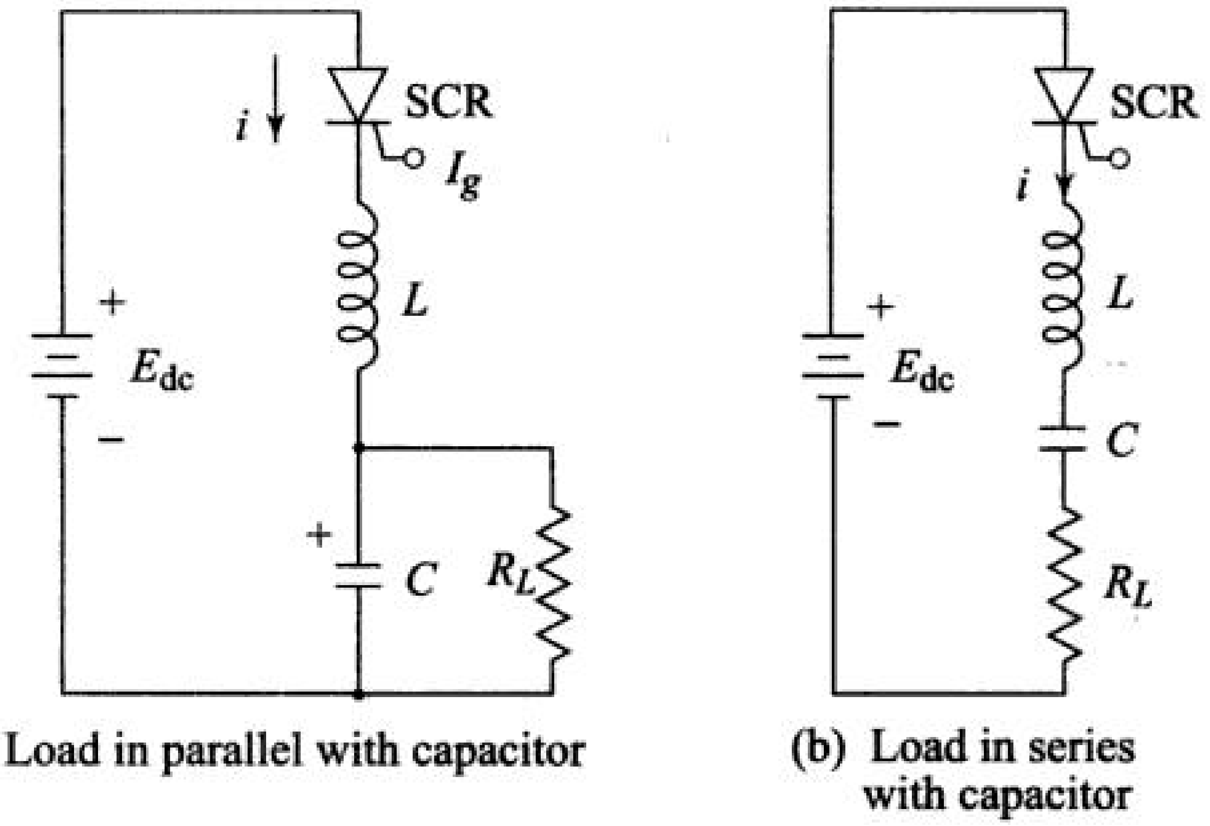
2.10.2 Forced Commutation

Once thyristors are operating in the ON state, carrying forward current, they can only be turned OFF by reducing the current flowing through them to zero for sufficient time to allow the removal of charged carriers. In case of d.c. circuits, for switching off the thyristors, the forward current should be forced to be zero by means of some external circuits. The process is called *forced commutation* and the external circuits required for it are known as commutation circuits. The components (inductance and capacitance) which constitute the commutating circuits are called as commutating components. A reverse voltage is developed across the device by means of a commutating circuit that immediately brings the forward current in the device to zero, thus turning off the device. Producing reliable commutation is a difficult problem to be tackled while designing chopper and inverter circuits. The most important stage in the designing process is choosing a forced turn-off method and deciding its components.

The classification of the methods of forced commutation is based on the arrangement of the commutating components and the manner in which zero current is obtained in the SCR. There are six basic methods of commutation by which thyristors may be turned OFF.

1. Class A-self Commutation by Resonating the Load This is also known as resonant commutation. This type of commutation circuit using *L-C* components-in-series-with the load are shown in Fig. 2.12. In Fig. 2.12(a), load R_L is in parallel with the capacitor and in Fig. 2.12(b) load R_L is in series with the

L–C circuit. In this process of commutation, the forward current passing through the device is reduced to less than the level of holding current of the device. Hence, this method is also known as the current commutation method. The waveforms of the thyristor voltage, current and capacitor voltages are shown in Fig. 2.13.



(a) Load in parallel with capacitor

(b) Load in series with capacitor

Fig. 2.12 *Class A commutation circuit*

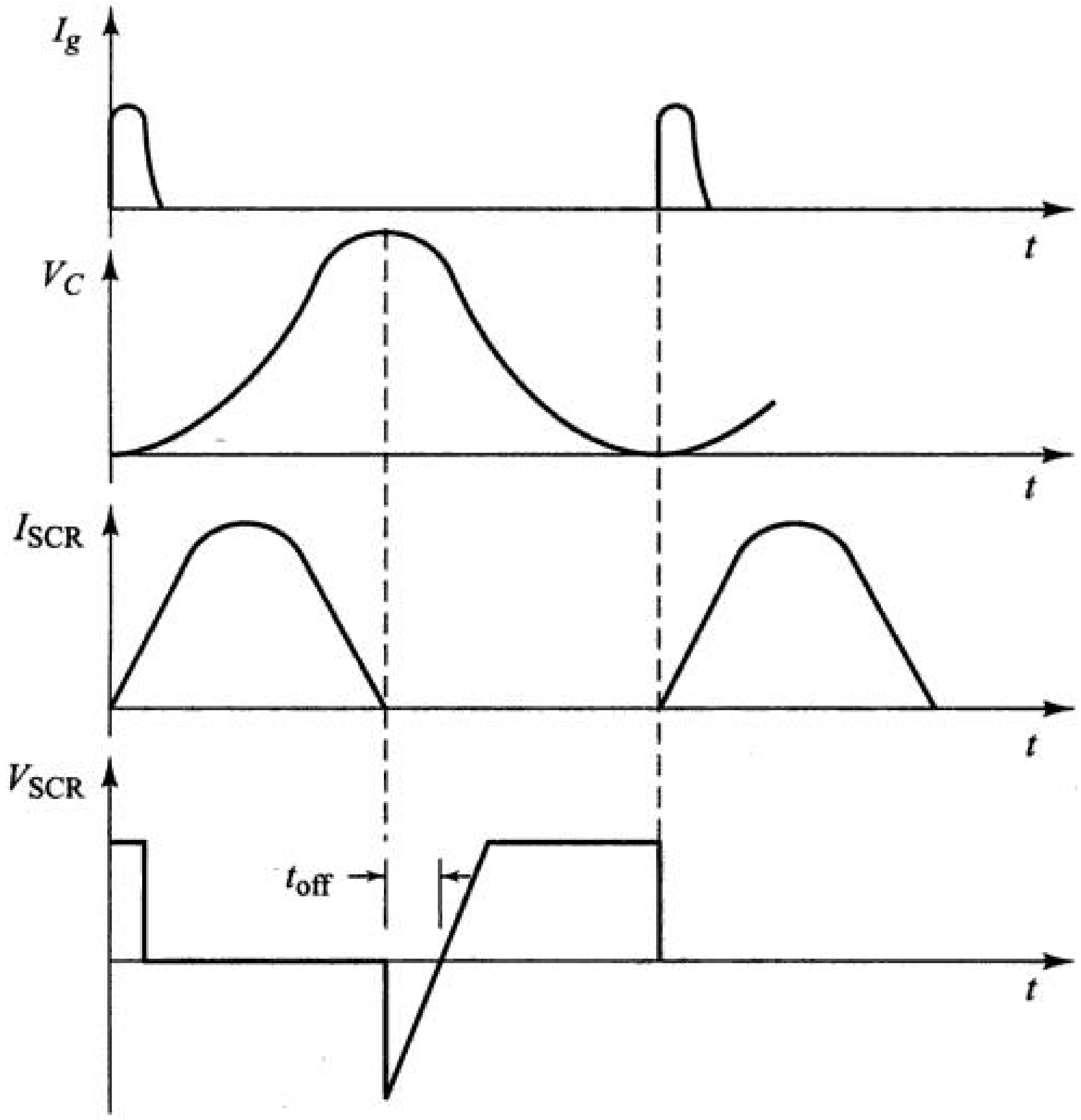
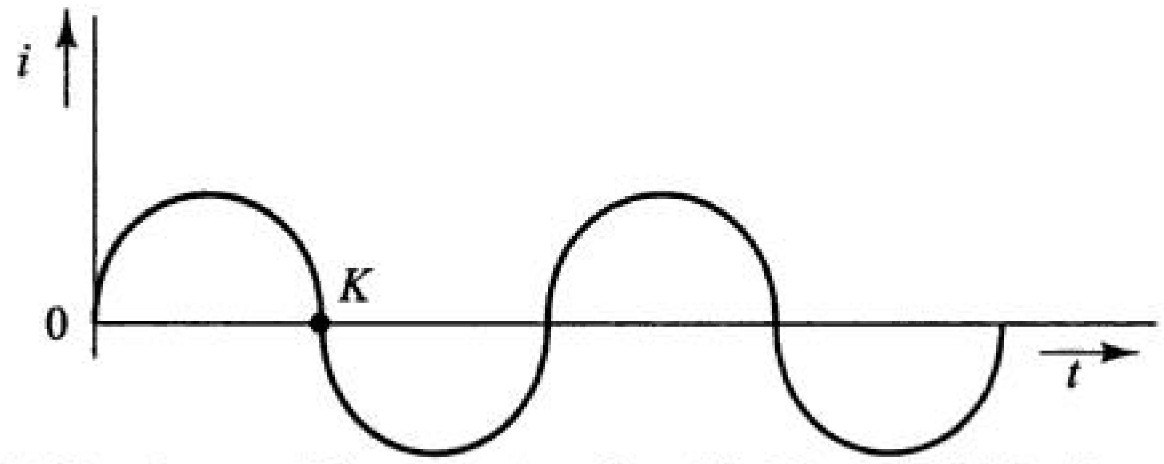
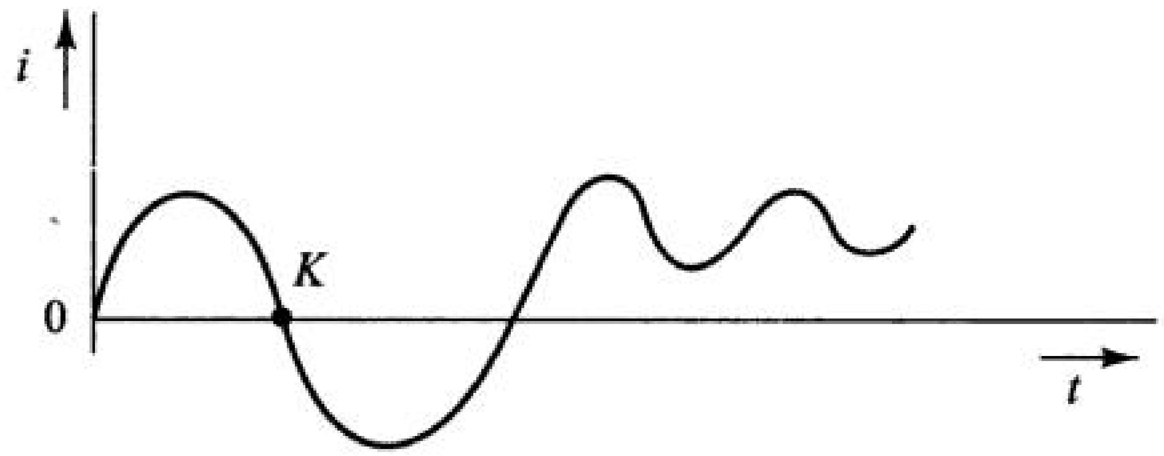


Fig. 2.13 *Voltages and currents in Class A (load is parallel with capacitor)*



(a) Waveforms of the current produced in Fig. 2.12(b) (series capacitor)



(b) Waveforms of the current produced in Fig. 2.12(a) (parallel capacitor)

Fig. 2.14

The load resistance R_L and the commutating components are so selected that their combination forms an underdamped resonant circuit. When such a circuit is excited by a d.c. source, a current of the nature shown in Fig. 2.14 will be obtained across the device. This current, as evident from its shape, has zero value at the point K where the device is automatically turned OFF. Beyond point K, the current is reversed in nature which assures definite commutation of the device. The thyristor when ON carries only the charging current of capacitor C which will soon decay to a valueless than the holding current of the device, when capacitor C is charged up to the supply voltage E_{dc}. This simultaneously switches off the thyristor. The time for switching off the device is determined by the resonant frequency which in turn depends on the values of the commutating components L and C, and the total load resistance.

This type of commutation circuits are most suitable for high frequency operation, i.e., above 1000 Hz, because of the need for an L–C resonant circuit which carries the full load current. This commutation circuit is used in series inverter.

Design Considerations

(a) Load in parallel with capacitor C Let us consider the resonant circuit of Fig. 2.12 (a). Let E_{dc} be the applied d.c. voltage, V be the load voltage, and i be the load current.

The circuit equation is

$$E_{dc} = L\frac{di}{dt} + V$$

and $$i = C\frac{dV}{dt} + \frac{V}{R}$$

By using Laplace transform, we can write

$$E_{dc}(s) - V(s) = S \cdot L\ I(s) \tag{2.15}$$

and $$I(s) = \frac{V(s)}{R} + S \cdot C \cdot V(s) \tag{2.16}$$

From Eq. (2.15), we can write

$$V(s) = E_{dc}(s) - SL\ I(s) \tag{2.17}$$

But $$E_{dc}(s) = \frac{E_{dc}}{S} \tag{2.18}$$

Substitute Eqs (2.17) and (2.18) in Eq. (2.16)

$$\therefore \quad I(s) = \frac{E_{dc}}{R \cdot S} - \frac{SLI(s)}{R} + SC\left[\frac{E_{dc}}{s} - SLI(s)\right]$$

$$I(s) + SL\frac{I(s)}{R} + S^2\ CLI(s) = \frac{E_{dc}}{R \cdot S} + \frac{E_{dc}SC}{S}$$

$$\therefore \quad I(s)\left[1 + \frac{SL}{R} + S^2CL\right] = \frac{E_{dc}}{S}\left[\frac{1}{R} + SC\right]$$

$$I(s)\left[\frac{R + LS + RCLS^2}{R}\right] = \frac{E_{dc}}{s}\left[\frac{1 + RCS}{R}\right]$$

$$I(s) = \frac{E_{dc}}{s}\left[\frac{1 + RCS}{R + LS + RCLS^2}\right]$$

$$I(s) = \frac{E_{dc}}{RLCS}\left[\frac{1 + RCS}{S^2 + \frac{1}{RC}S + \frac{1}{LC}}\right] \tag{2.19}$$

Taking inverse Laplace transform of Eq. (2.19), we get

$$i(t) = \frac{E_{dc}}{R}\left[1 + \frac{1}{\sqrt{1-\varepsilon^2}}\frac{W_n^2}{\varepsilon}e^{-t/RC}\sin(\omega t + \phi)\right]$$

where $$\varepsilon = \frac{1}{2R}\sqrt{\frac{L}{C}} \quad = \text{damping ratio}$$

$$W_n = \frac{1}{\sqrt{LC}} \quad = \text{undamped natural angular frequency.}$$

$$\omega = \omega_n \sqrt{1-\varepsilon^2}$$

or,

$$\omega = \frac{1}{\sqrt{LC}} \sqrt{1 - \frac{L}{4R^2C}} = \sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}$$

$$\phi = \tan^{-1} \frac{2RC\omega}{-\varepsilon} - \tan^{-1} \frac{\sqrt{1-\varepsilon^2}}{-\varepsilon} = \tan^{-1} 2RC\omega$$

If $i(t) = 0$ at $t = 0$,

$$\phi = -\sin^{-1} \frac{1}{A}$$

$$\therefore \quad i(t) = \frac{E_{dc}}{R}\left[1 + A\,e^{-t/2RC} \sin\left(\omega t - \sin^{-1}\frac{1}{A}\right)\right] \tag{2.20}$$

Now, load voltage from Eqs (2.15) and (2.16) can be written as

$$V(s) = \frac{E_{dc}}{LC\left(S^2 + \frac{1}{RC}S + \frac{1}{LC}\right)} \tag{2.21}$$

Taking inverse Laplace transform of Eq. (2.21), we get

$$V(t) = E_{dc}\,\frac{W_n}{\sqrt{1-\varepsilon^2}}\,e^{-t/2RC} \sin \omega t + E_{dc} \tag{2.22}$$

In this case, the triggering frequency of the thyristor must be less than W_n, so that the conduction cycle is completed.

(b) Load in series with capacitor C Let us consider the series resonant circuit of Fig. 2.12 (b). Let the thyristor be turned ON at $t = 0$ with the initial capacitor voltage zero.

The circuit equation is

$$E_{dc} = iR + L\,\frac{di}{dt} + \frac{1}{C}\int i\,dt \tag{2.23}$$

On differentiating and dividing by L, we get

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{i}{LC} = \frac{1}{L}\frac{d}{dt}E_{dc} \tag{2.24}$$

The corresponding homogeneous equation is of the second order and is as below.

$$\frac{d^2i}{dt^2} + \frac{R}{L}\cdot\frac{di}{dt} + \frac{1}{LC}i = 0 \tag{2.25}$$

The solution of this well known second order equation for under damped case is

$$i = e^{-\varepsilon t}\left[A_1 \cos \omega t + A_2 \sin \omega t\right] \tag{2.26}$$

where

$$\varepsilon = \frac{R}{2l} \tag{2.27}$$

and

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{2.28}$$

$$\omega = \omega_o \sqrt{1-\varepsilon^2} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{2.29}$$

When $i(0+) = i(0-) = 0$

$$A_1 = 0, \qquad A_2 = \frac{E_{dc}}{L}$$

This gives

$$i(t) = e^{-\frac{R}{2L}t}\left[\frac{E_{dc}}{\omega L} \sin \omega t\right] \tag{2.30}$$

This equation shows that the thyristor-current i goes to zero at

$$\omega t = \pi$$

or

$$t = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \tag{2.31}$$

Now,

$$\frac{di}{dt} = -\, e^{-\frac{\pi R}{2\omega L}} \left(\frac{E_{dc}}{l}\right)$$

Therefore, the capacitor voltage at the end of conduction, $V_c = E_{dc} - V_L$

where $V_L = L\,di/dt$

$$\therefore \qquad V_c = E_{dc}\left[1 + e^{-\pi R/2\omega L}\right] \tag{2.32}$$

Now, if V_0 is the initial-state voltage of the capacitor then Eq. (2.30) becomes

$$i(t) = e^{-(R/2L)t}\left[\frac{E_{dc} - V_0}{\omega L} \cdot \sin \omega t\right] \tag{2.33}$$

and

$$V_c = E_{dc} + e^{-\pi R/2\omega t}\left(E_{dc} - V_0\right) \tag{2.34}$$

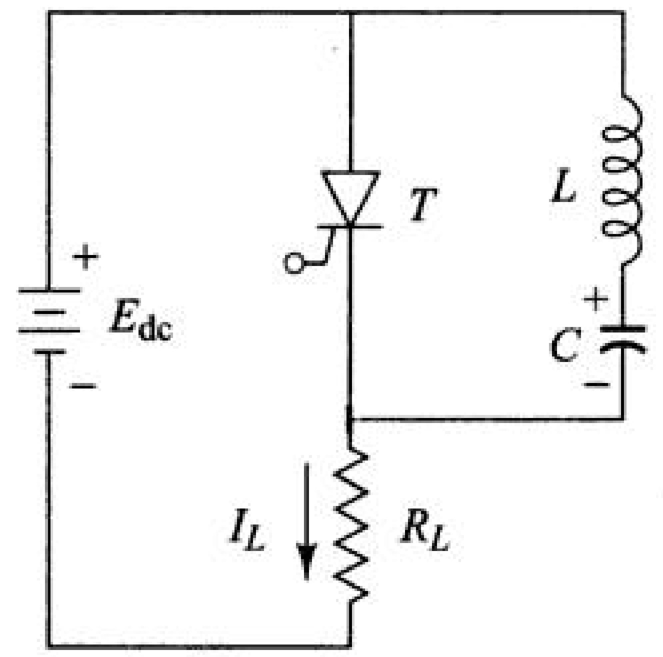
For $\omega > 0$, we now calculate the condition for underdamped.

$$\therefore \qquad \frac{1}{LC} - \frac{R^2}{4L^2} > 0 \qquad \text{i.e., } \frac{1}{LC} > \frac{R^2}{4L^2}$$

or

$$R < \sqrt{\frac{4L}{C}} \tag{2.35}$$

2. Class B—Self Commutation by an LC Circuit In this method, the *LC* resonating circuit is across the SCR and not in series with the load. The commutating circuit is shown in Fig. 2.15 and the associated waveforms are shown in Fig. 2.16.



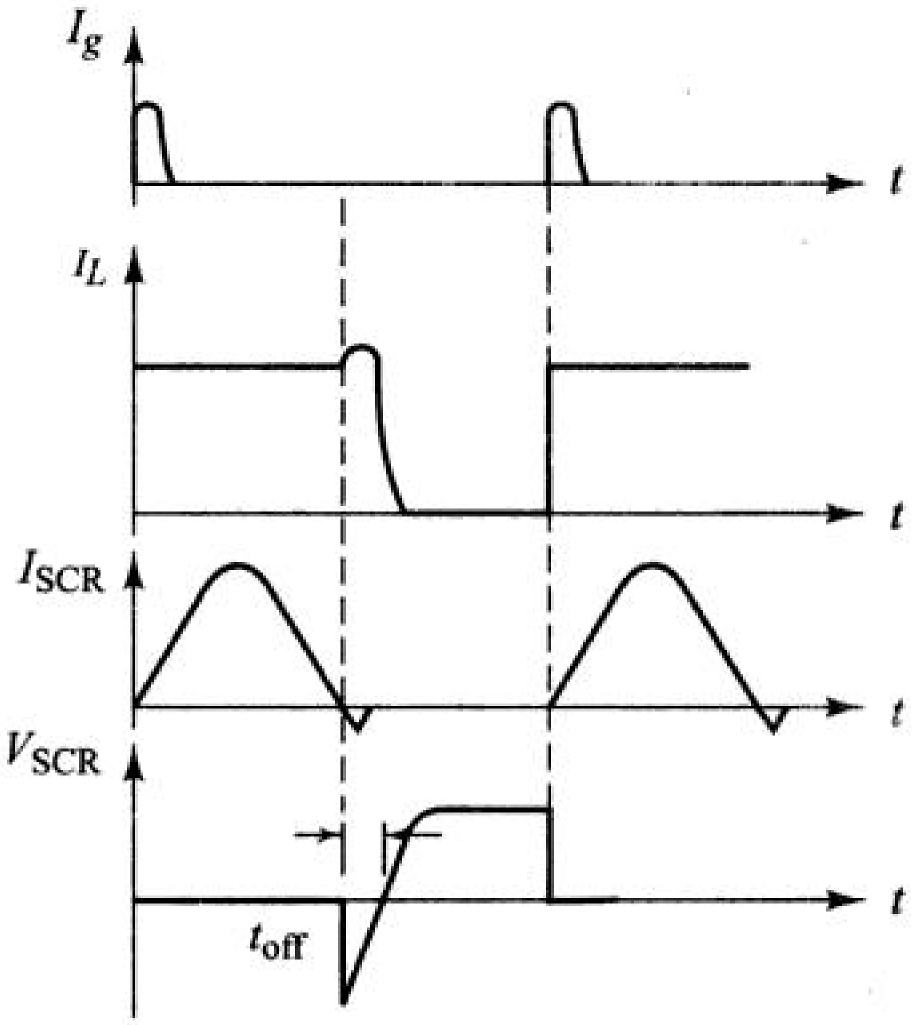


Fig. 2.15 *Class B commutation circuit* **Fig. 2.16** *Associated waveforms*

Initially, as soon as the supply voltage E_{dc} is applied, the capacitor *C* starts getting charged with its upper plate positive and the lower plate negative, and it charges up to the voltage E_{dc}.

When thyristor *T* is triggered, the circuit current flows in two directions: (1) The load current I_L flows through the path $E_{dc\,+} - T - RL - E_{dc\,-}$, and (2) Commutating current I_c.

The moment thyristor *T* is turned ON, capacitor C starts discharging through the path $C_+ - L - T - C-$. When the capacitor *C* becomes completely discharged, it starts getting charged with reverse polarity. Due to the reverse voltage, a commutating current I_C starts flowing which opposes the load current I_L. When the commutating current I_C is greater than the load current I_L, thyristor *T* becomes turned OFF. When the thyristor *T* is turned OFF, capacitor C again starts getting charged to its original polarity through *L* and the load. Thus, when it is fully charged, the thyristor will be ON again.

Hence, from the above discussion it becomes clear that the thyristor after getting ON for sometime automatically gets OFF and after remaining in OFF state for sometime, it again gets turned ON. This process of switching ON and OFF is a continuous process. The desired frequency of ON and OFF states can be obtained by designing the commutating components as per the requirement. The main application of this process is in d.c. chopper circuits, where the thyristor is required to be in conduction state for a specified duration and then to remain in the OFF state also for a specified duration. Morgan chopper circuit using a saturable reactor in place of the ordinary inductor L is a modified arrangement for this process. The circuit has the advantage of longer oscillation period and therefore of more assurance of commutation. In this Class B commutation method, the commutating component does not carry the load current. Both Class A and Class B turn-off circuits are self-commutating types, that is in both of these circuits the SCR turns-off automatically after it has been turned on.

Design Considerations

The circuit equations for the LC circuit are:

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = 0 \tag{2.36}$$

$$\therefore \quad L\frac{d^2i}{dt^2} + \frac{1}{C}i(t) = 0$$

Taking laplace transform of the above equation, $\left(S^2 L + \frac{1}{C}\right) I(s) = 0$

$$\therefore \quad i(t) = E_{dc}\sqrt{\frac{c}{L}}\sin\omega_0 t \tag{2.37}$$

where

$$\omega_0 = \sqrt{\frac{1}{LC}} \tag{2.38}$$

Therefore, the peak commutation current is

$$I_{C(\text{peak})} = E_{dc}\cdot\sqrt{C/L} \tag{2.39}$$

For this Class B commutation method, the peak discharge current of the capacitor is assumed to be twice the load-current I_L, and the time for which the SCR is reverse biased is approximately equal to one-quarter period of the resonant circuit.

Therefore,

$$I_{C(\text{peak})} = 2\,I_L = E_{dc}\sqrt{C/L} \tag{2.40}$$

And

$$t_{\text{off}} = \frac{\pi}{2}\sqrt{LC} \tag{2.41}$$

3. Class C—Complementary Commutation (Switching a Charged Capacitor by a Load Carrying SCR) The class C commutation circuit is shown in Fig. 2.17. In this method, the main thyristor (SCR T_1) that is to be commutated is connected in series with the load. An additional thyristor (SCR T_2), called the complementary thyristor is connected in parallel with the main thyristor.

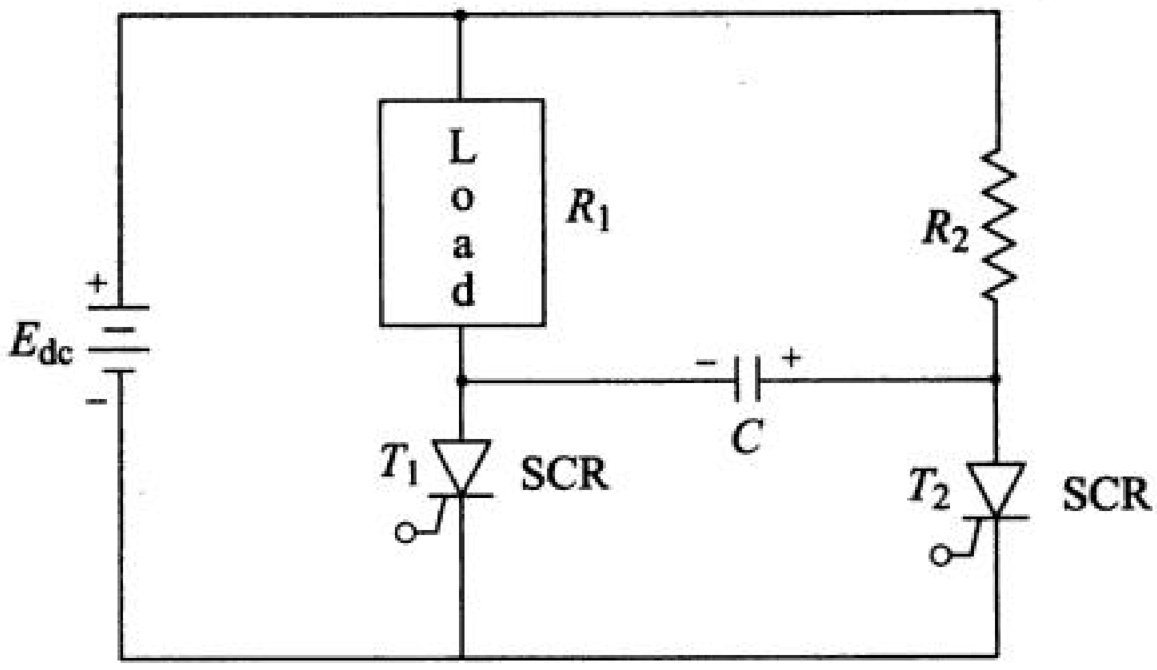


Fig. 2.17 *Class C–commutation circuit*

Circuit Operation

(a) Mode 0: [Initial-state of circuit] Initially, both the thyristors are OFF. Therefore, the states of the devices are –

$$T_1 \longrightarrow \text{OFF},\ T_2 \longrightarrow \text{OFF}, \quad \therefore \quad E_{c_1} = 0$$

(b) Mode 1: When a triggering pulse is applied to the gate of T_1, the thyristor T_1 is triggered. Therefore, two circuit current, namely, load current I_L and charging current I_C start flowing. Their paths are:

Load current I_L;

$$E_{dc}+ — R_1 — T_1 — E_{dc-}$$

Charging current I_C;

$$E_{dc}+ \ — R_2 — C_+ — C- \ — T_1 — E_{dc-}$$

Capacitor C will get charged by the supply voltage E_{dc} with the polarity shown in Fig. 2.17. The states of circuit components becomes

$$T_1 \longrightarrow \text{ON}, \quad T_2 \longrightarrow \text{OFF}, \quad E_{c_1} = E_{dc}$$

(c) Mode 2: When a triggering pulse is applied to the gate of T_2, T_2 will be turned on. As soon as T_2 is ON, the negative polarity of the capacitor C is applied to the anode of T_1 and simultaneously, the positive polarity of capacitor C is applied to the cathode. This causes the reverse voltage across the main thyristor T_1 and immediately turns it off.

Charging of capacitor C now takes place through the load and its polarity becomes reverse. Therefore, charging path of capacitor C becomes

$$E_{dc+} \ — R_1 — C_+ \ — C- \ — T_{2(a-k)} - E_{dc-}$$

Hence, at the end of Mode 2, the states of the devices are

$$T_1 \longrightarrow \text{OFF}, \quad T_2 \longrightarrow \text{ON}, \quad E_{c_1} = -E_{dc}$$

(d) Mode 3: Now, when thyristor T_1 is triggered, the discharging current of capacitor turns the complementary thyristor T_2 OFF. The state of the circuit at the end of this Mode 3 becomes

$$T_1 \longrightarrow \text{ON}, \quad T_2 \longrightarrow \text{OFF}, \quad E_{c_1} = E_{dc}$$

Therefore, this Mode 3 operation is equivalent to **Mode 1 operation.**

The waveforms at the various points on the commutation circuit are shown in Fig. 2.18. An example of this class of commutation is the well known McMurray–Bedford inverter (discussed in Chapter 9). With the aid of certain accessories, this class is very useful at frequencies below about 1000 Hz. Sure and reliable commutation is the other characteristic of this method.

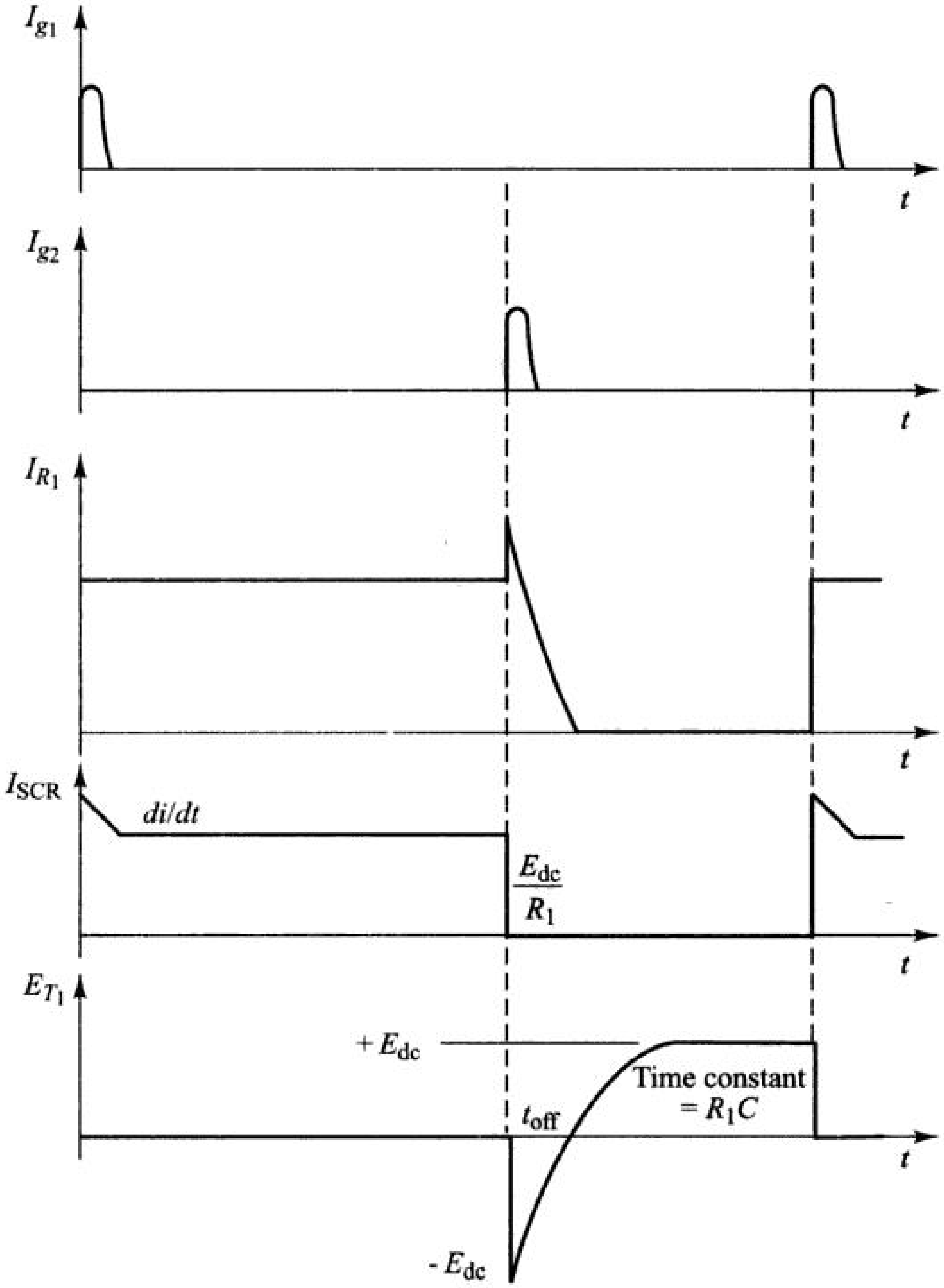


Fig. 2.18 *Circuit waveforms*

Design Considerations

As explained previously, when thyristor T_1 is conducting, capacitor C is charged to d.c. supply voltage E_{dc} through the resistor R_2. Now, when T_2 is triggered, a voltage twice the d.c. supply voltage E_{dc} is applied to the R_1C series circuit so that current through the circuit is,

$$i = \frac{2E_{dc}}{R_1} e^{-t/R_1C} \tag{2.42}$$

Therefore, the voltage across the thyristor T_1 is

$$E_{T_1} = E_{\mathrm{dc}} - i\,R_1 = E_{\mathrm{dc}} - \frac{2\,E_{\mathrm{dc}}}{R_1}\,e^{-t/R_1C}\cdot R_1 = E_{\mathrm{dc}}\left(1 - 2\,e^{-t/R_1C}\right)$$

For making thyristor T_1 OFF, the capacitor voltage must be equal to the voltage E_{t_1}.

$$\therefore \qquad E_c = E_{\mathrm{dc}}\left(1 - 2\,e^{-t/R_1C}\right) \tag{2.43}$$

Let $t = t_{\mathrm{off}}$ when $E_c = 0$.

$\therefore$ Equation (2.43) becomes

$$0 = E_{\mathrm{dc}}\left(1 - 2\,e^{-t_{\mathrm{off}}/R_1C}\right) \quad \text{or} \quad 0 = 1 - 2\,e^{-t_{\mathrm{off}}/R_1C} \tag{2.44}$$

$$\therefore \qquad t_{\mathrm{off}} = 0.6931\,R_1C \tag{2.45}$$

$$\text{or} \qquad C = 1.44\,\frac{t_{\mathrm{off}}}{R_1} \tag{2.46}$$

So, from Eq. (2.45), R_1 and C must be such that the turn-off time of SCR T_1, t_{off}, is satisfied.

The maximum allowable $\frac{\mathrm{d}V}{\mathrm{d}t}$ rating for SCR T_1 may be obtained from the SCR T_1 data sheet.

The maximum $\frac{\mathrm{d}V}{\mathrm{d}t}$ across T_1 using the commutating components is given by

$$\frac{\mathrm{d}V}{\mathrm{d}t}_{(\max)} > \frac{2\,E_{\mathrm{dc}}}{R_1C} \tag{2.47}$$

4. Class D—Auxiliary Commutation (An Auxiliary SCR Switching a Charged Capacitor) Figure 2.19 shows the typical Class D commutation circuit. In this commutation method, an auxiliary thyristor (T_2) is required to commutate the main thyristor (T_1), Assuming ideal thyristors and the lossless components, then the waveforms are as in Fig. 2.20. Here, inductor L is necessary to ensure the correct polarity on capacitor C.

Thyristor T_1 and load resistance R_L form the power circuit, whereas L, D and T_2 form the commutation circuit.

Circuit Operations

(a) Mode 0: [Initial Operation] When the battery E_{dc} is connected, no current flows as both thyristors are OFF. Hence, initially, the state of the circuit components becomes

$$T_1 \longrightarrow \text{OFF}, \quad T_2 \longrightarrow \text{OFF}, \quad E_C = 0$$

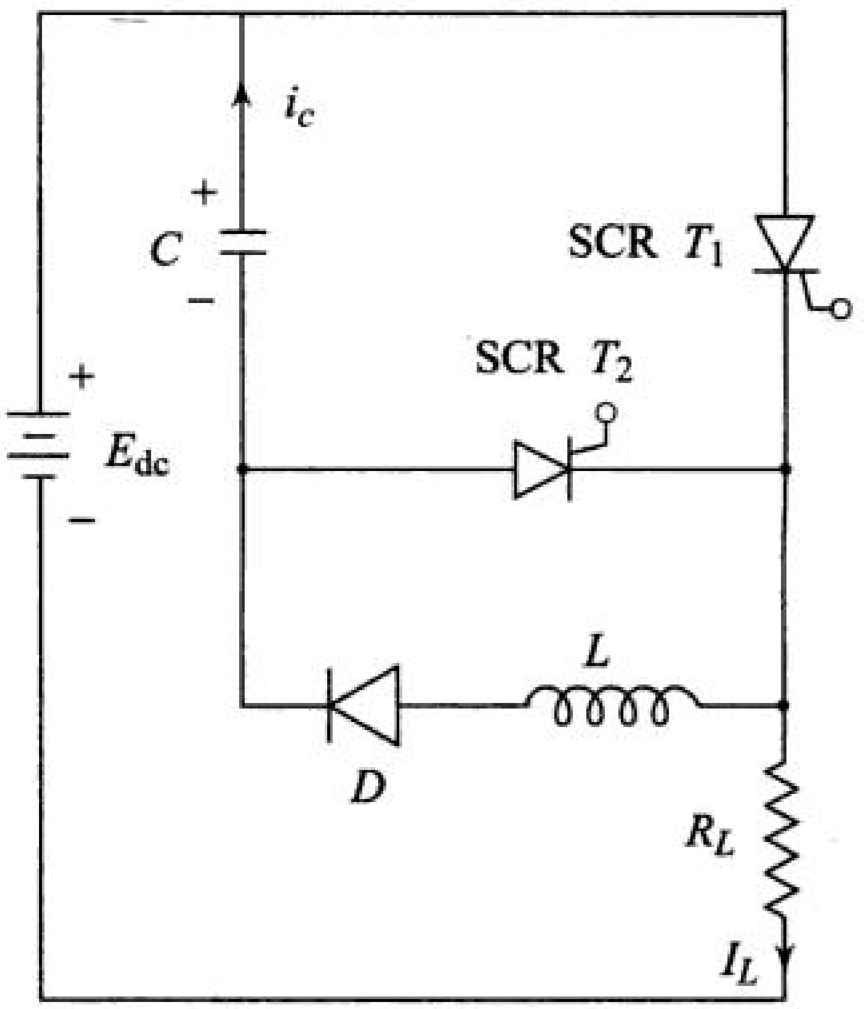


Fig. 2.19 *Class D commutation circuit*

(b) Mode 1: Initially, SCR T_2 must be triggered first in order to charge the capacitor C with the polarity shown. This capacitor C has the charging path E_{dc+} —C_+ —C_- —T_2 —R_L—E_{dc-}. As soon as capacitor C is fully charged, SCR T_2 turns-off. This is due to the fact that, as the voltage across the capacitor increases, the current through the thyristor T_2 decreases since capacitor C and thyristor T_2 form the series circuit.

Hence the state of circuit components at the end of Mode 1 becomes,

$T_1 \longrightarrow$ OFF, $T_2 \longrightarrow$ OFF, $E_C = E_{dc}$

(c) Mode 2: When thyristor T_1 is triggered, the current flows in two paths:

(a) Load current I_L flows through E_{dc+} —T_1—R_L—E_{dc-}

(b) Commutation current (Capacitor-discharges through) flows through C_+ —T_1—L—D—C_-.

After the capacitor C has completely discharged, its polarity will be reversed, i.e., its upper plate will acquire negative charge and the lower plate will acquire positive charge. Reverse discharge of capacitor C will not be possible due to the blocking diode D.

Therefore, at the end of Mode 2, the state of the circuit components becomes

$$T_1 \longrightarrow \text{ON}, \quad T_2 \longrightarrow \text{OFF}, \quad E_C = -E_{dc}$$

(d) Mode 3: When the thyristor T_2 is triggered, capacitor C starts discharging through the path C_+—$T_{2_{(A-K)}}$ — $T_{1_{(k-A)}}$—C_-. When this discharging current (commutating current I_C) becomes more than the load current I_L, thyristor T_1 gets OFF.

Therefore, at the end of Mode 3, the state of circuit component becomes

$$T_1 \longrightarrow \text{OFF}, \quad T_2 \longrightarrow \text{ON}$$

Again, capacitor C will charge to the supply voltage with the polarity shown and hence SCR T_2 gets OFF. Therefore, thyristors T_1 and T_2 both get OFF, which is equivalent to Mode 0 operation.

This type of commutation circuit is very versatile as both time ratio and pulse width regulation is readily incorporated. The commutation energy may readily be transferred to the load and so high efficiency is possible. This method is used in Jone's chopper circuit.

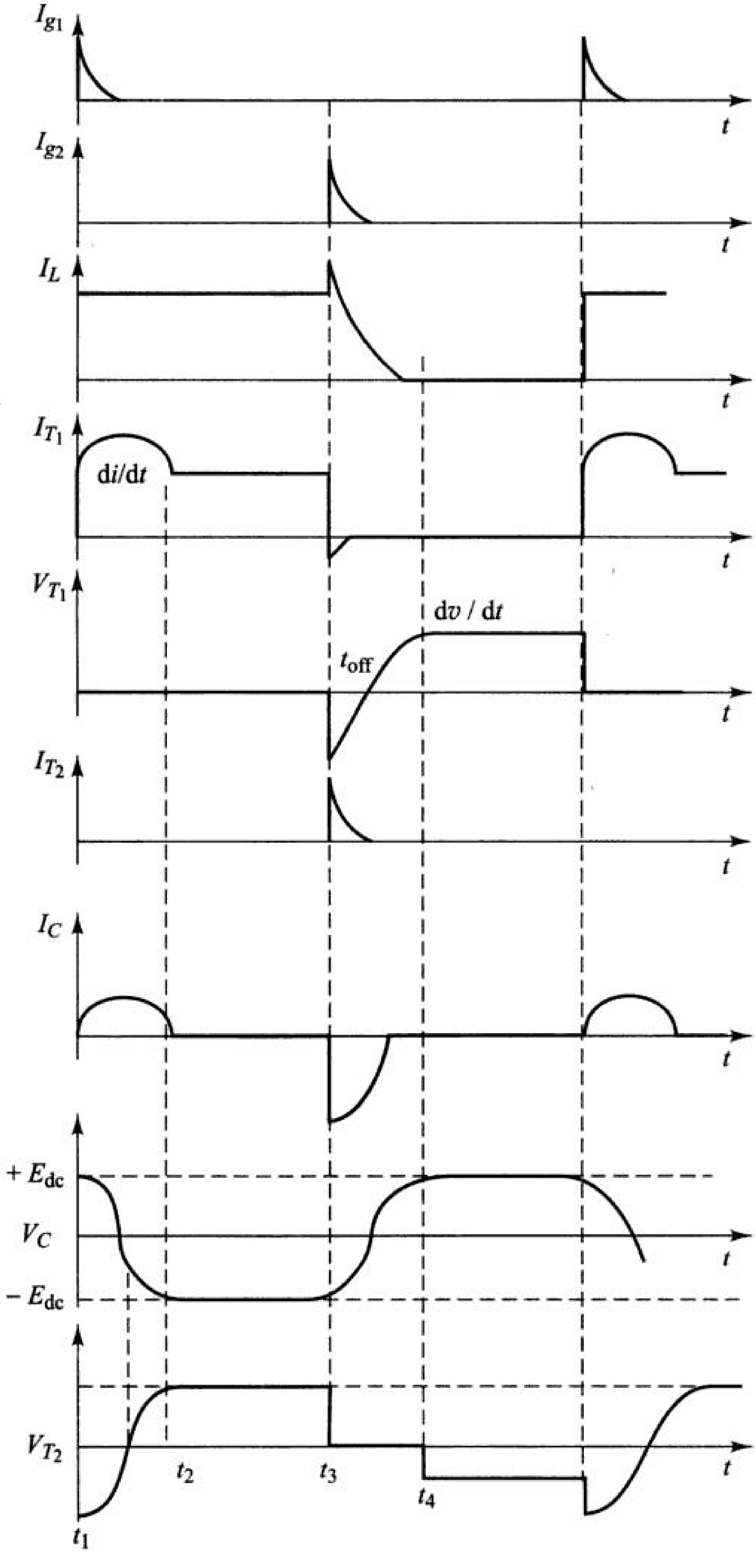


Fig. 2.20 *Associated waveforms*

Design Considerations

(a) Design of commutating capacitor The magnitude of the commutating capacitor is dependent on the following circuit parameters:

(i) Maximum load current to be commutated

(ii) Turn-off time of SCR, t_{off}

(iii) The battery voltage E_{dc}

The turn-off time t_{off}, of SCR T_1 is known from the manufacturer's data sheet. The capacitor voltage changes from $-E_{\text{dc}}$ to 0 during turn-off time, t_{off}. Assuming load current, I_L, remains constant during turn-off time, t_{off},

$$C\,E_{\text{dc}} = I_L\,t_{\text{off}} \quad \therefore \; C = \frac{I_L\,t_{\text{off}}}{E_{\text{dc}}} \tag{2.48}$$

(b) Designing of commutating inductor L The design of the inductor L is actually dependent on two contradictory criteria as follows:

(i) The acceptable maximum capacitor current, I_C, when thyristor T_1 is fired.

(ii) The time interval $(t_2 - t_1)$ during which capacitor voltage must reset to correct polarity for commutating SCR T_1.

Since the capacitor current (I_C) is an oscillatory current through SCR T_1, L, D, and C when SCR T_1 is triggered, therefore the peak value of current I_C is given by the expression,

$$I_{C_{(\text{peak})}} = \frac{E_{\text{dc}}}{W_r L} \tag{2.49}$$

where W_r = oscillating frequency = $\dfrac{1}{\sqrt{LC}}$ rad/sec. $\quad$ (2.50)

Substituting Eq. (2.50) in Eq. (2.49), we get

$$I_{C_{(\text{peak})}} = E_{\text{dc}}\sqrt{\frac{C}{L}} \tag{2.51}$$

Also, periodic time during oscillation T_r, is given by

$$T_r = \frac{2\pi}{W_r} = 2\,(t_1 - t_2) \tag{2.52}$$

Now, let $I_{L_{(\text{max})}}$ be the maximum current through SCR T_1. From Eq. (2.51),

$$E_{\text{dc}}\sqrt{\frac{C}{L}} \le I_{L_{(\text{max})}}$$

or

$$L \ge C.\left(\frac{E_{\text{dc}}}{I_{L_{(\text{max})}}}\right)^2 \tag{2.53}$$

5. Class E—External Pulse Commutation In Class E commutation method, the reverse voltage is applied to the current carrying thyristor from an external pulse source. A typical Class E commutation circuit is shown in

Fig. 2.21 and the associated waveforms are shown in Fig. 2.22. Here, the commutating pulse is applied through a pulse-transformer which is suitably designed to have tight coupling between the primary and secondary. It is also designed with a small air gap so as not to saturate when a pulse is applied to its primary. It is capable of carrying the load-current with a small voltage drop compared to the supply voltage. When the commutation of T_1 is desired, a pulse of duration equal to or slightly greater than the turn-off time specification of the thyristor is applied.

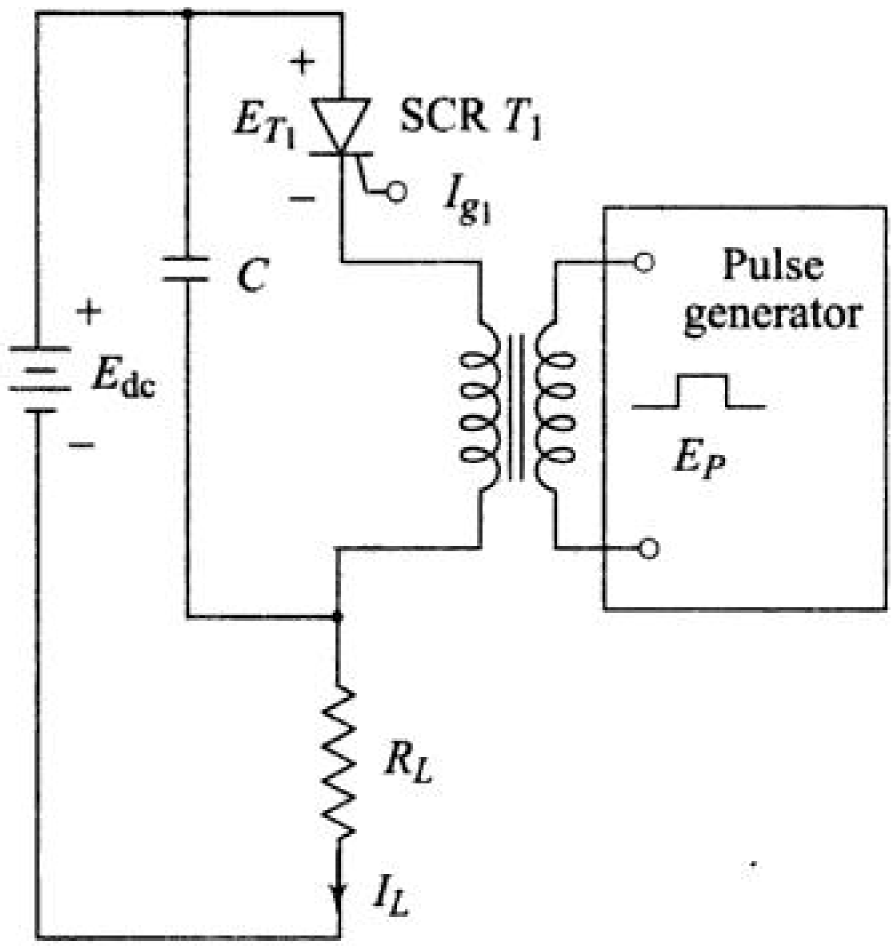


Fig. 2.21 *Class E commutation circuit*

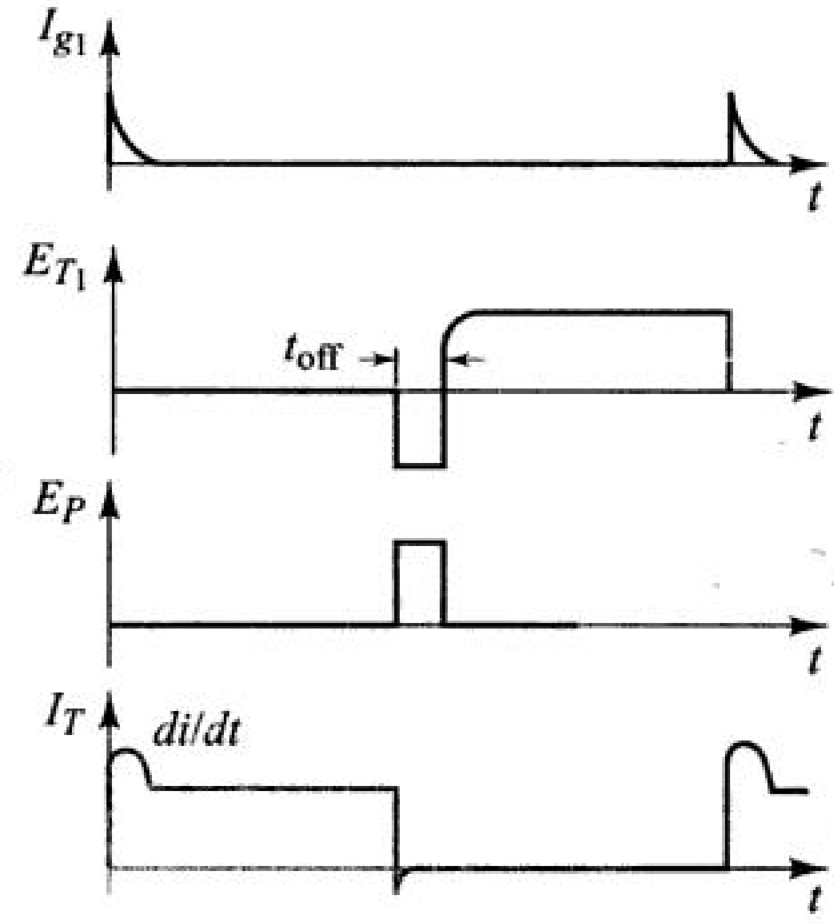


Fig. 2.22 *Associated waveforms*

When the SCR T_1 is triggered, current flows through the load R_L and the pulse transformer. When a pulse of voltage E_P from the pulse-generator is applied to the primary of the pulse transformer, the voltage induced in the secondary appears across thyristor T_1 as a reverse voltage ($-E_P$) and turn it off. Since the induced pulse is of high frequency, the capacitor offers almost zero impedance. After T_1 is turned off, the load current decays to zero. Earlier to the commutation, the capacitor voltage remains at a small value of about 1 V.

This type of commutation method is capable of very high efficiency as minimum energy is required and both time ratio and pulse width regulation are easily incorporated. However, equipment designers have neglected this class for the designing of power circuits.

6. Class F—a.c. Line Commutation A typical line commutated circuit is shown in Fig. 2.23 and its associated waveforms are shown in Fig. 2.24. If the supply is an alternating voltages, load current will flow during the positive half cycle. During the negative half cycle, the SCR will turn-off due to the negative polarity across it. The duration of the half cycle must be longer than the turn-off time of the SCR. The maximum frequency at which this circuit can operate depends on the turn-off time of SCR.

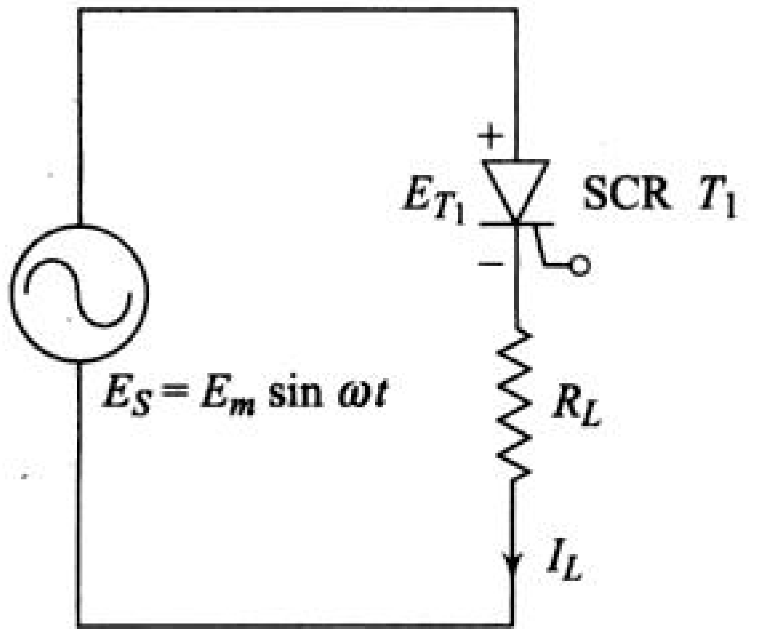


Fig. 2.23 *Class F commutation circuit*

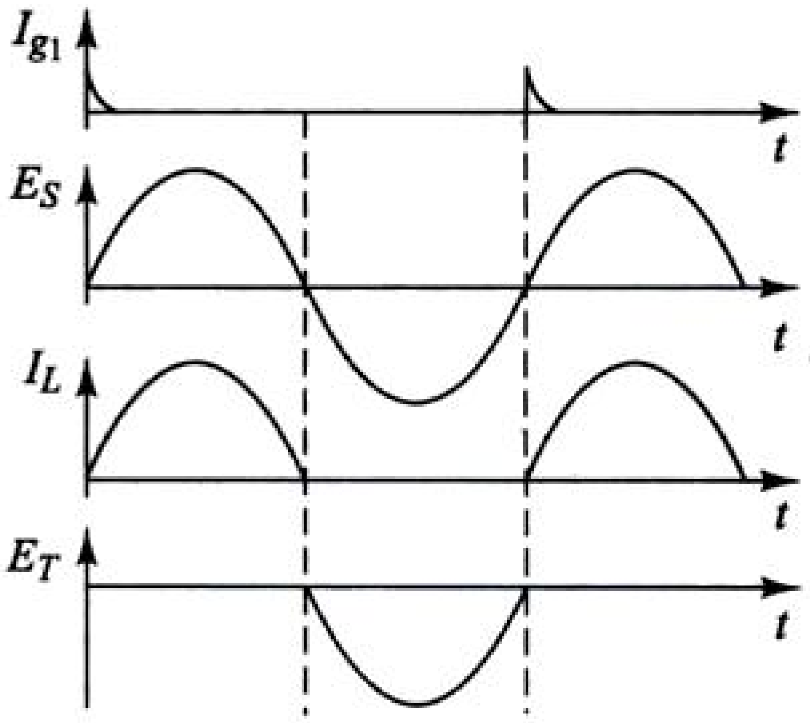


Fig. 2.24 *Associated waveforms*

SOLVED EXAMPLES

Example 2.9 For the Class *C* commutation circuit of Fig. 2.17, the d.c. source voltage $E_{dc} = 120$ V and current through R_1 and $R_2 = 20$ A. The turn-off time of both the SCRs is 60 µs. Calculate the value of commutating capacitance *C* for successful commutation.

Solution: The resistances $R_1 = R_2 = \frac{E_{dc}}{I} = \frac{120}{20} = 6$ W

Now, we have the relation for *C* for successful commutation as

$$C = 1.44 \,.\, \frac{t_{off}}{R_1} = 1.44 \times \frac{60 \times 10^{-6}}{6} = 14.4\ \mu F.$$

Example 2.10 For the Class *D* commutation circuit of Fig. 2.19, compute the value of the commutations capacitor *C* and commutating inductor *L* for the following data:

$E_{dc} = 50V, I_{L(max)} = 50$ A, t_{off} of $SCR_1 = 30$ µs

Chopping frequency $f = 500$ Hz and the load voltage variation required is 10 to 100%.

Solution: For reliable operation, let us assume 50% tolerance on turn-off time of SCR_1.

$$\therefore \qquad t_{off} = \left(30 + \frac{50}{100} \times 30\right) = 45 \mu s$$

Now, we have the relation for the commutating capacitor, *C* as

$$C = \frac{I_L\, t_{off}}{E_{dc}} = \frac{50 \times 45 \times 10^{-6}}{50} = C = 45\ \mu F.$$

The resetting time for capacitor voltage could be reduced by decreasing the value of *L*, but the peak capacitor current would increase as seen from Eq. (2.51). A large resetting time would limit the minimum voltage available at the load, which means the range of voltage available at the load is reduced.

Therefore, the minimum load voltage available is given by

$$V_{0(\min)} = \frac{t_1 - t_2}{T} E_{dc}$$

where t is chopping time period, or

$$V_{0(\min)} = \frac{\pi\sqrt{LC}}{T} E_{dc}$$

$$\therefore \qquad L \le \left(\frac{V_{0_{(\min)}}}{E_{dc}}\right)^2 \frac{T^2}{\pi^2 C} \qquad \text{(i)}$$

Given $\qquad V_{0(\min)} = 10\%(50) = 5\text{ V}$

$$T = \frac{1}{f} = 2 \times 10^{-3}\text{ s}$$

$$\therefore \qquad L \le \frac{(2\times10^{-3})^2}{\pi^2 \times 45 \times 10^{-6}} \times \left(\frac{5}{50}\right)^2 \quad \text{or} \quad L \le 90\ \mu\text{H}$$

Also, we have the relation

$$L \ge C\left(\frac{E_{dc}}{I_{L_{(\max)}}}\right)^2 \quad \text{or} \quad L \ge 45 \times 10^{-6}\left(\frac{50}{50}\right)^2$$

or $\qquad L \ge 45\ \mu\text{H}$

Hence, the range of commutating inductor is 45 μH < L < 90 μH

The choice of lower value of L would allow a larger voltage variation at the load.

2.11 THYRISTOR RATINGS

All semiconductor devices have definite limits to their capability and exceeding these even for short times will result in failure, loss of control, or irreversible deterioration. All thyristors, therefore, have to be used within their limits and this must include extreme conditions as may exist during circuit faults and it must take into account load, supply system, temperature and environmental variations. If extreme conditions are not precisely known and cannot be calculated, then appropriate safety margins have to be chosen to allow for the unknown factors. Correct safety margins can only be decided from practical operating experience. Therefore, the reliable operation of the device can be ensured only if its ratings are not exceeded under all operating conditions. The objective of this section is to discuss the various SCR ratings.

2.11.1 Voltage Ratings

It is essential that the voltage capability of a thyristor is not exceeded during operation even for a very short period of time. Therefore, the voltage rating of the device should be high enough to withstand anticipated voltage transients as