5

Thyristor Commutation

5.1 INTRODUCTION

Thyristor being a switching device, it is required to turn it *on* and *off* according to the requirement. During turning on of a thyristor, forward conduction of the thyristor starts while the turn off ceases this forward conduction and even the reapplication of the positive voltage to anode will not cause current flow through it till proper gate signal is applied. ***Commutation** is a process of turning off a thyristor.* A commutation circuit may consist of additional components in order to make successful commutation. There are a number of commutation circuits available where the main objective of these circuits is to initiate the process of commutation as well as to reduce the commutation time.

Broadly speaking, there are two types of commutations namely

(*i*) *Natural Commutation,*

(*ii*) *Forced Commutation.*

5.2 NATURAL COMMUTATION

A thyristor being fired synchronously with zero crossing of each positive half cycle of the input ac voltage (*e.g.,* the case of rectifier), it is commutated naturally as soon as the thyristor current passes through the natural zero and a reverse voltage appears across the thyristor. This is called *natural commutation.*

In the operation of phase-controlled rectifiers, ac voltage controllers and cycloconverters, natural commutations are widely used.

5.3 SOME BASIC TERMS

Commutation. It is the transfer of current from one circuit to the another. In power electronics it means that the current is transferred from one semiconductor valve to another.

Commutation Interval (t_k). During this period two semiconductor valves conduct simultaneously and a closed circuit is formed. This time the commutation inductance is the total inductances of the commutating phases, the *commutation voltage* is a resulting voltage in the commutating circuit and this voltage forms a circulating current in the closed commutating circuit which is called *commutation current* (i_k).

Types of Commutation. Commutation between two principal semiconductor valves is called *direct commutation.* A commutation between a semiconductor valve and an auxiliary valve is called *indirect commutation.*

A converter is called *line commutated, load commutated* or *self commutated* depending on where the source of commutation voltage is *i.e.*, either on the line side, load side or within the converter itself.

Once the commutation starts, the commutation current flows as an increasing current through the valve which is turning on, and at the same time the total current $(i_1 - i_k)$, through the valve which is turning off, decreases. When this total current has decreased to zero, the commutation is over.

5.4 FORCED COMMUTATION

In some thyristor applications, the input voltage being dc, during switching off the thyristor, the forward current is forced to zero by some additional circuitry. This type of commutation is known as *forced commutation.*

Forced commutation of thyristor can be categorised by the following ways:

(*i*) External pulse commutation [Class-B Commutation]
(*ii*) Load-side commutation [Class-C commutation]
(*iii*) Line side commutation [Class-F commutation]
(*iv*) Impulse commutation [Class-E commutation]
(*v*) Resonant pulse commutation [Class-A commutation]
(*vi*) Complementary commutation [Class-D commutation]

5.5 DESCRIPTION OF COMMUTATING CIRCUITS

(*a*) ***External Pulse Commutation.*** In this method a pulse current is obtained from an external source to turn off the conducting thyristor. Here, in addition to the supply, another source is required (the auxiliary voltage source).

Figure 5.1 represents the circuit suitable for DC operation of the thyristor, to be commutated by external pulses.

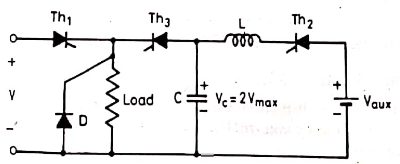


Fig.5.1. External pulse commutation circuit.

Let us first fire Th_2, the thyristor connected in the auxiliary circuit and supplied by the auxiliary dc voltage V_{aux}. Assuming the capacitor to be initially uncharged, resonant current charging would take place charging the capacitor with $(2V_{aux})$ voltage in the polarities shown. Assuming Th_1 to be conducting, next, Th_3 is fired. Immediately, the voltage across the capacitor would appear across Th_1 in reverse bias mode and Th_1 would turn off. The capacitor would discharge through the load. In this circuit an external pulse is thus utilised to then off the main thyristor Th_1.

(*b*) ***Load Side Commutation.*** In this method of commutation, the load is in series with the capacitor, the main commutating element. Discharging as well as recharging of the capacitor take place through the load. Thus, the commutation is only possible when load is connected.

Figure 5.2 exhibits a typical load side commutating circuit. Let thyristor Th_1 be conducting with dc input voltage V_0. The circuits associated with Th_2 and Th_3 represent the commutating circuits. Let us assume that the capacitor is charged to $-V_i$ at the begining (as indicated in the figure). With firing of Th_2, the capacitor voltage appears across Th_1 in reverse bias mode and the conduction of Th_1 will cease. The capacitor would carry the load current and subsequently it would discharge from $-V_i$ to zero and then again charged to the supply voltage $+V_0$. Obviously, Th_2 would then turn off.

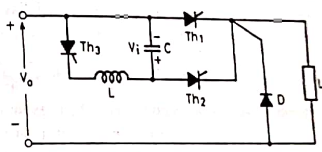


Fig. 5.2. Load-side commutation circuit.

The firing of Th_3 would then make the voltage across the capacitor to discharge through the inductor and recharging the capacitor itself, put at reverse polarity *i.e.*, the capacitor is now again charged to $-V_i\ (= -V_0)$ and is ready for next operation.

It may be noted that the commutation of Th_1 could take place due to presence of the load circuit. Hence this type of commutation is called *load side commutation*. Since the capacitor voltage is responsible for commutating Th_1 immediately after firing of Th_2, hence this type of commutation is also called *voltage commutation* or *auxiliary commutation*. In this circuit, the time required for capacitor to discharge for –ve voltage to zero is called turn off time and it is inversely proportional to the load current.

(*c*) ***Line Side Commutation.*** In this type of commutation, the discharging and recharging of the main commutating element, *i.e.*, the capacitor does not

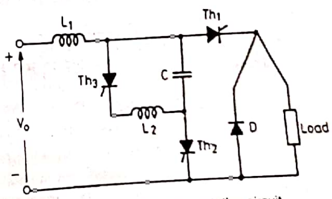


Fig. 5.3. Line-side commutation circuit.

require the load. Fig. 5.3 exhibits a line side commutating circuit. The process of commutation is described below :

1st Step : Th_2 being fired, C gets charged by the resonant current (I_C) (Fig. 5.3*a*). The steady state voltage of the capacitor is V_C at the polarities shown.

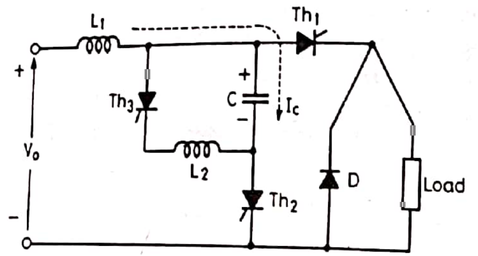


Fig. 5.3(a). Charging of C by Th_2 at twice the supply voltage.

2nd Step : Th_2 being naturally commutated, Th_3 is fired. This will make circulating current through Th_3 and L_2 and the capacitor voltage will be reversed (Fig. 5.3*b*). the reverse polarities are shown by dotted lines across the capacitor.

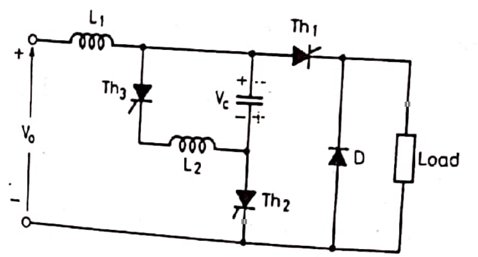


Fig. 5.3(b). Reversal of polarity of C.

3rd Step : Th_3 being self commuted, the voltage (V_c) of C would appear across Th_1 which has been assumed to be conducting.

Next, Th_2 is fired. Thus, diode D will find forward bias and a reverse voltage V_C would apply to the thyristor Th_1 which would stop conduction.

The discharging and recharging of the capacitor are done through the supply and requirement of the load circuit is nil.

(*d*) ***Impulse Commutation.*** The circuit used in load side commutation can be used for *impulse commutation* too. However, slight modification of the circuit as shown in Fig. 5.4 improves the commutating time. The commutating time becomes

more or less independent of load current. In Fig. 5.4 the discharging of the capacitor C is accelerated by using diode D_X as well as an inductor L_X across the main thyristor Th_1.

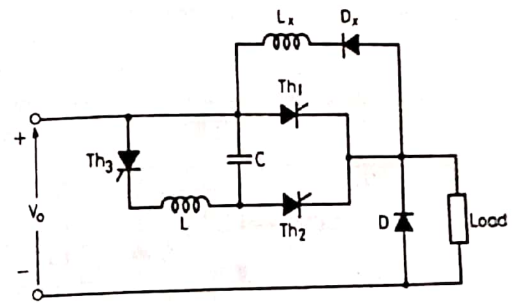


Fig. 5.4. Impulse commutation circuit.

(*e*) ***Resonant Pulse Commutation.*** Fig. 5.5 represents *a resonant pulse commutation* circuit where the capacitor is initially charged with polarity as shown in the figure. Let Th_1 be the main thyristor and is assumed to be in the conduction mode.

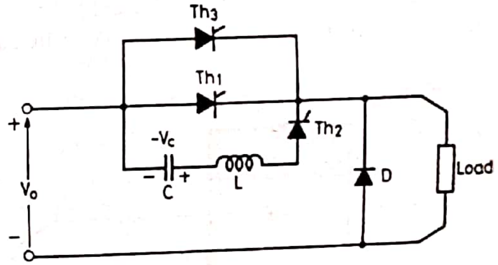


Fig. 5.5. Resonant pulse commutation circuit.

Let us now fire thyristor Th_2. Then a resonant circuit is immediately created with circuit elements L, C and devices Th_1 and Th_2. A series resonant current would start to flow in the anticlocking direction in the loop (Fig.5.6). This will cease the

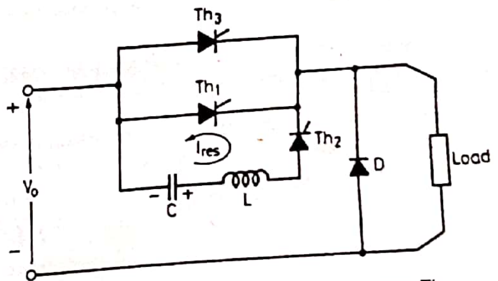


Fig. 5.6. Resonant pulse current to commutate Th_1.

load current through Th_1. The capacitor would discharge to zero and then would be recharged to the supply voltage V_0. However, due to stored energy transfer from L to C, the capacitor will be slightly overcharged (Ref. Fig. 5.7).

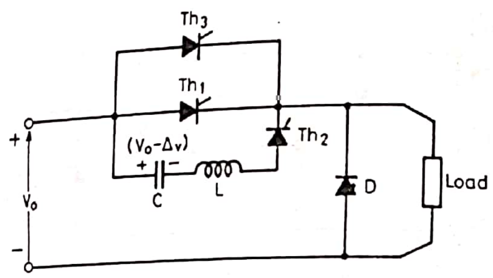


Fig. 5.7. Capacitor discharging and subsequent recharging.

Next, Th_3 is fired. Immediately, the capacitor C would discharge through Th_3, Th_2 and L in the clockwise direction (Fig. 5.8) making the capacitor voltage to get reversed after discharging to $-V_C$. Th_2 would be naturally commutated.

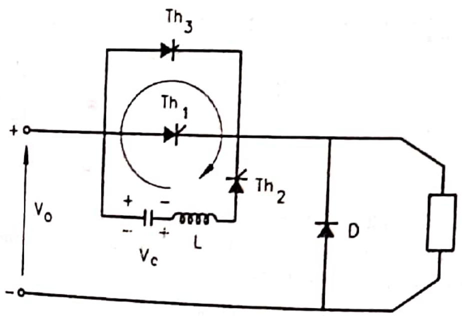


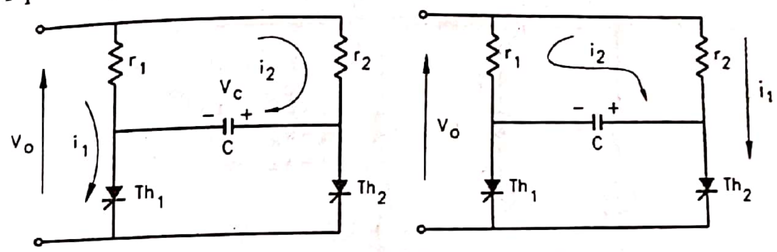
Fig. 5.8. Reverse voltage build-up in capacitor.

Since a resonant pulse circuit is utilised in this circuit to commutate the main thyristor hence this type of commutation is also called *current commutation*.

(*f*) ***Complementary Commutation.*** In this circuit firing of one thyristor commutates the other one and current transfers between the two loads.

Let us assume that Th_1 is first fired [Fig. 5.9(*a*)]. Current through r_1 is i_1 while the capacitor charges through r_2 (current i_2). The polarity of the capacitor voltage is shown in Fig. 5.9(*a*).

Let us now fire Th_2 [Fig. 5.9(*b*)] immediately, the capacitor would appear across Th_1 and its voltage V_C would reverse bias Th_1 forcing it to commutate. r_2 is across the supply. Once the thyristor Th_1 is pushed to non-conducting mode, capacitor C is charge through r_1 and then stores charging to have voltage $-V_C$. If Th_1 is now fired, Th_2 is turned off and the cycle is repeated. Each thyristor is thus commutated due to *complementary commutation* (this type of commutation is also called *complementary impulse commutation*. In practice, the resistant r_1 and r_2 are replaced by the loads.



(*a*) Th_1 is conducting. (*b*) Th_2 is conducting.

Fig. 5.9. Complementary commutation.

5.6 CONDITIONS FOR COMMUTATION

The following conditions must be fulfilled for successful commutation :

(*i*) The forward current of the thyristor must be reduced to zero.

(*ii*) A reverse voltage is to appear across the thyristor for more than the turn-off time to the device.

(*iii*) The rate of rise of voltage build up across the thyristor commutated should not exceed the critical value and there should not be any automatic retriggering.

(*iv*) Stored energy in the inductance should not cause retriggering. A free wheeling diode must be included in order to allow the dissipation of the stored energy (it may be noted here that due to this reason, free wheeling diode is kept in all the forced commutating circuits mentioned earlier).

5.7 AC LINE COMMUTATION

In case the supply to the thyristor to be commutated is ac, it is obvious that the reverse voltage is applied to the conducting thyristor during the negative half cycle. If the duration of negative half cycle is longer than the turn of time of thyristor, the corresponding thyristor is turned off. Inverters use this mode of commutation. However, the maximum frequency at which the ac line commutated circuit can be operated obviously depends on the turn off time of the thyristor. Fig. 5.10 represents three phase AC line commutation.

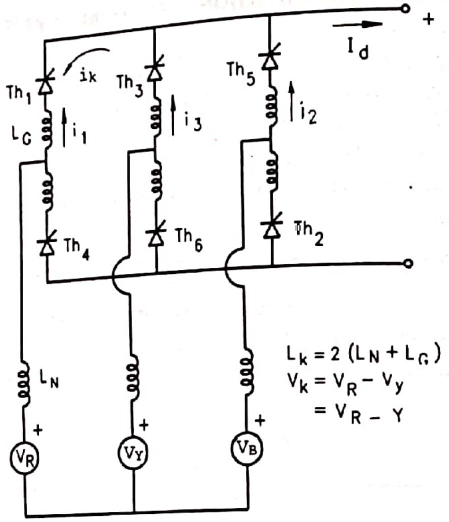


Fig. 5.10. Commutation in three phase circuit from Th_1 to Th_3

5.8 JONES COMMUTATING CIRCUIT (Fig. 5.11)

Assume Th_1 to be the main thyristor, it is in conducting mode. With commencement of conduction of L_1, current increases through the load rapidly and this would induce a voltage at L_1 [L_1 and L_2 are the two half windings across same core and this acts as an auto transformer]. Sudden current rise in L_1 would induce the voltage in L_2 also whose positive polarity will be at the diode (D) end. D will then conduct charging the capacitor C [charging current would flow through L_2, D, C, Th_1, L_2]. The capacitor will be charged with V_c voltage, the positive polarity being towards x junction in Fig. 5.11.

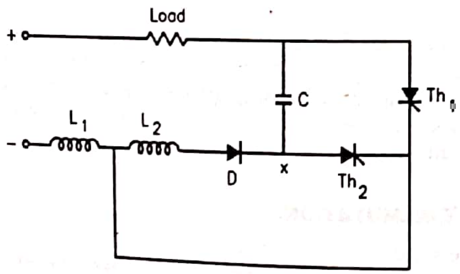


Fig. 5.11. Jone's commutating circuit.

Next, Th_2 being fired, the discharging condition of C would force the thyristor Th_1 to stop conduction. Consequently, the voltage across C reverses while discharging to zero and recharging to opposite polarity. Th_2 is then naturally commutated and the capacitor voltage is restored the next time Th_1 is fired.

5.9 GENERALISED COMMUTATION CIRCUIT ANALYSIS (Fig. 5.12)

Let the current flowing through the arms be I. It is assumed that the current remains constant during commutation [the commutation time is short in comparison to the time interval between triggering of two consecutive valves]. At first let us assume that Th_1 conducts while Th_2 is in blocking state *i.e.*, $i_1 = I$ and $i_2 = 0$. When Th_2 is triggered, the current continues in the first instance to flow unchanged through Th_1 because of the inductance in the circuit. Th_1 and Th_2 both conduct at the same time and the two arms form a closed circuit for which $v_2 - v_1 = (L_1 + L_2)\frac{di_k}{dt}$, i_k being the commutating current ; i_K circulates in the circuit superimposed on the current i_1 and i_2. Assuming $v_2 - v_1 = v_k$ and $L_1 + L_2 = L_K$, the rate of rise of the current is given by,

$$\frac{di_k}{dt} = \frac{v_k}{L_k}$$

or,

$$i_K = \frac{1}{L_K}\int_{t_1}^{t_2} v_K\,dt \qquad [i_k = 0 \text{ at } t = t_1]$$

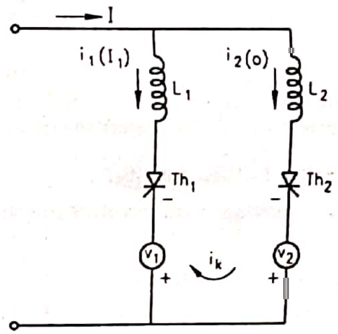


Fig. 5.12. Generalised commutating circuit.

All the current has been transferred from branch-1 to branch-2 when $t = t_2$, $i_1 = 0$ and $i_2 = i_K = I$. The commutation being over,

$$I = \frac{1}{L_K}\int_{t_1}^{t_2} v_k\,dt$$

i.e., for v_k being constant,

$$I = \frac{v_K(t_2 - t_1)}{L_K} = \frac{v_K t_K}{L_K}.$$

[It may be noted that $\int_{t_1}^{t_2} v_k\,dt$ is the voltage-time area which is needed to give a change of current equal to I through the inductance L.]

Figure 5.13 shows a commutation for which v_K is constant and $i_2 = i_K$, increasing proportionally with time during the interval t_K at the same rate as $i_1 = I_1 - i_K$ decreases.

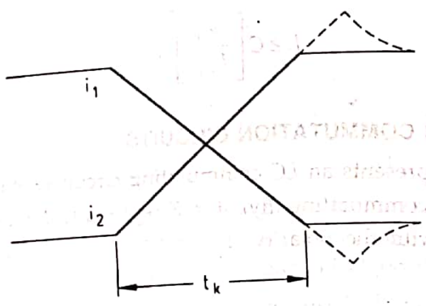


Fig. 5.13. Commutation in the generalised commutation circuit.

With non-ideal semi-conductor valves, the course of commutation will be like that shown in Fig. 5.13 (dashed curves). If a valve has been conducting and immediately after it is subjected to a reverse blocking voltage, then it will be reverse conducting for some microseconds. This time i_1 will continue with the same rate of decay through zero to a negative maximum value. After that the current decreases to zero as the reverse blocking capability is reestablished. The course of commutation depends on the property of the semi-conductor valve, the rate of decary of the current and on the protective circuits.

5.10 DESIGN OF COMMUTATING CIRCUIT

Design of the commutating circuit involves proper choice of the capacitor and inductor.

Design of the Commutating Capacitor

Let C be the capacitance, V_0 the supply voltage, t_0 the turn off time and I the load current (assumed constant during turn off period).

Then, $$CV_0 = It_0$$

i.e., $$C = \frac{I t_0}{V_0}.$$

C gives the required capacitance.

Design of the Commutating Inductor in Resonant Pulse Commutation

The capacitor current I_c is given by

$$I_c = \frac{V}{\omega L}$$

while the peak resonant current is given by

$$I_p = V_0 \sqrt{\frac{C}{L}}$$

If I_{max} is the maximum current at which the current is to be limited,

$$I_{max} \geq V_0 \sqrt{\frac{C}{L}}$$

$$\therefore \quad L \geq C\left[\frac{V_0}{I_{max}}\right]^2.$$

5.11 SOME OTHER COMMUTATION CIRCUITS

(*a*) Fig. 5.14 represents an *LC* commutating circuit when Th_1 is the main thyristor and Th_2 the commutating thyristor. *R* represents the load. At the beginning, *C* is charged with the polarity shown and the charging current passes through *C*, *L* and D_r through the load. Thus, with firing of thyristor Th_1, the load is served by it. To commutate Th_1, Th_2, the commutating thyristor is fired. C then starts discharging through Th_2 and *L* resonantly and reverses its potential. Thus, the right hand side of C in Fig. 5.14 becomes +ve. Then, C will start discharging through *L*, D_r and Th_1, the direction of the discharge current being opposite to that of the load current through Th_1. This will lead to commutation of Th_1. The excess discharge current will flow through D_x. Again the cycle will be ready for repetition with charging of C from the source.

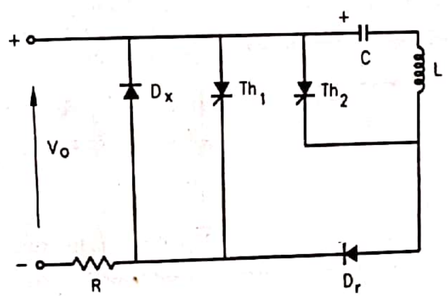


Fig. 5.14. *L-C* type commutation circuit.

Since $L - C$ type commutating circuit is used in this scheme, it is also called a *resonating type commutating circuit.*

(*b*) Fig. 5.15 represents a capacitor based commutation circuit where Th_1 being the main thyristor, Th_2 is the commutating thyristor. The capacitor is previously charged with upper plate + ve. When Th_1 is fired, if connects the load *R*. Simultaneously the capacitor C gets discharged with the upper plate +ve polarity through L_2, Th_1, *D* resonately and then reverses the polarity of the capacitor voltage. Thus, the lower plate gets positive polarity.

Next, the thyristor Th_2 is fired and the capacitor discharge through $Th_2 - Th_1 - L_2$ commutating Th_1. The additional charge across C is discharged through Th_2 and load and the capacitor is then recharged by the supply voltage V_0 through L_1 and L_2 thus becoming ready for the next cycle of repetition. Th_2 is naturally commutated.

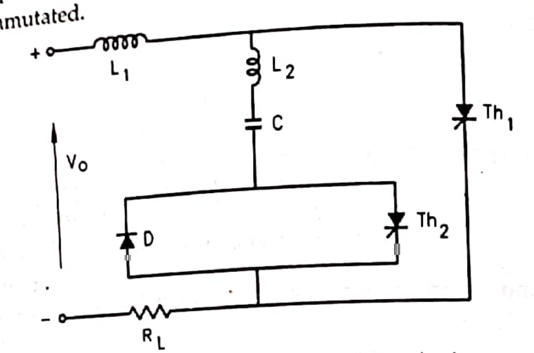


Fig. 5.15. Capacitor based commutating circuit.

Example 5.1. *In Fig. E5.1, I = 100 A ; initial voltage across the capacitor is 500 volts. If L = 25 μH, C = 10 μF calculate :*

(i) *maximum value of* (di_k/dt)

(ii) *the commutation current and voltage versus time.*

(iii) *the commutating time.*

(iv) *the capacitor voltage* $v_k = V_1$ *at* $t = t_k$.

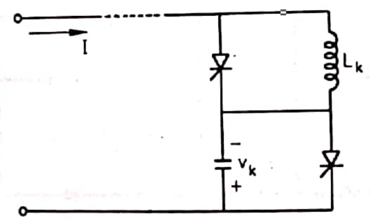


Fig. E5.1.

Solution. (i) $\frac{di_K}{dt} = \frac{V_0}{L} = \frac{500}{25 \times 10^{-6}} = $ **20 A/μ sec.**

$$\left[\frac{di_K}{dt} \text{ has its maximum when } v_k = V_0 = 500 \text{ volts} \right]$$

(ii) As soon as the auxiliary thyristor is turned on, an oscillation begins between C and L.

$$\omega = \frac{1}{\sqrt{LC}} = \frac{10^6}{\sqrt{25 \times 10}} = 63200 \text{ rad/sec.}$$

$$I = \sqrt{\frac{C}{L}} \cdot V_0 = \sqrt{\frac{10}{25}} \cdot 500 = \mathbf{316 \ A.}$$

The oscillation continues till the current through the main thyristor decays to zero.

This time $i_k = I, t = t_k$

(iii) Since $I = I_m \sin \omega t_k$,

$$t_k = \frac{1}{\omega} \sin^{-1} \frac{I}{I_m} = \frac{1}{63200} \sin^{-1} \frac{100}{316} = \mathbf{5 \ \mu \ sec.}$$

(iv) Voltage across the capacitor is

$$V_1 = V_0 \cos \omega t_k = 500 \cos (63200 \times 5 \times 10^{-6}) = \mathbf{475 \ V.}$$

EXERCISE

1. Describe a commutation circuit where external voltage is used for commutation of a thyristor.
2. What is load side-commutation ? Discuss the operation of load-side commutating circuit.
3. Why Line-side commutation is sometimes preferred over load side commutation ? Discuss a typical scheme of a line side commutating circuit.
4. Describe an impulse commutation circuit.
5. Write a short note on
   (i) Resonant pulse commutation. (ii) Complementary commutation.
6. State the conditions of commutation of a thyristor.
7. Develop the design equation for obtaining the values of L and C in resonant pulse commutating circuit.
8. What is the difference between self and forced commutation ?
9. What are the differences between voltage and current commutation ?
10. Why in ac supply commutation the reverse bias time across the thyristor be greater than the turn off time of a thyristor ?
11. Why does the commutating capacitor in a resonant pulse commutating circuit get over voltage ?
12. How does the voltage of the commutating capacitor get reversed in a commutating circuit ? Give examples.