## 1

## THYRISTORS AND COMMUTATION TECHNIQUES

Thyristor, also called SCR (silicon controlled rectifier) is four layer, 3 junction PNPN device. There are three terminals in a thyristor, that is, anode, cathode and gate as shown below.


Fig. 1.1
The junctions are generally known as $J_{1}, J_{2}$ and $J_{3}$ as shown. The gate is used to turn on a thyristor. Anode must be at a high voltage than cathode in order to function. The following are the methods to turn on a thyristor.

1. Forward voltage triggering 2. Gate triggering 3. $\frac{d v}{d t}$ triggering 4. Temperature triggering and 5. Light triggering. Among these, gate triggering is commonly used as it gives accurate firing of SCR at the desired instant. Sometimes high frequency carrier gating is used. This leads to lower power requirement, reduced dimensions
and, therefore, an overall economical design of pulse transformer required for isolating the low power circuit from the main power circuit.

A current $\mathrm{v} / \mathrm{s}$ voltage characteristic of a thyristor is as shown below.


Fig. 1.2
The characteristics can be divided in two parts, that is, forward characteristics and reverse characteristics.

## FORWARD CHARACTERISTICS

In forward characteristics, anode is +ve with respect to cathode. As we go on increasing this voltage current goes on increasing. The current passing through the SCR is small. During this mode, outer junctions $J_{1}$ and $J_{3}$ are forward biased and middle junction $J_{2}$ is reverse biased. The whole of the applied voltage drop takes place across $J_{2}$ during this forward blocking mode. At a certain voltage, known as forward break over voltage, breakdown of $J_{2}$ occurs and the device starts conducting. A low voltage drop across SCR takes place during conduction. If a positive pulse is applied to gate, the conduction of SCR takes place at a lower voltage.

It takes some time for SCR to come to conduction state from forward blocking state. Anode current increases slowly and this current should become more than latching current to turn on SCR. An SCR will go to blocking state if gate pulse is removed before anode
current goes more than latching current. Thus, latching current is the minimum anode current which it must attain during turn on process to maintain conduction after gate signal is removed. Turn on time of a SCR is given by

$$
\begin{equation*}
T_{O N}=\text { delay time }+ \text { rise time }+ \text { spread time } \tag{1.1}
\end{equation*}
$$

During delay time, anode current reaches $10 \%$ of its final value after gate current reaches $0.9 I_{g}$ and the anode current reaches from $10 \%$ to $90 \%$ during rise time. Anode current from $90 \%$ to $100 \%$ reaches during spread time.

To turn off an SCR, the anode current should come below holding current. Holding current is the minimum anode current below which it must fall for turning off the thyristor. Holding current is less than latching current. Gate loses control after an SCR has turned on. An SCR keeps on conduction even if gate signal is removed. The only way to turn off an SCR is to reduce anode current below holding current. When a thyristor conducts, it acts like a conducting diode.

There is a transition state between conduction state and forward blocking state. The time taken in switching over from forward blocking state to conduction state is very small. During transition state, a thyristor exhibits negative resistance.

When cathode is positive with respect to anode, reverse blocking state takes place. During this state, outer junctions are reverse biased and middle junction is forward biased. The device acts as a reverse diode. If we go on increasing cathode to anode voltage, reverse break down occurs leading to anode current shooting up.

The following losses take place in a thyristor during working conditions.

1. Forward conduction losses
2. Losses due to leakage current during forward and reverse blocking
3. Switching losses at turn on and turn off
4. Gate triggering losses

Gate signal should be present till the anode current goes beyond latching current. Therefore, there is a minimum pulse width of gate signal below which a thyristor will not be turned on. Gate cathode junction acts as a forward biased pn junction. A gate characteristic is as shown below.

The gate signal has no function after turning on of thyristor. Hence, gate signal should be removed. If gate signal remains continuously present, it generates unnecessary gate losses and it may damage the thyristor.


Fig. 1.3
Gate signal is applied in pulses. If we increase the amplitude of pulse, delay time of thyristor reduces. As a result turn on time of thyristor reduces. Hence, higher pulse magnitude is desirable from this point of view but we can not go on increasing the pulse magnitude as it will result in more than permissible gate losses. Hence, there is maximum limit to gate pulse loss. If $P_{g m}$ is the maximum gate pulse loss and $P_{\text {gav }}$ is average permissible loss, we have

$$
\begin{equation*}
P_{g m} \times T^{\prime}=P_{g a v} \times T \tag{1.2}
\end{equation*}
$$

Where $T^{\prime}$ is pulse duration and $T$ is the period. If $f$ is switching frequency, $f=\frac{1}{T}$.

From (2), we get $P_{g m}=\frac{P_{g a v}}{T^{\prime} / T}$
$\frac{T^{\prime}}{T}$ is called duty ratio. The above equation gives maximum permissible gate power drive. To keep $P_{g a v}$ within acceptable limits, a resistance is added in the gate cathode circuit as shown below.


Fig. 1.4

If $V_{g}$ and $I_{g}$ are gate voltage and current respectively, we have power dissipated in gate circuit as

$$
\begin{equation*}
P=V_{g} \times I_{g} \tag{1.4}
\end{equation*}
$$

A gate cathode characteristic is linear of the form given below.

$$
\begin{equation*}
V_{g}=c+p I_{g} \tag{1.5}
\end{equation*}
$$

Where $c$ and $p$ are constants and decide the characteristics. We can get $V_{g}$ and $I_{g}$ from (1.4) and (1.5). Once we know $V_{g}$ and $I_{g}$, we get the following equation from the figure given above.

$$
\begin{equation*}
V=V_{g}+\left(I_{g}+\frac{V_{g}}{R_{g k}}\right) R \tag{1.6}
\end{equation*}
$$

We can get $R$ from this equation.

## SERIES AND PARALLEL CONNECTIONS

When the voltage and current to be handled are more than the voltage and current ratings of a single thyristor can handle, we connect many single thyristor to handle the required voltage and connect many single thyristors in parallel to handle the required current. If $V_{D}$ is the voltage rating of a single thyristor unit and $n_{s}$ is the number of thyristors connected in series, the voltage rating of the string will be equal to $n_{s} V_{D}$. There will be some derating in the voltage and $\%$ voltage derating is given by

$$
\begin{equation*}
\% \text { voltage derating }=\left(1-\frac{V_{s}}{n_{s} V_{D}}\right) \times 100 \tag{1.7}
\end{equation*}
$$

Where $V_{s}$ is the string voltage rating.
Similarly there is current derating handled by the string and \% current derating is given by

$$
\begin{equation*}
\% \text { current derating }=\left(1-\frac{I_{m}}{n_{p s} I_{T}}\right) \times 100 \tag{1.8}
\end{equation*}
$$

Where $I_{m}$ is the current of thyristors connected in parallel, $n_{p}$ is the number of thyristors connected parallel and $I_{T}$ is the current rating of individual thyristor.

If the characteristics of all the connected thyristors are exactly identical, the voltage applied across the string will be distributed uniformly and, hence, the voltage across each thyristor will be same. But the characteristics are never same for all the thyristors. Hence, voltage distribution across all the thyristors can never be same. To achieve uniform voltage distribution across all the thyristors under static condition, a resistance is connected across each thyristor as shown below.


Fig. 1.5
Value of $R$ is given by

$$
\begin{equation*}
R=\frac{n_{s} V_{D}-V_{s}}{\left(n_{s}-1\right) I_{1}} \tag{1.9}
\end{equation*}
$$

Where $I_{1}$ is the maximum leakage current under forward blocking state. Connecting resistance of same value across each thyristor does not result in exact voltage across each thyristor. Strictly speaking, a resistance of different value, decided by the characteristics, operating temperature etc., should be connected across each thyristor to get the uniform voltage distribution but it will be quite difficult to decide the resistance value for each thyristor under all operating conditions. Hence, a resistance of same values is connected across each thyristor. It results in more or less uniform voltage distribution across the string thyristors.

Similarly, voltage distribution should be uniform across all the thyristors connected in series during 'on' condition. This is achieved by connecting a capacitance across each thyristor. The value of capacitance is given by

$$
\begin{equation*}
C=\frac{(n-1) \Delta Q}{n_{s} V_{D}-V_{s}} \tag{1.10}
\end{equation*}
$$

Where $\Delta Q$ is maximum reverse recovery charge on any thyristor in the string.

## PROTECTION AGAINST $d v / d t$ AND $d i / d t$.

As mentioned above, high $\frac{d v}{d t}$ can result in conduction of thyristor. Hence, $\frac{d v}{d t}$ should not be allowed to go beyond the permissible value. A series connected $R$ and $C$ is connected across the thyristor to control $\frac{d v}{d t}$ appearing across the thyristor. Series connected $R$ and $C$ is called snubber circuit. Similarly, high $\frac{d i}{d t}$ can damage a thyristor.

An inductance is connected in the anode circuit to keep the $\frac{d i}{d t}$ within permissible limits. The following circuit shows snubber circuit and $\frac{d i}{d t}$ inductor connection.


Fig. 1.6
Insertion of $\frac{d i}{d t}$ inductor in anode circuit increases the gate pulse duration required to turn on thyristor. As a result, turn on time of thyristor increases as it will take more time for anode current to go beyond latching current. Maximum value of $\frac{d i}{d t}$ occurs at the instant of switching on the supply to the circuit and it is given by

$$
\begin{equation*}
\left(\frac{d i}{d t}\right)_{\max }=\frac{V}{L} \tag{1.11}
\end{equation*}
$$

From this equation, we can get $L$.
Similarly, maximum value of $\frac{d v}{d t}$ occurs at $t=0$ and it is given by

$$
\begin{equation*}
\left(\frac{d v}{d t}\right)_{\max }=\left(\frac{d i}{d t}\right)_{\max } R \tag{1.12}
\end{equation*}
$$

We can get $R$ from this equation.
When supply (DC) is switched on, the circuit becomes series connected RLC circuit and the current will be oscillatory if resistance is less than the critical value. This should not become oscillatory. If, at all, it becomes oscillatory, the frequency period should be low. We don't know load parameters. Hence, we can not determine exact value of critical resistance. Critical value of resistance is given by

$$
\begin{equation*}
R=2 \sqrt{\frac{L}{C}} \tag{1.13}
\end{equation*}
$$

without considering the load parameters. As we don't know load parameters, we take half of this value so that circuit will remain near criticality anyhow. Hence,

$$
\begin{equation*}
R=\sqrt{\frac{L}{C}} \tag{1.14}
\end{equation*}
$$

If we know that discharging current, $R$ can be calculated and the higher one should be selected.

The above equations give exact values of $R, L$ and $C$. Practically, $C$ is selected somewhat lower and resistance is selected somewhat more than the calculated values to make thyristor safe. Lower value of capacitance and higher value of resistance inject lower current through thyristor at the instant of its turning on.

## THYRISTOR COOLING

The junction temperature of a thyristor depends on the power loss in the thyristor and heat dissipation rate, environment and ambient temperature. Thermal resistance between the junction and case, case and sink and sink and ambient is different. The relationship between thermal resistance $\theta$, temperature difference $\Delta T$ and power loss $P$ is given by

$$
\begin{equation*}
\Delta T=P \times \theta \tag{1.15}
\end{equation*}
$$

Thermal equivalent for thyristor is represented as given below.


Fig. 1.7
From this figure, we get the following equations.

$$
\begin{align*}
& T_{J}-T_{C}=P \times \theta_{J C}  \tag{1.16}\\
& T_{C}-T_{S}=P \times \theta_{C S}  \tag{1.17}\\
& T_{S}-T_{A}=P \times \theta_{S A}  \tag{1.18}\\
& T_{S}-T_{A}=P \times \theta_{S A} \tag{1.19}
\end{align*}
$$

Thermal resistance depends on cooling method adopted.

## FIRING CIRCUITS

Resistance and resistance-capacitance triggering is used where accurate firing of thyristors is not that important. Resistance triggering can not give firing angle more than $90^{\circ}$. RC triggering can control the firing angle beyond $90^{\circ}$ also. The gate power loss is more with $R$ and $R C$ firing circuits and accurate firing angles can not be achieved.

The function of isolation transformer is to isolate the low voltage gate cathode circuit from the high voltage anode circuit.

Uni Junction Transistor (UJT) often used for designing relaxation oscillators whose output triggers thyristors. The circuit for a relaxation oscillator using UJT is as shown below.


Fig. 1.8
The firing frequency of the oscillator is given by

$$
\begin{equation*}
f=\frac{1}{R C \ln \frac{1}{1-\eta}} \tag{1.20}
\end{equation*}
$$

Where $\eta$ is intrinsic ratio of UJT. If frequency $f$ is known, we can find out $R$.

From the above equation, it is clear that we can vary frequency by varying $R$ or $C$.

## COMMUTATION TECHNIQUES

The process of turning off a conducting thyristor is commutation. Basically there are two methods of turning off a conducting thyristor.

1. Voltage commutation
2. Current commutation

In voltage commutation, anode is made -ve with respect to cathode for a period at least equal or more than turn off time of thyristor. This makes the anode current less than holding current of thyristor leading to its turn off. If reverse voltage is maintained for a time less than turn off time, reapplication of positive voltage will trigger the thyristor even without gate signal.

In current commutation, no reverse voltage is applied but current reduces below holding current because of circuit configuration and remains below holding current for a time more than turn off time of the thyristor. Here also, if anode current goes more than holding
current before turn off time of thyristor, it will again start conducting even without gate signal.

Thyristors can be forcibly commutated or naturally commutated. Force commutation has to be used when input voltage to thyristor is $D C$ and, hence, anode current does not go to zero naturally. Hence, this requires special commutation circuit to turn off thyristor. When input voltage is $A C$, the voltage across anode and cathode becomes negative naturally and thyristor commutates. This does not require any special circuit for commutation to turn off thyristor.

As mentioned above, special circuits are designed for force commutation. Variously commonly used commutation circuits are given below.

## SELF COMMUTATION

This is also called load commutation or class A commutation. The circuit for class A commutation is given below.


Fig. 1.9
In this circuit, $R$ is selected to make the circuit under damped. Under this condition, the current oscillates and the oscillation frequency is given by

$$
\begin{equation*}
\omega=\sqrt{\frac{1}{L C}-\frac{R^{2}}{4 L^{2}}} \mathrm{rad} / \mathrm{sec} \tag{1.21}
\end{equation*}
$$

The value $R$ is given by

$$
R<2 \sqrt{\frac{L}{C}}
$$

The current in the circuit is given by

$$
\begin{equation*}
i(t)=\frac{V-V_{c}(0)}{\omega L} e^{\frac{-R}{2 L} t} \sin \omega t \tag{1.23}
\end{equation*}
$$

Where $V_{c}(0)$ is initial capacitance voltage.
Peak value of current occurs at

$$
\begin{equation*}
t=\frac{1}{\omega} \tan ^{-1} \frac{2 \omega L}{R} \tag{1.24}
\end{equation*}
$$

By putting value of $t$ from the above equation in (1.23), we can find out peak current.

Capacitor voltage is given by

$$
\begin{equation*}
V_{c}(t)=V-\frac{V-V_{c}(0)}{\omega} e^{\frac{-R}{2 L} t}\left[\frac{R}{2 L} \sin \omega t+\omega \cos \omega t\right] \tag{1.25}
\end{equation*}
$$

Thyristor switches off at $\omega t_{0}=\pi$. Hence

$$
\begin{align*}
V_{c}\left(t_{0}\right) & =V-\frac{V-V_{c}(0)}{\omega}[\omega \cos \pi] \\
& =V+V-V_{c}(0) \tag{1.26}
\end{align*}
$$

$V_{c}\left(t_{0}\right)$ will be equal to $2 V$ if $V_{c}(0)=0$.
Thyristor conduction time $=\frac{\pi}{\omega}$
If $R=0$ and $I(0)=I_{0}$, the current and capacitor voltage are given by

$$
\begin{align*}
i(t) & =\left[V-V_{c}(0)\right] \sqrt{\frac{C}{L}}-\sin \omega t+I_{0} \cos \omega t  \tag{1.27}\\
V_{c}(t) & =I_{0} \sqrt{\frac{L}{C}} \sin \omega t-\left[V-V_{c}(0)\right] \cos \omega t  \tag{1.28}\\
\omega & =\sqrt{\frac{1}{L C}} \tag{1.29}
\end{align*}
$$

## RESONANT PULSE COMMUTATION

This is also known as type $B$ commutation. In this type of commutation circuit, a series $L C$ circuit is connected across the conducting thyristor as shown below.


Fig. 1.10
Initially capacitor is charged to supply voltage with the polarity as shown. Let $T_{1}$ be conducting and feeding load current $I$. To turn
off $T_{1}, T_{2}$ is fired at $t=0$. As a result, resonant current $i_{c}$ starts flowing and it is given by

$$
\begin{align*}
i_{c}(t) & =V_{c}(0) \sqrt{\frac{C}{L}} \sin \omega t  \tag{1.30}\\
\omega & =\sqrt{\frac{1}{L C}} \tag{1.31}
\end{align*}
$$

Voltage across capacitor is given by

$$
\begin{equation*}
V_{c}(t)=-V_{c}(0) \cos \omega t \tag{1.32}
\end{equation*}
$$

When $i_{c}(t)$ becomes equal to $I$, the current through $T_{1}$ becomes zero leading to its turning off. If this happens at $t_{0}$, we have

$$
\begin{align*}
I & =V_{c}(0) \sqrt{\frac{C}{L}} \sin \omega t_{0}  \tag{1.33}\\
t_{0} & =\sqrt{L C} \sin ^{-1}\left[\frac{1}{V_{c}(0)} \sqrt{\frac{L}{C}}\right]  \tag{1.34}\\
V_{c}\left(t_{0}\right) & =-V_{c}(0) \cos \omega t_{0} \tag{1.35}
\end{align*}
$$

Circuit turn off time is given by

$$
\begin{equation*}
t_{0}=\frac{C V_{c}\left(t_{1}\right)}{I} \tag{1.36}
\end{equation*}
$$

Normally $V_{c}\left(t_{1}\right) \approx V$
For reliable commutation, $t_{0}$ should be greater than thyristor turn off time. Circuit turn off time depends on load current. The higher the loads current, the lower will be the circuit turn off time.

Many times, a diode across thyristor $T_{1}$ is connected to reduce circuit turn off time as shown below. It provides a separate path for discharging of capacitor after $T_{1}$ has turned off.


Fig. 1.11

In this case, circuit turn off time is given by

$$
\begin{align*}
t_{0} & =\sqrt{L C}\left[\pi-2 \sin ^{-1} \frac{1}{x}\right]  \tag{1.38}\\
x & =\frac{I_{p}}{I}-\frac{V_{c}(0)}{I} \sqrt{\frac{L}{C}} \tag{1.39}
\end{align*}
$$

If we know $x$ and $t_{0}$, we can find out circuit commutating components $L$ and $C$.

## COMPLEMENTARY COMMUTATION

This type of commutation is also known as class $C$ commutation. The circuit for this type of commutation is as shown below.


Fig. 1.12
Each thyristor is used for turning off the other thyristor. For example, $T_{1}$ is fired to turn off $T_{2}$ and vice versa. That's why; we call it as complementary commutation.

Capacitor voltage is given by

$$
\begin{equation*}
V_{c}(t)=V_{f}+\left(V_{i}-V_{f}\right) e^{\frac{-t}{\tau}} \tag{1.40}
\end{equation*}
$$

Where $V_{r}$ is initial voltage, $V_{i}$ is the initial voltage and $\tau$ is the time constant.

If $t_{01}$ is turn off time of thyristor $T_{1}$, we have $V_{i}=-V,=R_{1} C$, $V_{f}=V, V_{c}\left(t_{01}\right)=0$, we have

$$
\begin{equation*}
0=V+(-V-V) e^{\frac{-t_{01}}{R_{1} C}} \tag{1.41}
\end{equation*}
$$

This gives $t_{01}=R_{1} C \ln 2$
Similarly, when $T_{2}$ is commutated,

$$
\begin{equation*}
t_{02}=R_{2} C \ln 2 \tag{1.43}
\end{equation*}
$$

Generally, $R 1=R 2=R$. Hence,

$$
\begin{equation*}
t_{02}=t_{01}=R C \ln 2 \tag{1.44}
\end{equation*}
$$

## IMPULSE COMMUTATION

This type of commutation is also known as type $D$ commutation. In this type of commutation technique, a voltage is applied across the conducting thyristor. The circuit for this type of commutation is as shown below.


Fig. 1.13
Initially capacitor is charged to supply voltage with the polarity as shown. $T_{1}$ is conducting and feeding load current $I$. $T_{2}$ is fired at $t=0$ to turn off $T_{1}$. The capacitor voltage is applied across $T_{1}$ reverse biasing $T_{1}$ and turning it off. After this, the capacitor discharges through $T_{2}$ and load. Once the capacitor is charged to $V$ with upper plate positive, the current through the capacitor becomes zero turning off $T_{2}$. Voltage on capacitor is reversed by firing $T_{3}$ to make it ready for next turning of $T_{1}$.

Circuit turn off time is given by

$$
\begin{equation*}
t_{0}=\frac{C V_{c}}{I} \tag{1.45}
\end{equation*}
$$

When $T_{2}$ is fired, the voltage across load becomes $\left(V+V_{c}\right)$, almost double of supply voltage, hence, the load current shoots up and then decreases as the capacitor starts discharging. If load is resistive $R$, circuit turn of time $=R C \ln 2$.

As in case of resonant pulse commutation, a diode is connected across $T_{1}$ to facilitate capacitor discharging after $T_{1}$ has turned off as shown below.

The resonant current and capacitor is given by

$$
\begin{align*}
i(t) & =V \sqrt{\frac{C}{L}} \sin \omega t+I \cos \omega t  \tag{1.46}\\
V_{c}(t) & =I \sqrt{\frac{L}{C}} \sin \omega t-V \cos \omega t \tag{1.47}
\end{align*}
$$



Fig. 1.14
At turn of $V_{c}(t)=0$. Hence,

$$
\begin{equation*}
t_{0}=\sqrt{L C} \tan ^{-1}\left[\frac{V}{I} \sqrt{\frac{C}{L}}\right] \tag{1.48}
\end{equation*}
$$

## SOLVED PROBLEMS

Problem 1. A thyristor sheet gives 1.5 V and 100 mA as the minimum values of gate trigger voltage and gate trigger current respectively. The value of resistance between gate and cathode is $20 \Omega$. If the trigger circuit supply is 10 V , compute the value of the resistance to be connected in series with the gate to turn the thyristor on.

Solution: The following figure gives the diagram for resistance insertion in gate circuit of a thyristor.


Fig. 1.15

$$
V_{g}=1.5 \mathrm{~V}, I_{g}=100 \mathrm{~mA}
$$

We can write the following equation for the gate cathode circuit.

$$
10=\left(I_{g}+\frac{V_{g}}{20}\right) R_{s}+V_{s}
$$

Putting values of $V_{g}$ and $I_{g}$, we get

$$
\begin{aligned}
10 & =\left(100 \times 10^{-3}+\frac{1.5}{20}\right) R_{s}+1.5 \\
10 & =(0.1+0.075) R_{s}+1.5 \\
\text { Hence, } \quad R_{s} & =\frac{10-1.5}{0.175} \\
& =48.571 \Omega \quad \text { Ans. }
\end{aligned}
$$

Problem 2. In the circuit shown below, the load and stray inductances are negligible and thyristor is operated at 2 kHz . If the required $\frac{d v}{d t}$ is $100 \mathrm{~V} / \mu$ sec and the discharge current is to be limited to $100 A$, determine the (a) value of $R_{s}$ and $C_{s}$ and (b) snubber losses.


Fig. 1.16
Solution: ( $a$ ) $R_{s}=$ ? , $C_{s}=$ ?
When the supply is switched on, the governing equation is given by

$$
200=\left(10+R_{s}\right) i+\frac{1}{C} \int i d t
$$

If we assume capacitance voltage to be zero at $t=0$, we have

$$
\begin{equation*}
i=\frac{200}{10+R_{s}} e^{\frac{-t}{\left(10+R_{s} C_{s}\right.}} \tag{1.49}
\end{equation*}
$$

The circuit becomes a $R C$ circuit excited by a $D C$ voltage. The solution can easily be written as given above.

Thyristor discharge current $=100 \mathrm{~A}$. Hence,
or

$$
\begin{aligned}
& R_{s}=\frac{200}{100} \\
& R_{s}=2 \Omega
\end{aligned}
$$

Putting this value in (1.49), we get

$$
i=\frac{200}{12} e^{\frac{-t}{12 C_{s}}}=16.67 e^{\frac{-t}{12 C_{s}}}
$$

Thyristor voltage $V_{t}(t)=200-10 i$

$$
\begin{aligned}
& =200-10 \times 16.67 e^{\frac{-t}{12 C_{s}}} \\
& =200-166.7 e^{\frac{-t}{12 C_{s}}}
\end{aligned}
$$

Hence, $\quad V_{t}(0)=200-166.7=33.3 \mathrm{~V}$

$$
V_{t}(\tau)=200-166.7 e^{-1}=138.674 \mathrm{~V}
$$

Hence, $\quad \frac{d v}{d t}=\frac{V_{t}(\tau)-V_{t}(0)}{\tau}$
or,

$$
\frac{100}{10^{-6}}=\frac{138.674-33.3}{12 C_{s}}
$$

or,

$$
C_{s}=\frac{105.374}{12 \times 100 \times 10^{6}}=0.0878 \mu \mathrm{~F} \quad \text { Ans. }
$$

(b) Snubber losses = ?

Energy stored in snubber capacitance in each cycle

$$
\begin{aligned}
& =\frac{1}{2} C_{s} V^{2}=\frac{1}{2} \times 0.0878 \times 10^{-6} \times 200^{2} \\
& =1.756 \times 10^{-3} J
\end{aligned}
$$

Thyrsitor operating frequency $=2 \mathrm{kHz}$
Hence, snubber losses $=1.756 \times 10^{-3} \times 2 \times 10^{3}$

$$
=3.512 \mathrm{~W} \quad \text { Ans. }
$$

Problem 3. The gate-cathode characteristics of a thyristor is $V_{g}=0.5+8 I_{g}$. For a triggering frequency of 200 Hz and duty cycle of $10 \%$, determine the value of resistance to be connected in series with the gate circuit. The amplitude of the rectangular pulse applied is 15 V and average gate power loss is $05 . \mathrm{W}$

Solution: $V_{g}=0.5+8 I_{g}$
Average gate power loss $=0.5 \mathrm{~W}$
As gate pulse width is less than period, the $D C$ data does not apply.

Hence, $\quad V_{g} I_{g}=0.5$
From (1.51), we get $I_{g}=\frac{0.5}{V_{g}}$
Putting this value in (1.50), we get $V_{g}=0.5+\frac{4}{V_{g}}$
or,

$$
\begin{aligned}
& \qquad \begin{aligned}
& V_{g}^{2}-0.5 V_{g}-4=0 \\
& \text { Solving this, we get } V_{g}=\frac{0.5 \pm \sqrt{0.25+16}}{2} \\
&=2.265 \mathrm{~V} \text { taking +ve sign } \\
& \text { So } \quad I_{g}=\frac{0.5}{2.265}= 0.22 \mathrm{amps}
\end{aligned}
\end{aligned}
$$

As trigger voltage is 15 , we have $15=2.265+0.22 R$, where $R$ is the resistance inserted in the gate cathode circuit.

$$
\text { So } \quad R=\frac{15-2.265}{0.22}=57.886 \text { say } 58 \Omega \quad \text { Ans. }
$$

Problem 4. A train of pulses of frequency 5 kHz having a duty ratio of $20 \%$ triggers a thyristor. Determine the pulse width. If the average gate power dissipation is 0.5 W , determine the maximum allowable gate power drive.

Solution: Frequency $f=5 \mathrm{kHz}$
Hence, period $=\frac{1}{5 \times 10^{3}}=0.2 \times 10^{-3}$ secs
Pulse width $=$ ? Duty ratio $=20 \%=0.2$

$$
\text { Duty ratio }=\frac{\text { Pulse width }}{\text { Period }}
$$

Hence, pulse width $=0.2 \times 0.2 \times 10^{-3}=40 \mu$ secs

## Ans.

$P_{g a v} \times$ period $=P_{g m} \times$ pulse width
or

$$
P_{g a v}=P_{g m} \times \frac{\text { pulse width }}{\text { period }}=P_{g m} \times \text { duty ratio }
$$

Hence, $\quad P_{g m}=\frac{0.5}{0.2}=2.5 \mathrm{~W} \quad$ Ans.

Problem 5. Consider the following circuit.
Determine whether the thyristor will turn on successfully or not if the latching current of the thyristor is 50 mA and gate trigger pulse duration is $50 \mu$ secs. What you can propose to turn the thyristor on successfully if the gate triggering pulse remains the same.

Solution: $V=100$ volts $, R=10 \Omega, L=0.6 \mathrm{H}$
After the thyristor switches on, the governing differential equation is given by

$$
100=10 i+0.6 \frac{d i}{d t}
$$



Fig. 1.17
The solution of this equation gives

$$
\begin{gathered}
i(t)=\frac{100}{10}\left(1-e^{\frac{-10}{0.6} t}\right)=10\left(1-e^{\frac{-10}{0.6} t}\right) \\
\text { At } t=50 \times 10^{-6} \operatorname{secs}, i=10\left(1-e^{\frac{-10 \times 50 \times 10^{-6}}{0.6}}\right)=8.3298 \mathrm{~mA}
\end{gathered}
$$

Latching current is 50 mA . Hence, for the thyristor to turn on successfully anode current should at least be 50 mA ; but anode current is only 8.3298 mA . Hence, the thyristor will not turn on.

For successfully turning on the thyristor, a resistance can be connected in parallel to the load as shown below.

For the thyristor to turn on, the minimum current passing through $R$ at the end of pulse


Fig. 1.18

$$
\begin{aligned}
& =50-8.33=41.67 \mathrm{~mA} \\
\text { Hence, } \quad R_{\max } & =\frac{100}{41.67 \times 10^{-3}} \\
& =2.399 \text { say } 2.4 \Omega \quad \text { Ans }
\end{aligned}
$$

Problem 6. In the figure shown below, determine the minimum pulse width to turn the thyristor successfully on if latching current of thyristor is 40 mA .


Fig. 1.19
Solution: After turning on of the thyristor, the current passing through the thyristor is given by

$$
i(t)=\frac{100}{5}\left(1-e^{\frac{-5}{0.5} t}\right)=20\left(1-e^{-10 t}\right)
$$

We have to find out $t$ at which $i=40 \mathrm{~mA}$. Hence,
or,

$$
40 \times 10^{-3}=20\left(1-e^{-10 t}\right)
$$

or,

$$
\left(1-e^{-10 t}\right)=2 \times 10^{-3}
$$

$$
e^{-10 t}=0.998
$$

So $\quad t=200 \mu$ secs
Hence, pulse width should at least be $200 \mu$ secs duration.
Ans.

Problem 7. The gate-cathode characteristics of a thyristor is a straight line having slope of $150 \mathrm{~V} / \mathrm{amp}$. Calculate the gate source resistance for this thyristor if the trigger source voltage is 12 volts and allowable gate power dissipation is 0.5 W .


Fig. 1.20

Solution: Consider the figure 1.20 for solving this problem.
After thyristor turns on, we can write

$$
V_{g}=I_{g} R_{g}+V_{g k}
$$

$V_{g k}=0.7$ volts, hence,

$$
\begin{align*}
12 & =I_{g} R_{g}+0.7 \\
I_{g} R_{g} & =11.3 \tag{1.52}
\end{align*}
$$

or,
Gate power dissipation $=0.5 \mathrm{~W}$. Hence,

$$
\begin{aligned}
V_{g h} I_{g} & =0.5 \\
I_{g} & =\frac{0.5}{0.7}
\end{aligned}
$$

Putting this value of $I_{g}$ in (1.52), we get

$$
\begin{aligned}
R_{g} & =\frac{11.3 \times 0.7}{0.5} \\
& =15.82 \Omega \quad \text { Ans. }
\end{aligned}
$$

Problem 8. The protection circuit for $\frac{d v}{d t}$ and $\frac{d i}{d t}$ is as shown below. Determine the permissible maximum $\frac{d v}{d t}$ and $\frac{d i}{d t}$ for this circuit.


Fig. 1.21
Solution: Input voltage $=230 \mathrm{Vrms}$
Or instantaneous value of input voltage $=230 \sqrt{2} \sin \omega t$

$$
R_{s}=20 \Omega, C_{s}=0.15 \mu \mathrm{~F}, L_{s}=100 \mu \mathrm{H}
$$

$$
\operatorname{Load} R=10 \Omega
$$

We know that $\frac{d v}{d t}=\frac{0.632 V_{p}}{R_{s} C_{s}}=\frac{0.632 \times 230 \sqrt{2}}{20 \times 0.15 \times 10^{-6}}$

$$
=68.523 \mathrm{~V} / \mu \mathrm{secs}
$$

$$
\begin{aligned}
\frac{d i}{d t} & =\frac{V_{p}}{L_{s}}=\frac{230 \sqrt{2}}{100 \times 10^{-6}} \\
& =3.252 \mathrm{~A} / \mu \mathrm{secs}
\end{aligned}
$$

## Ans.

Problem 9. A thyristor with a latching current of 50 mA is used in the circuit shown. If a firing pulse of $50 \mu$ secs duration is applied at the instant of maximum source voltage, show whether the thyristor would stay on or not. What value of $R$ connected as shown will ensure the thyristor's turn on?


Fig. 1.22
Solution: After thyristor turns on, we have

$$
i=\frac{V_{m}}{Z} \sin (\omega t-\theta)+A e^{\frac{-R}{L} t}
$$

where ' $A$ ' is constant.

$$
\begin{align*}
Z & =R+j \omega L=10+j 2 \pi 50 \times 0.4 \\
& =126.063 \angle 85.45^{\circ} \\
\text { Hence, } \quad i & =\frac{230 \sqrt{2}}{126.063} \sin \left(2 \pi 50 t-85.45^{\circ}\right)+A e^{\frac{-10}{0.4} t} \\
& =2.58 \sin \left(2 \pi 50 t-85.45^{\circ}\right)+A e^{-25 t} \quad . . \tag{1.53}
\end{align*}
$$

Firing pulse is applied when voltage is maximum, that is, $2 \pi 50 t=\frac{\pi}{2}$ or $t=5 \mathrm{~m}$ secs.

Hence, putting $i=0$ at $t=5 \mathrm{~m}$ secs in (1.53), we get
or,

$$
\begin{aligned}
& 0=2.58 \sin \left(90^{\circ}-85.45^{\circ}\right)+A e^{-25 \times 5 \times 10^{-3}} \\
& 0=0.2046+0.8824 A
\end{aligned}
$$

Hence,

$$
A=-\frac{0.2046}{0.8824}
$$

$$
=-0.2318
$$

Hence, $\quad i=2.58 \sin \left(2 \pi 50 \cos t-85.45^{\circ}\right)-0.2318 A e^{-25 t}$
Differentiating this, we get

$$
\begin{aligned}
& \quad \frac{d i}{d t}=2.58 \times 2 \pi 50 \cos \left(2 \pi 50 t-85.45^{\circ}\right)+0.2318 \times 25 e^{-25 t} \\
& \text { Hence, }\left.\frac{d i}{d t}\right|_{t=5 m \text { secs }}=2.58 \times 2 \pi 50 \cos \left(90^{\circ}-85.45^{\circ}\right) \\
& \\
& =2.58 \times 2 \pi 50 \times 0.99684+0.2318 \times 25 e^{-25 \times 5 \times 10^{-3}} \\
& =808.174 \mathrm{~A} / \mathrm{sec}
\end{aligned}
$$

Hence, anode current at the pulse end $=808.174 \times 50 \mu$ secs

$$
=40.408 \mathrm{~mA} \quad \text { Ans. }
$$

This is less than latching current of 50 mA . Hence, thyristor will not turn on.

For thyristor to turn on, $\left.\frac{d i}{d t}\right|_{t=5 \mathrm{msec}}=\frac{50 \times 10^{-3}}{50 \times 10^{-6}}$

$$
=1000 \mathrm{~A} / \mathrm{sec}
$$

We have

$$
\begin{aligned}
& i=\frac{V_{m}}{Z} \sin (\omega t-\theta)+A e^{\frac{-R}{L} t} \\
& \frac{d i}{d t}=\frac{V m \omega}{Z} \cos (\omega t-\theta)-\frac{A R}{L} e^{\frac{-R}{L} t} \\
& \approx \frac{V_{m} \omega}{Z} \cos (\omega t-\theta), \text { as second term is almost zero. }
\end{aligned}
$$

Hence,

$$
\begin{aligned}
\left.\frac{d i}{d t}\right|_{t=5 \mathrm{~m} \text { secs }} & \approx \frac{V_{m} \omega}{Z} \cos \left(90^{\circ}-\theta\right) \\
& \approx \frac{V_{m} \omega}{Z} \sin \theta \\
& \approx \frac{V_{m} \omega^{2} L}{Z^{2}} \operatorname{as~} \sin \theta=\frac{\omega L}{Z} \\
\text { Hence, } \quad 1000 & \approx \frac{230 \sqrt{2}(100 \pi)^{2} \times 0.4}{Z^{2}} \\
\text { or } \quad Z & \approx 113.318 \Omega
\end{aligned}
$$

As $Z$ is less than $\omega L$ itself, hence, it will not be possible to turn on thyristor by reducing $R$.

Problem 10. A thyristor has gate cathode characteristics as $V_{g}=1+81_{g}$. A pulse of $15 \mu$ secs and amplitude of 12 V is to be applied to the gate. If the average gate power loss is 0.25 W and peak gate drive power is $4 W$, compute (a) the resistance to be connected in series with
the gate (b) the triggering frequency and (c) the duty cycle of the triggering pulse.

Solution: (a) Peak power is delivered to the gate when pulse is applied.

Hence, $\quad V_{g} I_{g}=4$
Gate cathode characteristics is given by

$$
V_{g}=1+8 I_{g}
$$

Eliminating $V_{g}$ from (1.54) and (1.55), we get

$$
I_{g}\left(1+8 I_{g}\right)=4
$$

or,

$$
8 I_{g}^{2}+8 I_{g}-4=0
$$

Hence, $\quad I_{g}=\frac{-1 \pm \sqrt{1+128}}{16}=0.647 \mathrm{amps}$.
If $R_{s}$ is the resistance to be connected in series, we have

$$
12=I_{g} R_{s}+V_{g}
$$

or,

$$
12=0.647 R_{s}+1+8 \times 0.647
$$

or,

$$
R_{s}=\frac{5.824}{0.647}=9 \Omega \quad \text { Ans. }
$$

(b) $P_{g a v}=0.25 \mathrm{~W}, P_{g m}=4 \mathrm{~W}$, duty ratio $\delta=$ ?

$$
P_{g a v}=P_{g m} \times \delta
$$

Hence, $\quad \delta=\frac{P_{g a v}}{P_{g m}}=\frac{0.25}{4}=0.0625 \quad$ Ans.
(c) Triggering frequency $f=$ ?

$$
\begin{array}{ll} 
& f=\frac{1}{T} \\
& \delta=\frac{T^{\prime}}{T}, \text { Where } T^{\prime} \text { is pulse duration and } T \text { is period. } \\
\text { Hence, } \quad T=\frac{T^{\prime}}{\delta} \\
\text { Hence, } \quad f=\frac{\delta}{T^{\prime}}=\frac{0.0625}{15 \times 10^{-6}}=4166.67 \mathrm{~Hz} \quad \text { Ans. }
\end{array}
$$

Problem 11. Consider the following circuit in which a thyristor controls the power fed to a resistive load.

The value of $\frac{d v}{d t}$ and $\frac{d i}{d t}$ for safe working of the thyristor are $200 V / \mu$ secs and $60 A / \mu$ sec respectively. Determine the values of $R_{s}, C_{s}$ and $L$ to meet these requirements.


Fig. 1.23
Solution: After switch $S$ is closed, the capacitance gets short circuited and thyristor is in forward blocking state. The governing equation is given by

$$
220=\left(R_{s}+R\right) i+L \frac{d i}{d t}
$$

Its solution is

Hence,

$$
\begin{aligned}
i & =\frac{220}{R_{s}+R}\left[1-e^{\frac{-\left(R+R_{s}\right)}{L} t}\right] \\
\frac{d i}{d t} & =\frac{220}{R_{s}+R} \cdot \frac{R_{s}+R}{L} e^{\frac{\left(-R+R_{s}\right)}{L} t} \\
& =\frac{220}{L} e^{\frac{-\left(R+R_{s}\right) t}{L} t}
\end{aligned}
$$

$\frac{d i}{d t}$ will be maximum at $t=0$. Hence, $\left(\frac{d i}{d t}\right)_{\max }=\frac{220}{L}$

$$
\text { But } \begin{aligned}
\left(\frac{d i}{d t}\right)_{\max } & =60 \mathrm{~A} / \mu \text { secs, hence, } L=\frac{220}{60} \times 10^{-6} \\
& =3.667 \mu \mathrm{H}
\end{aligned}
$$

At the instant of closing the switch, thryistor voltage

$$
V_{t}=R_{s} i
$$

or,

$$
\frac{d V_{t}}{d t}=R_{s} \frac{d i}{d t}
$$

$\frac{d i}{d t}$ is maximum at $t=0$, hence, $\frac{d V_{t}}{d t}$ will also be maximum.
Therefore,

$$
\left(\frac{d V_{t}}{d t}\right)_{\max }=R_{s} \times 60 A / \mu \mathrm{secs}
$$

or, $\quad 200 \mathrm{~V} / \mu \mathrm{secs}=R_{s} \times 60 \mathrm{~A} / \mu \mathrm{secs}$

$$
\begin{array}{rlrl}
\text { Hence, } & R_{s} & =\frac{200}{60}=3.33 \Omega \\
R_{s} & =\sqrt{\frac{L}{C_{s}}} \\
\text { So } & C_{s} & =\frac{L}{R_{s}^{2}}=\frac{3.667 \times 10^{-6}}{3.33^{2}} \\
& & =0.33 \mu \mathrm{~F}
\end{array}
$$

What we have found are the exact values of $C_{s}, R_{s}$ and $L$ and there is no safety margin available for thyristor operation. Generally, snubber circuit parameters are elected to be on safer side. We can have $R_{s}$ slightly higher than the calculated value. Let us have

$$
\begin{aligned}
R_{s} & =5 \Omega \\
\left(\frac{d V_{t}}{d t}\right)_{\max } & =R_{s} \times \frac{220}{L} \\
\text { Hence, } \quad L & =\frac{5 \times 220 \times 10^{-6}}{200}=5.5 \mu \mathrm{H}
\end{aligned}
$$

$C_{s}$ is also selected somewhat less than the exact value as it will force lower current at the time of conduction of thyristor. Let us choose $C_{s}=0.25 \mu$ F Ans.

Problem 12. Latching current of a thyristor delivering a load from 200 V source is 75 mA . Determine the minimum gate pulse current width required to turn the thyristor if the load consists of (a) $L=0.15 H(b) R=15 \Omega$ in series with $L=0.15 H$ and $(c) R=15 \Omega$ in series with $L=0.75 \mathrm{H}$.

Solution: (a) $L=0.15 H$
The governing equation is $V=L \frac{d i}{d t}$
or,

$$
200=0.15 \frac{d i}{d t}
$$

or, $\quad t=\frac{0.15}{200} i \quad$ as $i=0$ at $t=0$.

$$
i=75 \mathrm{~mA}, \text { hence, } t=\frac{0.15}{200} \times 75 \times 10^{-3}
$$

$$
=56.25 \mu \mathrm{secs}
$$

Ans.
(b) $R=15 \Omega, L=0.15 \mathrm{H}$

The governing equation is given by

$$
V=R i+L \frac{d i}{d t}
$$

Its solution is $i=\frac{V}{R}\left[1-e^{\frac{-R}{L} t}\right]$
or, $\quad 75 \times 10^{-3}=\frac{200}{15}\left[1-e^{\frac{-15}{0.15} t}\right]$
or, $\quad e^{-100 t}=0.994375$
or

$$
t=56.408 \times 10^{-6}
$$

Hence, required pulse width $=56.408 \mu$ secs

## Ans.

(c) $R=15 \Omega, L=0.75 H$

The governing equation is given by

$$
V=R i+L \frac{d i}{d t}
$$

Its solution is $i=\frac{V}{R}\left[1-e^{\frac{-R}{L} t}\right]$
or, $\quad 75 \times 10^{-3}=\frac{200}{15}\left[1-e^{\frac{-15}{0.75} t}\right]$
or, $\quad e^{-20 t}=0.994375$
or $\quad t=282.043 \times 10^{-6}$
Hence, required pulse width $=282.043 \mu$ secs
Ans.

Problem 13. The maximum allowable junction temperature of a thyristor is $125^{\circ} \mathrm{C}$. The thermal resistance for the thyristor-sink combination are $\theta_{j c}=0.16$ and $\theta_{c s}=0.08^{\circ} \mathrm{C} / W$. For a heat sink temperature of $50^{\circ} \mathrm{C}$, determine the total power loss in the thyristorsink combination. In case, we bring the heat sink temperature to $40^{\circ} \mathrm{C}$ by forced cooling, find the \%age change in the device rating.

Solution: We know that

$$
\begin{aligned}
T_{j} & =T_{s}+P_{a v}\left(\theta_{j c}+\theta_{c s}\right) \\
\text { Hence, } \quad P_{a v} & =\frac{125-50}{0.16+0.08}=312.5 \mathrm{~W}
\end{aligned}
$$

When cooling is improved, we have

$$
=\frac{85}{0.24}=354.167 \mathrm{~W}
$$

Thyristor rating is proportional to the square root of average power loss. Hence,

$$
\begin{array}{r}
\text { \%age increase in thyristor rating }=\frac{\sqrt{354.167}-\sqrt{312.5}}{\sqrt{312.5}} \\
=\frac{18.819-17.677}{17.67}=6.46 \% \quad \text { Ans. }
\end{array}
$$

Problem 14. A thyristor has a thermal capacity of $0.25 \mathrm{~J} /{ }^{\circ} \mathrm{C}$ and thermal resistnace of $0.7^{\circ} \mathrm{C} / \mathrm{W}$. Determine the maximum power dissipation which the thyristor can withstand for 0.1 sec for a temperature not exceeding $50^{\circ} \mathrm{C}$.

Solution: Thermal capacity $=0.25 \mathrm{~J} /{ }^{\circ} \mathrm{C}$
Thermal resistance $=0.7^{\circ} \mathrm{C} / \mathrm{W}$
Hence, power dissipated for $1^{\circ} \mathrm{C}$ temperature rise

$$
=\frac{1}{0.7} \mathrm{~W} /{ }^{\circ} \mathrm{C}=1.4285 \mathrm{~W} /{ }^{\circ} \mathrm{C}
$$

Thermal time constant $\tau=\frac{\text { Thermal capacity }}{\text { Power dissipation for } 1^{\circ} \mathrm{C} \text { rise }}$

$$
=\frac{0.25}{1.4285}=0.175
$$

We know that $T_{j}=T_{\text {jmax }}\left(1-e^{\frac{-t}{\tau}}\right)$
If the temperature has to increase $50^{\circ} \mathrm{C}$ after 0.1 sec , we have

$$
50=T_{j \max }\left(1-e^{\frac{-0.8}{0.175}}\right)
$$

$$
\text { or, } \quad T_{j \max }=114.868^{\circ} \mathrm{C}
$$

Hence, the maximum junction temperature $=114.868^{\circ} \mathrm{C}$
So Power $=T_{\text {jmax }} \times$ power dissipated per ${ }^{\circ} \mathrm{C}$ temperature rise

$$
=114.868 \times 1.4285=164.088 \mathrm{~W} \quad \text { Ans. }
$$

Problem 15. Consider the following circuit showing details of heat transfer from the junction of a transistor to the ambient.


Fig. 1.24
Power loss in the transistor is 100 W and the ambient temperature is $45^{\circ} \mathrm{C}$ and maximum junction temperature is $150^{\circ} \mathrm{C}$. Calculate $\theta_{C A}$ if $\theta_{J} C$ is $0.5^{\circ} C / W$.

Solution: From the given figure, we have

$$
\begin{equation*}
\theta_{C A}=\theta_{J A}-\theta_{J C} \tag{1.56}
\end{equation*}
$$

$\Delta T$ between junction and the ambient temperature

$$
\begin{aligned}
& =150^{\circ}-45^{\circ}=105^{\circ} \mathrm{C} \\
\text { Power } & =100 \mathrm{~W}
\end{aligned}
$$

Hence, heat resistance $\theta_{J A}=\frac{0.25}{1.4285}=\frac{105}{100}=1.05^{\circ} \mathrm{C} / \mathrm{W}$
Putting this value in (1),
we get

$$
\theta_{C A}=1.05-0.5=0.55^{\circ} \mathrm{C} / \mathrm{W}
$$

Ans.

Problem 16. The power dissipation in a thyristor is 150W. The ambient temperature is $40^{\circ} \mathrm{C}$ and the sink temperature is not to exceed $70^{\circ} \mathrm{C}$. Determine the thermal resistance of the heat sink including that of the case.

Solution: Power $=150 \mathrm{~W}$

$$
\begin{aligned}
T_{\text {cmax }} & =70^{\circ} \mathrm{C} \\
T_{A} & =40^{\circ} \mathrm{C}
\end{aligned}
$$



Fig. 1.25
Temperature rise from ambient to case $=70^{\circ}-40^{\circ}=30^{\circ} \mathrm{C}$
Hence,

$$
\theta_{C A}=\frac{30}{150}=0.2^{\circ} \mathrm{C} / \mathrm{W}
$$

Ans.
Problem 17. A transistor is mounted on a heat sink. The thermal resistances are:

$$
\theta_{J C}=0.5^{\circ} \mathrm{C} / W ; \theta=0.2^{\circ} \mathrm{C} / \mathrm{W} ; \theta=1.6^{\circ} \mathrm{C} / \mathrm{W}
$$

If maximum junction temperature is $180^{\circ} \mathrm{C}$ and ambient temperature is $40^{\circ} \mathrm{C}$, determine the maximum permissible power flow through the transistor.


Fig. 1.26

## Solution:

$$
\Delta T=P\left(\theta_{J C}+\theta_{C S}+\theta_{S A}\right)
$$

Putting various values in this equation, we get

$$
180-40=P(0.5+0.2+1.6)
$$

Hence, $\quad P=\frac{140}{2.3}=60.869 \mathrm{~W}$
Ans.

Problem 18. A power transistor has $\theta_{J C}=0.5^{\circ} \mathrm{C} / W$ and $\theta_{C S}=0.2^{\circ} \mathrm{C} / W$. If the junction temperature is $125^{\circ} \mathrm{C}$ when the ambient
temperature is $30^{\circ} \mathrm{C}$, calculate the (a) maximum power dissipation and (b) case temperature.

Solution: (a) $T_{J}-T_{A}=P\left(\theta_{J C}+\theta_{C S}+\theta_{S A}\right)$
Putting the given data in this equation, we get

$$
\begin{aligned}
125-30 & =P(0.5+0.2+0.6) \\
\text { Hence, } \quad P & =\frac{95}{1.3}=73.076 \mathrm{~W}
\end{aligned}
$$

## Ans.

(b) We have $\quad T_{C}-T_{A}=P\left(\theta_{C S}+\theta_{S A}\right)$

Hence, $T_{C}-30=\frac{95}{1.3} \times(0.2+0.6)$
So $\quad T_{c}=88.46^{\circ} \mathrm{C} \quad$ Ans.

Problem 19. The junction temperature of a thyristor is $200^{\circ} \mathrm{C}$ and various thermal resistances are $\theta_{J C}=0.5^{\circ} \mathrm{C} / \mathrm{W}$; $\theta_{C S}=0.2^{\circ} \mathrm{C} / \mathrm{W}$. If power dissipated in the thyristor is 150 W and the ambient temperature is $40^{\circ} \mathrm{C}$, determine the temperature of case and sink and thermal resistance $\theta_{S A}$.

Solution: We know that

$$
\begin{aligned}
T_{J}-T_{C} & =P \times \theta_{J C} \\
T_{C}-T_{S} & =P \times \theta_{C S} \\
T_{S}-T_{A} & =P \times \theta_{S A} \\
P & =150 \mathrm{~W}, \theta_{J C}=0.5^{\circ} \mathrm{C} / W, \theta_{C S}=0.2^{\circ} \mathrm{C} / W
\end{aligned}
$$

Putting these values in the above equations, we get

$$
\begin{aligned}
200-T_{C} & =150 \times 0.5 \\
\text { Hence, } T_{C} & =200-75=125^{\circ} \mathrm{C} \\
125-T_{s} & =150 \times 0.2 \\
T_{S} & =125-30=95^{\circ} \mathrm{C} \\
\text { or, } \quad \text { Also } \quad 95-40 & =150 \times \theta_{S A} \\
\text { Hence, } \quad \theta_{S A} & =\frac{55}{150}=0.367^{\circ} \mathrm{C} / \mathrm{W}
\end{aligned}
$$

Ans.

Problem 20. Consider the following relaxation oscillator circuit using UJT for triggering a thyristor.

The UJT has the following data: $\eta=0.8, I_{p}=0.65 m A, V_{p}=$ $20 \mathrm{~V}, V_{v}=1 \mathrm{~V}, I_{v}=3, R_{B B}=5 k \Omega$, normal leakage current when emitter is opened $=4.5 \mathrm{~mA}$. The firing frequency is 2 Khz . For $C=0.5 \mu F$, computer $R, R_{1}$ and $R_{2}$.

Solution: The value of charging resistance is given by


Fig. 1.27

$$
R=\frac{T}{C \operatorname{In} \frac{I}{1-\eta}} \quad ; T=\frac{1}{f}
$$

Hence,

$$
\begin{aligned}
R & =\frac{1}{2 \times 10^{3} \times 0.5 \times 10^{-6} \ln \frac{1}{1-0.8}} \\
& =6.213 \mathrm{k} \Omega
\end{aligned}
$$

As $V_{D}$ is not given, we can neglect it. Hence,

$$
\begin{aligned}
V_{p} & =\eta V_{B B} \\
V_{B B} & =\frac{20}{0.8}=25 \text { volts } \\
R_{2} & =\frac{0.7 R_{B B}}{V_{p}}=\frac{0.7 \times 5000}{20}=175 \Omega
\end{aligned}
$$

When emitter is opened, we have

$$
V_{B B}=I_{1}\left(R_{1}+R_{2}+R_{B B}\right) \text { Where } I_{1} \text { is leakage current. }
$$

Hence, $\quad R_{1}=\frac{25}{4.5} \times 10^{3}-175-5000=380.55 \Omega$

Problem 21. A unijunction transistor circuit shown below is to be used as relaxation oscillator. The data for UJTare as given below:

$$
V_{v}=1.5 \mathrm{~V}, V_{p}=8 V, R=1 k \Omega, C=1 \mu F .
$$

Determine the frequency of the oscillator.
Solution: We know that
Assuming $V_{D}=0.7$ volts, we have

$$
8=\eta \times 12+0.7
$$

Hence, $\quad \eta=\frac{8-0.7}{12}=0.6083$


Fig. 1.28

Hence, $\quad f=\frac{1}{R C \ln \frac{1}{1-\eta}}$
Putting numerical values, we get

$$
\begin{aligned}
f & =\frac{1}{1 \times 10^{3} \times 1 \times 10^{6} \ln \frac{1}{1-0.6083}} \\
& =1066.94 \mathrm{~Hz} \quad \text { Ans. }
\end{aligned}
$$

Problem 22. A thyristor is to be triggered by using a relaxation oscillator which utilizes unijunction transistor. The characteristics of UJT are $\eta=0.7, V_{p}=15 \mathrm{~V}, I_{p}=0.6 \mu \mathrm{~A}$, normal leakage current with emitter opened $=3 \mathrm{~mA}, V_{v}=1 \mathrm{~V}, I_{v}=6 \mathrm{~mA}, R_{B 1 B 2}=5 \mathrm{k} \Omega$. The firing frequency is 200 Hz . If $C=0.1 \mu F$, calculate the values of charging resistance and external resistances. Also calculate maximum and minimum values of charging resistance. Hence, find out maximum and minimum values of frequency of operation.


Fig. 1.29

Solution: We know that $T=R C \ln \frac{1}{1-\eta} ; T=\frac{1}{f}$.
Hence, $\frac{1}{200}=R \times 0.1 \times 10^{6} \ln \frac{1}{1-0.7}$
Hence, $\quad R=\frac{1}{200 \times 0.1 \times 10^{-6} \operatorname{In} \frac{1}{1-0.7}}=41.529 k \Omega$

$$
V_{P}=\eta V_{B B}+V_{D}
$$

$$
15=0.7 V_{B B}+0.7
$$

Hence, $\quad V_{B B}=\frac{5-0.7}{0.7}=20.428$ volts.

$$
\begin{aligned}
R_{2} & =\frac{0.7 R_{B B}}{\eta V_{B B}} \\
& =\frac{0.7 \times 5000}{0.7 \times 20.428}=244.762 \Omega \quad \text { Ans. } \\
V_{B B} & =I_{1}\left(R_{1}+R_{2}+R_{B B}\right) \text { where } I_{1} \text { is leakage current. } \\
\text { Hence, } \quad R_{1} & =\frac{20.428}{3} \times 10^{3}-244.762-5000 \\
& =1564.571 \Omega \quad \text { Ans. }
\end{aligned}
$$

Ans.
$R_{\max }=\frac{V_{B B}-V_{P}}{I_{P}}=\frac{20.428-15}{0.6 \times 10^{-6}}$
$=9.046 M \Omega \quad$ Ans.
$R_{\min }=\frac{V_{B B}-V_{v}}{I_{V}}=\frac{20.428-1}{6 \times 10^{-3}}=3.238 k \Omega \quad$ Ans.

$$
\begin{aligned}
f_{\min } & =\frac{1}{R_{\max } C \ln \frac{1}{1-\eta}} \\
& =\frac{1}{9.046 \times 10^{6} \times 0.1 \times 10^{-6} \ln \frac{1}{1-0.7}}
\end{aligned}
$$

$$
=0.918 \mathrm{~Hz}
$$

Ans.

$$
\begin{aligned}
f_{\max } & =\frac{1}{R_{\min } C \operatorname{In} \frac{1}{1-\eta}} \\
& =\frac{1}{3.238 \times 10^{3} \times 0.1 \times 10^{-6} \ln \frac{1}{1-0.7}} \\
& =2565.112 \mathrm{~Hz} \quad \text { Ans. }
\end{aligned}
$$

Problem 23. Determine the conduction time of thyristor and the peak current that will flow in the following circuit employing series resonant commutation. Assume zero initial conditions.


Solution: Critical value of resistance

$$
=2 \sqrt{L / C}=2 \sqrt{\frac{5 \times 10^{-3}}{0.5 \times 10^{-6}}}=200 \Omega
$$

In the given circuit, $R=50 \Omega$ <critical resistance. Hence, the circuit is critically damped.

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

$$
\begin{aligned}
& =\sqrt{\frac{1}{5 \times 10^{-3} \times 0.5 \times 10^{-6}}-\frac{50^{2}}{4 \times\left(5 \times 10^{-3}\right)^{2}}} \\
& =\sqrt{4 \times 10^{8}-25 \times 10^{6}} \\
& =19364.916 \mathrm{rad} / \mathrm{sec} \quad \text { Ans. }
\end{aligned}
$$

As initial conditions are zero, current through the circuit given

$$
\begin{gathered}
i=\frac{V}{\omega L} e^{\frac{-R}{2 L} t} \sin \omega t, \text { where } \alpha=\frac{R}{2 L} \\
T=\frac{1}{f}=\frac{2 \pi}{\omega}=\frac{2 \pi}{19364.916}=324.462 \mu \mathrm{sec}
\end{gathered}
$$

Period
Thyristor conducts for half period. Hence, conduction period

$$
=\frac{324.462}{2}=162.231 \mu \mathrm{secs}
$$

Ans.
Peak value of current occurs at $t=\frac{1}{\omega} \tan ^{-1} \frac{\omega}{\alpha}$

$$
\begin{aligned}
& =\frac{1}{19364.916} \tan ^{-1} \frac{19364.916 \times 2 \times 5 \times 10^{-3}}{50} \\
& =\frac{1}{19364.916} \times 75.522^{\circ}=6.806 \times 10^{-5} \mathrm{sec} \\
\text { Hence, } \quad i_{\text {peak }} & =\frac{200}{19364.916} e^{\frac{-50 \times 6.806 \times 10^{-5}}{2 \times 5 \times 10^{-3}}} \sin 19364.916 \\
& \times 6.806 \times 10^{-5} \\
& =2.0655 \times 0.7115 \times 0.9682=1.422 \mathrm{amps} . \text { Ans. }
\end{aligned}
$$

Problem 24. For the input commutated circuit shown below, determine the available turn off time if $V=250$ volts, $R=20 \Omega$ and $C=15 \mu F$ and initial value of voltage on capacitance is $V$ with the polarity as marked up.


Fig. 1.31
Solution: After $T_{2}$ is fired, the voltage across capacitance is given by

$$
\begin{equation*}
V_{c}=\frac{q}{C} \tag{1.58}
\end{equation*}
$$

where $q$ is charge on the capacitance charge.

$$
\begin{equation*}
V=v_{c}+i R \tag{1.59}
\end{equation*}
$$

Differentiating (1.58), we get

$$
\frac{d q}{d t}=C \frac{d v_{c}}{d t}
$$

or,

$$
i=C \frac{d v_{c}}{d t}
$$

Putting this value in (1.59), we get $V-v_{c}=R C \frac{d v_{c}}{d t}$
Taking Laplace transform, we get

$$
\begin{array}{ll}
\frac{V}{s}-v_{c}(s) & =R C\left[s v_{c}(s)-v_{c}(0)\right] \\
\text { or, } \quad \frac{V}{s}-v_{c}(s) & =R C\left[s v_{c}(s)-V\right] \quad \text { As } v_{c}(0)=V
\end{array}
$$

Simplifying this, we get

$$
V_{c}(s)=\frac{V}{s}-\frac{2 V}{s+\frac{1}{R C}}
$$

Taking inverse Laplace transform, we get

$$
v_{c}(t)=V\left[1-2 e^{\frac{-t}{R C}}\right]
$$

At available turn off time, $v_{c}=0$. If $t_{0}$ is available turn off time, we get
or

$$
\begin{aligned}
e^{\frac{-t}{R C}} & =\frac{1}{2} \\
e^{\frac{t}{R C}} & =2 \\
t_{0} & =R C \ln 2=20 \times 15 \times 10^{-6} \ln 2 \\
& =207.944 \mu \text { secs } \quad \text { Ans. }
\end{aligned}
$$

Problem 25. Following figure shows a self commutating circuit. The initial current in the circuit is 50A and the capacitance carries an initial voltage of $V$, the supply voltage with polarity as marked. Determine the conduction time of the thyristor and the capacitance voltage at turn off.


Fig. 1.32
Solution: When thyristor is 'ON' the governing equation is given by

$$
V=L \frac{d i}{d t}+\frac{1}{C} \int i d t+v_{c}(0)
$$

Taking Laplace transform, we get

$$
\frac{V}{s}=L[s i(s)-i(0)]+\frac{i(s)}{C s}+\frac{v_{c}(0)}{s}
$$

Simplifying this, we get

$$
\begin{aligned}
& i(s)=\frac{V-v_{c}(0)}{L\left(s^{2}+\omega^{2}\right)}+\frac{s i(0)}{s^{2}+\omega^{2}} \\
& \omega^{2}=\frac{1}{L C}
\end{aligned}
$$

Taking inverse Laplace transform, we get

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

Here, $v_{c}(0)=V$ and $i(0)=50$. Hence, $i(t)=50 \cos \omega t$

$$
\begin{aligned}
v_{c}(t) & =\frac{1}{C} \int_{0}^{t} i(\tau) d \tau+v_{c}(0)=\frac{1}{C} \int_{0}^{t} 50 \cos \omega \tau d \tau+V \\
& =\frac{50}{\omega C \sin \omega}+V=50 \sqrt{\frac{L}{C}} \sin \omega t+V
\end{aligned}
$$

Turn off occurs when $i=0$, that is, $50 \cos \omega t_{0}=0$
Or,

$$
\begin{aligned}
t_{0} & =\frac{\pi}{2 \omega}=\frac{\pi}{2} \sqrt{L C} \\
& =\frac{\pi}{2} \sqrt{20 \times 10^{-6} \times 50 \times 10^{-6}}=49.673 \mu \mathrm{secs}
\end{aligned}
$$

At turn off, $v_{c}\left(t_{0}\right)=50 \sqrt{\frac{20 \times 10^{-6}}{50 \times 10^{-6}}} \sin \frac{\pi}{2}+200$

$$
=231.622 \text { volts } \quad \text { Ans. }
$$

Problem 26. In the circuit shown below, $V=400$ volts and initial capacitance voltage is zero. The thyristor is switched on at $t=0$. Determine the conduction time of thyristor, the peak capacitor voltage and the peak current. The circuit parameters are $L=25 \mu H, C=100 \mu F$. Assume the current through the inductance at the time of triggering the thyristor is 200A.


Fig. 1.33

## Solution:

$$
V=400 \text { volts, } L=25 \mu \mathrm{H}, C=100 \mu \mathrm{~F}, i(0)=200 \mathrm{~A}
$$

As derived in the last problem, we have

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

Here, $v_{c}(0)=0, i(0)=200 \mathrm{~A}$.
Hence, $\quad i(t)=400 \sqrt{\frac{100 \times 10^{-6}}{25 \times 10^{-6}}} \sin \omega t+200 \cos \omega t$

$$
=800 \sin \omega t+200 \cos \omega t
$$

$$
\begin{aligned}
& =\sqrt{800^{2}+200^{2}}\left[\frac{800}{\sqrt{800^{2}+200^{2}}} \sin \omega t+\frac{200}{\sqrt{800^{2}+200^{2}}} \cos \omega t\right] \\
& =824.621[\sin \omega t \cos \theta+\cos \omega t \sin \theta] \text { if } \tan \theta=\frac{200}{800} \\
& =824.621 \sin (\omega t+\theta) \quad \text { Ans. }
\end{aligned}
$$

Hence, peak current $=824.621 \mathrm{amps}$.

$$
\begin{aligned}
v_{c}(t) & =\frac{1}{C} \int_{0}^{t} i(\tau) d \tau+v_{c}(0) \\
& =\frac{824.621}{C} \int_{0}^{t} \sin (\omega \tau+\theta) d \tau \operatorname{as} v_{c}(0)=0 \\
& =824.621 \sqrt{\frac{L}{C}}[\cos \theta-\cos (\omega t+\theta)]
\end{aligned}
$$

$V c(t)$ will be maximum when $\omega t=\pi-\theta$. Hence,

$$
\begin{aligned}
v_{\text {cmax }} & =824.621 \sqrt{\frac{25 \times 10^{-6}}{100 \times 10^{-6}}}\left[\cos \left(\tan ^{-1} 0.25\right)+1\right] \\
& =\frac{824.621}{2} \times 1.970=812.292 \text { volts } \quad \text { Ans. }
\end{aligned}
$$

Thyristor conduction time $=\frac{\pi-\theta}{\omega}$

$$
\begin{aligned}
& =\frac{\pi-\tan ^{-1} 0.25}{\frac{1}{\sqrt{25 \times 10^{-6} \times 100 \times 10^{-6}}}} \\
& =\frac{2.8966}{20000}=144.83 \mu \text { secs } \quad \text { Ans. }
\end{aligned}
$$

Problem 27. The circuit below shows a resonant pulse impulse circuit. The initial capacitor voltage is $250 \mathrm{~V}, \mathrm{C}=50 \mu \mathrm{~F}$ and $L=5 \mu \mathrm{H}$. Determine the circuit turn off time $t_{c}$ if the load current is (a) 100A and (b) 150A.


Fig. 1.34

Solution: (a) Load current $=100 \mathrm{amps}$.
After $T_{2}$ is fired, the current through capacitor is given by

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

$T_{1}$ is turned off when $i_{c}(t)$ becomes equal to load current. Let this time be $t_{1}$. Hence,
or,

$$
\begin{aligned}
100 & =250 \sqrt{\frac{50 \times 10^{-6}}{5 \times 10^{-6}}} \sin \omega t_{1} \\
100 & =790.569 \sin \omega t_{1} \\
\omega t_{1} & =7.2668^{\circ}=0.1261 \text { radians }
\end{aligned}
$$

At $t=t_{1}$, the magnitude of capacitor voltage is $v_{c}=250 \cos \omega t_{1}$

$$
=250 \cos 0.1261(\mathrm{rad})=248 \text { volts }
$$

Circuit turn off time is given by $t_{c}=\frac{C V_{c}}{I}$

$$
=\frac{50 \times 10^{-6} \times 248}{100}=124 \mu \operatorname{secs} \quad \text { Ans. }
$$

(b) $I=150 \mathrm{~A}$
or,

$$
\begin{aligned}
& 150=250 \sqrt{\frac{50 \times 10^{-6}}{5 \times 10^{-6}}} \sin \omega t_{1} \\
& 150=790.569 \sin \omega t_{1} \\
& \omega t_{1}=10.9374^{\circ}
\end{aligned}
$$

At $t=t_{1}$, the magnitude of capacitor voltage is $v_{c}=250 \cos \omega t_{1}$ $=250 \cos 10.9374^{\circ}=245.458$ volts
Circuit turn off time is given by $t_{c}=\frac{C V_{c}}{I}$

$$
=\frac{50 \times 10^{-6} \times 248}{150}=81.819 \mu \mathrm{secs} \quad \text { Ans. }
$$

Problem 28. In the circuit shown below, find out the value of $L$ for proper commutation of thyristor. Also determine the conduction time of thyristor.

Solution: When thyristor is conducting, load current

$$
I=\frac{50}{25}=2 A
$$

If thyristor has to commutate properly, $I_{p}$, the peak value of the resonant current should be greater than the load current $I$. Let

$$
I_{p}=2 I=2 \times 2=4 A
$$



Fig. 1.35
or

$$
\begin{aligned}
& \quad \begin{aligned}
& i_{p}=I_{p} \sin \omega t \quad \text { where } \omega=\frac{1}{\sqrt{L C}} \\
&=V \sqrt{C / L} \sin \omega t \\
& I_{p}=V \sqrt{C / L} \\
& \text { Hence, } \quad \begin{aligned}
& 4=50 \sqrt{\frac{5 \times 10^{-6}}{L}} \\
& L=\frac{50^{2}}{4^{2}} \times 5 \times 10^{-6}=781.25 \mu \mathrm{H} \quad \text { Ans. } \\
& \text { Hence, } \quad \begin{aligned}
\omega & =\frac{1}{\sqrt{L C}} \\
& =\frac{1}{\sqrt{781.25}}
\end{aligned} \\
& \text { Thyristor conduction time }=\frac{\pi+\sin ^{-1}\left(I / I_{p}\right)}{\omega} \\
&=\frac{\pi+\sin ^{-1}(1 / 2)}{16000} \\
&=\frac{7 \pi}{6 \times 16000}=0.229 \mathrm{~m} \mathrm{secs} \text { Ans. }
\end{aligned}
\end{aligned} \begin{aligned}
\\
\end{aligned} \\
&
\end{aligned}
$$

Problem 29. In the circuit shown below, the load current of 20 A is to be commutated and turn off time required is $50 \mu$ secs. Determine the optimum values of $C$ and $L$.


Fig. 1.36

Solution: Peak value of resonant current i is given by

$$
I_{p}=V \sqrt{C / L}
$$

$I_{p}$ should be greater than load current $I$.
Let

$$
\frac{I_{p}}{I}=1.8 \text { or } I_{p}=1.8 \times 20
$$

Hence,

$$
\begin{equation*}
20 \times 1.8=100 \sqrt{C / L} \tag{1.60}
\end{equation*}
$$

Assuming that at the time of turning off of the thyristor, the capacitor voltage is equal to the supply voltage and capacitor charges linearly.

Hence,

$$
\begin{aligned}
& t_{c}=\frac{C V}{I} \\
& t_{c}=.50 \times 10^{-6}
\end{aligned}
$$

$$
\text { Hence, } \quad 50 \times 10^{\circ}=\frac{20}{20}
$$

or,

$$
C=\frac{50 \times 10^{-6} \times 20}{100}=10 \mu \mathrm{~F}
$$

Ans.
Putting this value of $C$ in (1.60), we get
or,

$$
\begin{aligned}
20 \times 1.8 & =100 \sqrt{\frac{10 \times 10^{-6}}{L}} \\
L & =\frac{10 \times 10^{-6}}{0.36 \times 0.36}=77.160 \mu \mathrm{H} \quad \text { Ans. }
\end{aligned}
$$

Problem 30. In a resonant commutation circuit, the supply voltage is 250 V . Load current is 25 A and the device turn off time is $20 \mu$ secs. The ratio of peak resonant current to the load current is 1.75. Find out the value of $L$ and $C$ of the commutation circuit.

Solution: $\frac{\text { Peak resonant current } I_{p}}{\text { Load current } I}=1.75$
Hence, $\quad I_{p}=1.75 \times 25=43.75 \mathrm{~A}$
We know that $I_{p}=V \sqrt{C / L}$
Hence, $\quad 43.75=250 \sqrt{C / L}$
Device turn off time is $20 \mu$ secs. Circuit turn off time should be more than device turn off time. To be on safer side, we take circuit turn off time as 1.5 times the devices turn off time. Hence, circuit turn off time

$$
\text { But } \quad \begin{aligned}
& t_{c}=20 \times 1.5=30 \mu \mathrm{secs} \\
& t_{c}=\frac{C V}{I}
\end{aligned}
$$

Hence, $30 \times 10^{-6}=\frac{C \times 250}{25}$
So $\quad C=3 \mu \mathrm{~F} \quad$ Ans.
Putting this value of $C$ in (1.61), we get
or,

$$
\begin{aligned}
43.75 & =250 \sqrt{\frac{3 \times 10^{-6}}{L}} \\
L & =\frac{250 \times 250 \times 3 \times 10^{-6}}{43.75 \times 43.75} \\
& =97.959 \times 10^{-6} \approx 97.6 \mu \mathrm{H}
\end{aligned}
$$

Ans.

Problem 31. The following circuit shows a complementary commutation circuit.


Fig. 1.37
For this circuit, calculate the turn off time.
Solution: For complementary commutation, circuit turn off time

$$
t_{c}=0.693 R C \text { secs }
$$

Here $\quad R=5 \Omega, C=10 \mu F$ Hence,
$t_{c}=0.693 \times 5 \times 10^{-6}$ secs $=34.65 \mu$ secs Ans.

Problem 32. The following figure shows a complementary commutation circuit. Calculate the values of $R$ and $C$ to be used for commutating the main thyristor when full load current of 50A flows. The thyristor needs to be reverse biased at least for $40 \mu$ secs for proper commutation. Also find $R$, given that the auxiliary thyristor will undergo natural commutation when forward current falls below the holding current value of $2 m A$.

Solution: Main thyristor carries the load current and auxiliary thyristor is used to turn off the main thyristor. After the main thyristor has turned off, the sum of charging current of capacitor and


Fig. 1.38
current passing through $R$ passes through the auxiliary thyristor; capacitor current reduces to zero after time $t_{c}$. Auxiliary thyristor turns off automatically if the current passing through $R$ is less than holding current of auxiliary thyristor.

Auxiliary thyristor holding current $=2 \mathrm{~mA}$

$$
\text { Hence, } \quad \begin{aligned}
R & \geq \frac{250}{2 \times 10^{-3}} \\
& \geq 125 \mathrm{k} \Omega \quad \text { Ans. }
\end{aligned}
$$

$I_{L}=50 A$, supply voltage $=250 \mathrm{~V}$.

$$
\text { Hence, } \quad \begin{aligned}
& R=\frac{200}{50}=4 \Omega \\
& t_{c}=0.693 R C \text { secs }
\end{aligned}
$$

Here $R=4, C=$ ? , $t_{c}=40 \mu \mathrm{secs}$. Hence,

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

So

$$
C=\frac{40 \times 10^{-6}}{0.693 \times 4}=14.43 \mu \mathrm{~F}
$$

Ans.

Problem 33. An impulse commutated thyristor is shown below.


Fig. 1.39
Determine the available turn off time of the circuit if $V=200$ volts, $R=10 \Omega$ and $C=15 \mu F$. Voltage on capacitor is $V$ with the polarity as shown before $T_{2}$ is fired.

Solution: After $T_{2}$ is fired, voltage $V$, as initial voltage of capacitor is $V$, appears at the cathode of $T_{1}$ leading to its commutation. The governing equations are given by

$$
\begin{align*}
V & =i R+V_{c}(t)  \tag{1.62}\\
i & =C \frac{d V_{c}(t)}{d t} \tag{1.63}
\end{align*}
$$

These two equations have been solved in problem no. 24. From there, we get

$$
V_{c}(t)=V\left[1-2 e^{\frac{-t}{R C}}\right]
$$

At available turn off time $t_{0}, V_{c}\left(t_{0}\right)=0$. Hence,
or,

$$
e^{\frac{-t_{0}}{R C}}=\frac{1}{2} \text { or, } r e^{\frac{t_{0}}{R C}}=22
$$

$$
t_{0}=R C \ln 2
$$

Here $\quad R=10 \Omega, C=15 \mu \mathrm{~F}$.
Hence,

$$
t_{0}=10 \times 15 \times 10^{-6} \ln 2=17.328 \mu \mathrm{secs}
$$

Ans.

Problem 34. In the commutation circuit shown below, $C=10 \mu F$ and the input voltage varies between 240 V to 260 V and the load current varies 25 A to 100A. Find out the maximum and minimum values of available turn off times.


Fig. 1.40
Solution: Input voltage varies between 240 V and 260 V and the load current $I$ varies from $25 A$ to 100 A . Available turn off time is given by

$$
t_{0}=\frac{C V}{1}
$$

$t_{0}$ will be maximum when $V$ is maximum and $I$ is minimum. Hence,

$$
t_{0 \max }=\frac{10 \times 10^{-6} \times 260}{25}=104 \mu \mathrm{secs}
$$

$$
\begin{aligned}
t_{0 \min } & =\frac{C V_{\min }}{I_{\max }}=\frac{10 \times 10^{-6} \times 240}{100} \\
& =24 \mu \text { secs } \quad \text { Ans. }
\end{aligned}
$$

Problem 35. The following figure gives the circuit of accelerated resonant pulse commutation.


Fig. 1.41
Determine the circuit turn off time for the load current of 100A.
Solution: Load current $I=100 \mathrm{~A}$
After $T_{2}$ is triggered at $t=0$, current through $T_{2}$ starts flowing and it increases with time. Let it reach equal to load current at $t_{1}$ and at this instant, $T_{1}$ turns off. The following gives $t_{1}$.

$$
t_{1}=\sqrt{L C} \sin ^{-1}\left[\frac{I}{V_{c}(0)} \sqrt{\frac{L}{C}}\right]
$$

Putting numerical values, we get

$$
\begin{aligned}
& t_{1}=\sqrt{50 \times 10^{-6}} \times 10 \times 10^{-6} \sin ^{-1}\left[\frac{100}{250} \sqrt{\frac{10 \times 10^{-6}}{50 \times 10^{-6}}}\right] \\
&=22.360 \times 10^{-6} \times 0.17985=4.021 \mu \mathrm{secs} \\
& \omega=\frac{1}{\sqrt{L C}} \\
&=\frac{1}{\sqrt{10 \times 10^{-6} \times 50 \times 10^{-6}}}=44721.359 \mathrm{rad} / \mathrm{sec}
\end{aligned}
$$

$i_{c}(t)$ flows through $D$ after $T_{1}$ turns off and $i_{c}(\mathrm{t})$ falls back $t$ load current at $t_{2}$.

$$
\begin{aligned}
t_{2} & =\pi \sqrt{L C}-t_{1} \\
& =\pi \sqrt{10 \times 10^{-6} \times 50 \times 10^{-6}}-4.021 \times 10^{-6} \\
& =66.227 \mu \mathrm{secs}
\end{aligned}
$$

Hence, circuit turn off time $t_{c}=66.227-4.021$

$$
=62.4 \mu \mathrm{secs} \quad \text { Ans. }
$$

Problem 36. The commutation circuit shown below has capacitance $C=25 \mu F$ and recharging inductance $L=40 \mu H$. The initial voltage on the capacitance is equal to the supply voltage with the polarity as shown. Determine the circuit turn off time if load current is 100A.


Fig. 1.42
Solution: Let $T_{2}$ be fired at $t=0$. Capacitor voltage will appear across $T_{1}$ and it will be turned off. Diode $D$ will be forward biased.

If an LC circuit is energized by a DC voltage $V_{s}$, current capacitor voltage are given by

$$
\begin{align*}
i(t) & =\left[V_{s}-V_{c}(0)\right] \sqrt{C / L} \sin \omega t+I(0) \cos \omega t  \tag{1.64}\\
V_{c}(t) & =I(0) \sqrt{L / C} \sin \omega t-\left[V_{s}-V_{c}(0)\right] \cos \omega t \tag{1.65}
\end{align*}
$$

Where $V_{c}(0)=$ initial voltage on the capacitor, $I(0)=$ initial current in the circuit and $\omega=\frac{1}{\sqrt{L C}}$.

Here $V_{c}(0)=-V, V_{s}=0, I(0)=I$. Putting these initial conditions in (1.64) and (1.65), we get

$$
\begin{aligned}
i(t) & =V \sqrt{C / L} \sin \omega t+I \cos \omega t \\
V_{c}(t) & =I \sqrt{L / C} \sin \omega t-V \cos \omega t
\end{aligned}
$$

If circuit turn off time is $t_{0}$, we have $V_{c}\left(t_{0}\right)=0$. Hence,

$$
0=I \sqrt{L \mathrm{C}} \sin \omega t-V \cos \omega t_{0}
$$

Simplifying this, we get $t_{0}=\sqrt{L C} \tan ^{-1}\left[\frac{V}{I} \sqrt{\frac{C}{L}}\right]$
Putting numerical values, we get

$$
\begin{aligned}
t_{0} & =\sqrt{40 \times 10^{-6} \times 25 \times 10^{-6}} \tan ^{-1}\left[\frac{250}{100} \sqrt{\frac{25 \times 10^{-6}}{40 \times 10^{-6}}}\right] \\
& =31.622 \times 10^{-6} \times 1.1023=34.856 \mu \mathrm{secs} \quad \text { Ans. }
\end{aligned}
$$

Problem 37. Consider the resonant pulse commutation circuit shown below.


Fig. 1.43
Determine the values of $L$ and $C$ if load current $I=200 A, V=$ 250 volts, circuit turn off time $t_{q}=20 \mu$ secs, ratio peak resonant current to load current $=1.5$.

Solution: For resonant pulse commutation circuit. Circuit turn off time $t_{q}$ is given by

$$
t_{0}=\sqrt{L C}\left[\pi-2 \sin ^{-1} \frac{1}{x}\right]
$$

where

$$
x=\frac{\text { Resonant peak current }}{\text { Load current }}
$$

Here,

$$
x=1.5 \text { and } t_{q}=205 \mu \text { secs. }
$$

Hence, $20 \times 10^{-6}=\sqrt{L C}\left[\pi-2 \sin ^{-1} \frac{1}{1.5}\right]$
or,

$$
\begin{align*}
L C & =6.8762 \times 10^{-11}  \tag{1.66}\\
I_{p} & =V \sqrt{C / L}
\end{align*}
$$

$I=200 A, x=1.5$. Hence $I_{p}=200 \times 1.5=300 A$. Putting this in above equation, we get

$$
300=250 \sqrt{C / L}
$$

or,

$$
\begin{equation*}
\frac{C}{L}=1.44 \tag{1.67}
\end{equation*}
$$

Solving (1.66) and (1.67), we get
$C=9.95 \mu \mathrm{~F}$ and $L=6.91 \mu \mathrm{H}$

## Ans.

Problem 38. Two thyristors having 300A and 500A current ratings are to be operated in parallel. The 'on' state voltage drops of these thyristors are 1.2 V and $1 V$ respectively. Find out the value of the resistance to be inserted in series with each SCR so that they will share the total load of 600A in proportion to their current ratings.

Solution: Dynamic resistance of 300A thyristor, say, $T_{1}=\frac{1.2}{300} \Omega$

Dynamic resistance of 500A thyristor, say, $T_{2}=\frac{1}{500} \Omega$
Let $R$ be the resistance to be inserted in series with each thyristor as shown below.


Fig. 1.44

$$
\begin{align*}
& \text { Current passing through }  \tag{1.68}\\
& \qquad T_{1}=600 \frac{R+\frac{1}{500}}{2 R+(1 / 500)+(1.2 / 300)} \alpha 300  \tag{1.69}\\
& \text { Current passing through } T_{2}=600 \frac{R+\frac{1.2}{300}}{2 R+\frac{1}{500}+\frac{1.2}{300}} \propto 500
\end{align*}
$$

Dividing (1.68) by (1.69), we get

$$
\frac{R+\frac{1}{500}}{R+\frac{1.2}{300}}=\frac{300}{500} \quad \text { or } \quad \frac{300(500 R+1)}{500(300 R+1)}=\frac{300}{500}
$$

or,

$$
R=\frac{0.2}{200} \Omega=1 \mathrm{~m} \Omega \quad \text { Ans }
$$

Problem 39. Find out the number of thyristors, each with a rating of 1000 V and 200A, need to be connected in each branch of series-parallel combination for a circuit with a total voltage of 10 kV and 1000A current. Assume a derating factor of $15 \%$.

Also determine the values of static equalizing resistance and dynamic equalizing capacitance for the string if maximum off state blocking current is 10 mA and the maximum difference in their reverse recovery charge $\Delta Q=20$ micro-coulombs.

Solution: We know that derating factor for series connected thyristors is given by

$$
\% \text { series derating }=\left[1-\frac{V_{s}}{n_{s} V_{D}}\right]
$$

where $V_{s}=$ string voltage, $V_{D}=$ voltage rating of one thyristor and $n_{s}=$ no. of series connected thyristors.

Here $V_{s}=10 \mathrm{kV}, V_{D}=1000$ volts .
Hence,

$$
0.15=\left[1-\frac{10 \times 10^{3}}{n_{s} \times 1000}\right]
$$

Solving this, we get $n_{s}=11.764$, say 12
Similarly, $\%$ parallel derating $=\left[1-\frac{I_{m}}{n_{p} I_{T}}\right]$
where $I_{m}=$ total current, $I_{T}=$ current rating of one thyristor and $n_{m}=$ no. of parallel strings. Here $I_{m}=1000 A, I_{T}=200 a$. Hence,

$$
0.15=\left[1-\frac{1000}{n_{s} \times 200}\right]
$$

Solving this, we get $n_{p}=5.8823$, say 6
Equalizing resistance $R=\frac{n_{s} V_{D}-V_{s}}{\left(n_{s}-1\right) I_{1}}$
Here,

$$
n_{s}=12, V_{D}=1000, V_{s}=10 \mathrm{kV}, I_{l}=10 \mathrm{~mA}
$$

Hence,

$$
\begin{aligned}
R & =\frac{12 \times 1000-10000}{11 \times 10 \times 10^{-3}} \\
& =18.181 \mathrm{k} \Omega
\end{aligned}
$$

Equalizing capacitance $C=\frac{\left(n_{s}-1\right) \Delta Q}{n_{s} V_{D}-V_{s}}$

Here,

$$
n_{s}=12, V_{D}=1000, V_{s}=10 \mathrm{kV}, \Delta Q=20 \mu \mathrm{C}
$$

Hence,

$$
C=\frac{11 \times 20 \times 10^{-6}}{12 \times 1000-10 \times 10^{-3}}=0.11 \mu \mathrm{~F}
$$

Ans.

Problem 40. The maximum on state RMS current of a thyristor is 80A. If we use this thyristor in a resistive circuit, determine the average on state current rating for half sine wave for a conduction angle of $60^{\circ}$.

Solution: The heating effect in thyristor depends on average current also passing through it. Here, we have to find out equivalent average current. This we can do by finding form factor.

For half sine wave, $I_{a v}=\frac{I_{m}}{2 \pi}(1+\cos \theta)$
where $I_{m}$ is peak value and $\theta$ is the firing angle.

$$
\begin{aligned}
& \qquad \begin{aligned}
I_{r m s} & =\sqrt{\frac{I_{m}^{2}}{2 \pi} \int_{0}^{\pi} \sin ^{2} \theta d \theta}=\sqrt{\frac{I_{m}^{2}}{2 \pi} \int_{0}^{\pi} \frac{\cos 2 \theta}{2} d \theta} \\
& =\sqrt{\frac{I_{m}^{2}}{2 \pi}\left[\frac{\pi-\theta}{2}+\frac{\sin 2 \theta}{4}\right]}
\end{aligned} \\
& \text { Here, } \theta=60^{\circ} \text {, hence, } I_{a v}=\frac{I_{m}}{2 \pi}\left(1+\cos 60^{\circ}\right)=0.2387 I_{m}
\end{aligned}
$$

$$
\begin{aligned}
I_{r m s} & =\sqrt{\frac{I_{m}^{2}}{2 \pi}\left[\frac{\pi-(\pi / 3)}{2}+\frac{\sin 120^{\circ}}{4}\right]} \\
& =\sqrt{\frac{I_{m}^{2}}{2 \pi} \times 1.2636}=0.4484 I_{m}
\end{aligned}
$$

Hence, from factor $=\frac{0.4484 I_{m}}{0.23871 I_{m}}=1.8785$
So, equivalent average current $=\frac{80}{1.8785}=42.587 A$ Ans.

## UNSOLVED PROBLEMS

Problem 1. It is specified that a voltage of 2 V and current of 100 mA be applied to turn on a thyristor. A resistor of $20 \Omega$ is connected across the gate cathode terminals of thyristor. If the trigger supply voltage is 10 V , determine the value of the resistance to be connected in series with the gate circuit to turn on the thyristor. [Ans. 40 $\Omega$

Problem 2. A train of pulses of frequency 2 kHz and $25 \%$ duty cycle triggers a thyristor. Determine the pulse width. If the average gate power dissipation is not to exceed 1.5 W , find out the maximum allowable gate power drive.
[Ans. 0.125 m secs, 6W]

Problem 3. A 220VDC source supplies a resistive load $R$ through a thyristor. The $\frac{d i}{d t}$ and $\frac{d v}{d t}$ limits for thyristor are $75 A / \mu \mathrm{sec}$ and $250 \mathrm{~V} / \mu \mathrm{sec}$ respectively. Determine the value of inductance to be connected in the anode circuit and snubber circuit parameters to achieve these specified limits.
$\left[\right.$ Ans. $L=2.933 \mu H, R_{s}=3.33 \Omega, C_{s}=0.2644 \mu F ;$
these are exact values.]

Problem 4. A thyristor carries full current when the allowable case temperature is $100^{\circ} \mathrm{C}$ and maximum allowable junction temperature is $140^{\circ} \mathrm{C}$. The thermal resistance between case and ambient is $0.5^{\circ} \mathrm{C} / \mathrm{W}$ and between sink and ambient is $0.4^{\circ} \mathrm{C} / \mathrm{W}$. Find the sink temperature and resistance between junction and case if ambient temperature is $30^{\circ} \mathrm{C}$.
[Ans. $\left.\boldsymbol{T}_{s}=\mathbf{8 6}{ }^{\circ} \mathbf{C}, \theta_{J C}=\mathbf{0 . 2 8 5 7}{ }^{\circ} \mathbf{C} / \mathbf{W}\right]$
Problem 5. The reverse biased junction capacitance of a thyristor is 50 pF . Determine the maximum permissible value of $\frac{d v}{d t}$ appearing across thyristor if the charging current flowing through the junction capacitance is $4 m A$.
[Ans. 80V/ $\mu$ secs]
Problem 6. A thyristor string has a voltage and current rating of 11 kV and $3 k A$ respectively. The thyristor available has a voltage and current rating of $2 k V$ and 1500 A respectively. Determine the number of series and parallel connected thyristors if string efficiency has to be $90 \%$. Also find out the value of static equalizing resistnace and capacitance to be used in the static and dynamic equalizing circuits if the maximum forward leakage current is 12 mA and maximum difference in their reverse recovery charge is $25 \mu \mathrm{C}$.
[Ans. $\boldsymbol{n}_{\boldsymbol{s}}=\mathbf{7}, \boldsymbol{n}_{\boldsymbol{p}}=\mathbf{3}, \boldsymbol{R}=\mathbf{4 1 . 6 7 k} \Omega, \boldsymbol{C}=\mathbf{0 . 0} \mu \mathrm{F}$ ]
Problem 7. Consider the following circuit in which a capacitance is connected across the thyristor to limit $\frac{d v}{d t}$ appearing across it.


Fig. 1.45

Calculate the minimum value of $C$ so that thyristor will not turn on due to reapplied $\frac{d v}{d t}$. Junction capacitance of thyristor is $25 p F$ and minimum charging current is $4 m A$.
[Ans. $0.0375 \mu$ F]
Problem 8. In the following circuit, the switch is closed at $t=0$.
Find out expression of current if initial voltage on capacitor is $V$ with polarity as shown.


Fig. 1.46

$$
\left[\text { Ans. } i(t)=V \sqrt{\frac{C}{L}} \sin \omega t\right]
$$

Problem 9. The gate cathode characteristic of an SCR is straight line having slope of 20A/amp and passes through origin; the maximum turn on time is $4 \mu \mathrm{sec}$ and the minimum gate current required to turn o is 400 mA . Calculate the resistance to be connected in series with the SCR gate source voltage is 12 V .
[Ans. 10 ${ }^{\text {] }}$
Problem 10. Find the current through the following circuit and the voltage on the capacitor as function of time after the switch is closed if initial voltage on capacitor is 100 V and current passing through inductance is 10 A .

[Ans. $\boldsymbol{i}(\boldsymbol{t})=10.488 \sin \left(\omega t+72.452^{\circ}\right)$,
$\left.v_{\boldsymbol{c}}(\boldsymbol{t})=\mathbf{2 0 0}+\mathbf{3 3 1 . 6 6 1} \sin \left(\omega t-\mathbf{1 7 . 5 4 8}{ }^{\circ}\right), \omega=31622 \mathrm{rad} / \mathrm{sec}\right]$
Problem 11. The thermal capacity of a thyristor is $0.4 J /{ }^{\circ} \mathrm{C}$ and thermal resistance is $0.8^{\circ} \mathrm{C} / \mathrm{W}$. Find out the maximum power dissipation the thyristor can withstand for 0.1 seconds for a temperature not exceeding $50^{\circ} \mathrm{C}$.
[Ans. 232.873 W]

Problem 12. The $S C R$ in the figure given below controls power in a resistance $R$. The supply voltage is 220 V , and the maximum permissible values of $\frac{d V}{d t}$ and $\frac{d i}{d t}$ for the $S C R$ are $150 \mathrm{~V} / \mu$ sec and $50 A / \mu$ sec respectively. Determine the value of $\frac{d i}{d t}$ inductance and snubber circuit parameters.


Fig. 1.48
[Ans. $L=4.4 \mu H, R_{s}=3 \Omega, C_{s}=0.488 \mu \mathbf{F}$;
these are exact values.]
Problem 13. A relaxation oscillator uses UJT for triggering a thyristor. The circuit is as shown below.


Fig. 1.49
The UJT parameters are as given below.

$$
\begin{aligned}
\eta & =0.7, I_{p}=0.5 \mathrm{~mA}, V_{p}=15 \mathrm{volts} \\
V_{v} & =0.8 \mathrm{~V}, I_{v}=\mathrm{mA}, R_{B B}=6 \mathrm{~K} \Omega
\end{aligned}
$$

Normal leakage current with emitter open is $3 m A$. The firing frequency is 2 kHz . If $C=0.2 \mu \mathrm{~F}$, compute the values of $R, R_{1}$ and $R_{2}$.
[Ans. $R=2078 \Omega, R_{1}=280 \Omega, R_{2}=862.67 \Omega$ ]
Problem 14. A relaxation oscillator using UJT triggers an SCR. The UJT has the following parameters.

$$
\begin{aligned}
& \eta=0.7, I_{p}=0.7 \mathrm{~mA}, V_{p}=16.5 \text { volts } \\
& V_{v}=I V, I_{v}=6 \mathrm{~mA}, R_{B B}=5500 \Omega \text { and } V_{D}=0.7 \mathrm{~V}
\end{aligned}
$$

Normal leakage current with emitter open is 3.5 mA . The firing frequency is 1.5 kHz . If $C=0.1 \mu F$, compute the values of $R, R_{1}$ and $R_{2}$.


Fig. 1.50
[Ans. $R=5537.558 \Omega, R_{1}=705.187 \Omega, R_{\mathbf{2}}=\mathbf{2 4 3 . 6 7} \Omega$ ]
Problem 15. In the problem no. 14, the firing frequency is varied by varying $R$. Determine the maximum and minimum values of $R$ and corresponding frequencies.

$$
\begin{aligned}
{\left[\text { Ans. } \boldsymbol{R}_{\max }\right.} & =8672.857 \Omega, \boldsymbol{R}_{\min }=3595.166 \Omega \\
f_{\max } & \left.=2259.738 \mathrm{~Hz}, \boldsymbol{f}_{\min }=936.73 \mathrm{~Hz}\right]
\end{aligned}
$$

Problem 16. Consider the following complementary commutation circuit shown below.


Fig. 1.51
Determine the values of $R$ and $C$ to be used for commutating the main thyristor $T_{1}$ when it is conducting a full load current of 44A. Circuit turn off time is $40 \mu \mathrm{sec}$ and $T_{2}$ will undergo natural commutation when its forward current falls below the holding current of $2 m A$.
[Ans. $\boldsymbol{R}=110 k \Omega, \boldsymbol{C}=11.541 \mu$ F]
Problem 17. Find pout the conduction time of SCR and peak SCR current in the following circuit assuming zero initial conditions.


Fig. 1.52
[Ans. 0.14m secs, 1.337A]
Problem 18. In the following self commutating circuit, the inductance carries an initial current of 100A and the initial voltage across the capacitor is equal to the supply voltage with the polarity as marked.


Fig. 1.53
Find out the conduction time of SCR and the capacitor voltage at turn off.
[Ans. $49.672 \mu$ secs , 251.622V]
Problem 19. In the circuit shown below, the applied voltage $V$ is 500volts. Initial capacitor voltage is zero, $L=20 \mu H$ and $C=50 \mu$ and the current passing through the inductance at the time of $S C R$ triggering is $I_{0}=250 \mathrm{~A}$.


Fig. 1.54
Determine (a) the peak values of capacitor voltage and current (b) the conduction time of SCR.
[Ans. (a) $I_{\text {cmax }}=829.155 A V_{\text {cmax }}=1024.28 \mathrm{~V}($ b $) 89.66 \mu$ secs]

Problem 20. Following is the circuit of resonant pulse commutation.


Fig. 1.55
The initial voltage on the capacitor is $V_{c}(0)=220$ volts with the polarity as marked, $C=25 \mu F$ and $L=5 \mu H$. Find out the circuit turn off time if the load current is 300A. [Ans. $14.529 \mu$ secs]

Problem 21. Repeat the above problem if an anti-parallel diode $D$ is connected across thyristor $T_{1}$ as shown below.

Problem 22. Find out the value of $L$ for proper commutation of SCR in the following circuit. Also find out the commutation time of SCR.
[Ans. $L=125 \mu \mathrm{H}$ assuming ratio of resonant peak current to load current as $2,91.629 \mu$ secs]


Fig. 1.57

Problem 23. In the circuit shown below, the load current to be commutated is 20A, turn off time required is $40 \mu$ sec and the supply voltage is 200 V . Find out the proper values of these commutating elements.


Fig. 1.58
[Ans. $L=100 \mu \mathrm{H}, C=4 \mathrm{~F}$ assuming ratio of resonant peak current to load current as 2]
Problem 24. In a resonant commutation circuit, the supply voltage is 220V DC. Load current is 25A and the circuit turn off time is $40 \mu s e c$. The ratio of peak resonant current to load current is 1.5. Determine the value of $L$ and $C$ of the commutating circuit.
[Ans. $C=4.545 \mu \mathbf{F}, L=156.428 \mu \mathrm{H}$ ]
Problem 25. In the complementary commutation circuit shown below, determine the circuit turn off time $t_{q}$.


Fig. 1.59
[Ans. 51.986 $\mu \mathrm{secs}$ ]
Problem 26. Calculate the values of $R_{L}$ and $C$ required for commutation of the main thyristor in the following circuit when the load current is 20 A .

The main SCR has to reverse biased at least for $40 \mu \mathrm{sec}$ for proper com-


Fig. 1.60
mutation. Also find out $R_{1}$ if auxiliary thyristor $T_{1}$ will go natural commutation when its forward current falls below the holding current of 3 mA . [Ans. $\boldsymbol{R}_{L}=\mathbf{1 0 \Omega}, \boldsymbol{C}=\mathbf{5 . 7 7} \mu \mathbf{F}, \boldsymbol{R}_{\mathbf{1}}=\mathbf{6 6 . 6 7 k} \Omega$ ]

Problem 27. Consider the impulse commutation circuit shown below.


Fig. 1.61
Determine the available turn off time of the circuit if $V=200$ volts, $R=20 \Omega$ and $C=40 \mu \mathrm{~F}$. Voltage across $C$ is $V$ with the polarity as shown before auxiliary thyristor $T_{2}$ is fired.
[Ans. 0.5545m secs]
Problem 28. In the commutation circuit shown in right side, $C=40 \mu F$ and the input voltage varies between 150 V and 200 V and, as a result, the load current varies between 100A and 200A. Determine the maximum and minimum values of available turn off time $t_{q}$.


Fig. 1.62
[Ans. $80 \mu$ secs, $30 \mu$ secs]
Problem 29. Consider the circuit shown below and find out the values of $L$ and $C$ for proper commutation of 200 V thyristor.

The load current is 50A and the resonant peak current is 2 times the load current. The cir-


Fig. 1.63 cuit turn off time should at least be $40 \mu \mathrm{sec}$. Determine the value of $L$ and C.

$$
\text { [Ans. } C=\mathbf{1 0} \mu \mathbf{F}, \boldsymbol{L}=\mathbf{4 0} \mu \mathrm{H} \text { ] }
$$

Problem 30. The maximum rms on state current of a thyristor is 100A. If we use this SCR in a resistive circuit, determine average on state current rating for half sine wave current for conduction angle of $45^{\circ}$.
[Ans. 52.565A]
Problem 31. In the resistive trigger shown below, calculate the trigger angle ' $a$ ' at which the SCR fires when variable resistor is set at $5 k \Omega$. Assume ideal diode.
[Ans. 2.837 ${ }^{\circ}$ ]


Fig. 1.64
Problem 32. An $S C R$ has $V_{g}-I_{g}$ characteristics given by $V_{g}=1.8+8 I_{g}$. If gate pulses of 10 V amplitude with $20 \%$ duty are applied, determine the value of series resistor to be inserted in the gate circuit to limit the peak power dissipation to $5 W$. [Ans. 3.953 ${ }^{\text {] }}$

Problem 33. In the following circuit, $L=20 \mu H, C=40 \mu \mathrm{~F}$ and initial value of current is 200A.

Find out (a) the peak capacitor voltage and (b) the conduction time of thyristor. [Ans. (a) 1019.46V (b) $81.061 \mu$ secs]


Problem 34. Consider the following circuit in which the junction capacitance of thyristor is 20 pF .

The thyristor turns on when anode current is 5 mA and the critical
 value of $\frac{d v}{d t}$ is $200 \mathrm{~V} / \mu \mathrm{sec}$. Determine the value of capacitance $C$ so that the thyristor will not be turned on due to $\frac{d v}{d t}$.
[Ans. $0.04 \mu$ F]

Fig. 1.66

Problem 35. A 300A SCR having voltage drop of 0.75 V at rated current is to be connected in parallel with 200A SCR having voltage drop of $1 V$ at rated current. Determine the resistance to be connected in series with each SCR so that they will share the load of 500 A in proportions to their ratings.

## MULTIPLE CHOICE QUESTIONS

Q. 1 The gate lead in a thyristor is welded to
(a) p layer to which anode is connected.
(b) n layer nearest to the anode
(c) p layer nearest to the cathode terminal
(d) outside $n$ layer that is nearest to the anode
[Ans. (c)]
Q. 2 When we reverse bias an $S C R$
(a) Two junctions are reverse biased and one junction is forward biased.
(b) All the junctions are reverse biased.
(c) One junction is reverse biased and two junctions are forward biased.
(d) Any of the above depending on the magnitude of reverse bias.
[Ans. (c)]


Fig. 1.67
Q. 3 The latching current in the following circuit is $4 m A$.

The minimum width of the gate pulse required to properly turn on the thyristor is
(a) $6 \mu \mathrm{secs}$
(b) $4 \mu \mathrm{secs}$
(c) $2 \mu \mathrm{secs}$
(d) $1 \mu \mathrm{sec}$
[Ans. (b)]
Q. 4 The snubber circuit is used in the thyristor circuits for
(a) triggering
(b) $\frac{d v}{d t}$ protection
(c) $\frac{d i}{d t}$ protection
(d) pulse shifting
[Ans. (b)]
Q. 5 It is preferable to use a train of pulses of high frequency for gate triggering of SCR to reduce
(a) $\frac{d v}{d t}$ problem
(b) $\frac{d i}{d t}$ problem
(c) the size of the pulse transformer
(d) the complexity of the firing circuit.
[Ans. (c)]
Q. 6 The following figure shows a thyristor with junctions $J_{1}, J_{2}$ and $J_{3}$.

When the thyristor is turned on and conducting
(a) $J_{1}$ and $J_{2}$ are forward biased and $J_{3}$ is reverse biased.
(b) $J_{1}$ and $J_{3}$ are forward biased and $J_{2}$ is reverse biased
(c) $J_{1}$ is forward biased and $J_{2}$ and $J_{3}$ are reverse biased
(d) $J_{1}, J_{2}$ and $J_{3}$ are reverse biased.
[Ans. (b)]
Q. 7 During the turn off process of a


Fig. 1.68 thyristor, the current flow does not stop at the instant when the current reaches zero but continues to flow to a peak value in the direction. This is due to
(a) commutation failure
(b) hole storage effect
(c) presence of reverse voltage across the thyristor
(d) protection provided to the inductance in series with the thyristor.
[Ans. (b)]
Q. 8 A thyristor converter of $415 \mathrm{~V}, 100 \mathrm{~A}$ rating is operating at rated load. Details of thyristor used are as follows:
'ON' state power loss $=150 \mathrm{~W}$.
Thermal resistance: $\theta_{J C}=0.01^{\circ} \mathrm{C} / \mathrm{W} ; \theta_{C S}=0.08^{\circ} \mathrm{C} / \mathrm{W} ; \theta_{S A}$

$$
=0.09^{\circ} \mathrm{C} / \mathrm{W}
$$

Assume ambient temperature as $35^{\circ} \mathrm{C}$. The junction temperature for $100 \%$ load is
(a) $48.5^{\circ} \mathrm{C}$
(b) $54.5^{\circ} \mathrm{C}$
(c) $60^{\circ} \mathrm{C}$
(d) $62^{\circ} \mathrm{C}$
[Ans. (d)]
Q. 9 Static voltage equalization in series connected SCRs is obtained by the use of
(a) one resistor across the string
(b) resistors of different values across each SCR
(c) resistors of the same value across each SCR
(d) one resistor in series with the string
[Ans. (c)]
Q.10 A SCR has half cycle current rating of 3000A for 50 Hz supply. One cycle surge rating will be
(a) 1500 A
(b) 2121.32 A
(c) 4242.64 A
(d) 6000 A
[Ans. (b)]
Q. 11 If the amplitude of gate pulse to the thyristor is increased, then
(a) Both delay time and rise time would increase.
(b) Delay time would increase but rise time would decrease.
(c) Delay time would decrease but rise time would increase
(d) Delay time would decrease while the rise time remains unchanged.
[Ans. (d)]
Q. 12 In a thyristor, latching current is
(a) equal to holding current
(b) less than holding current
(c) more than holding current
(d) very small
[Ans. (c)]
Q.13 On insertion of an inductance in anode circuit of an $S C R$, the turn on time
(a) decreases
(b) increases
(c) remains the same
(d) does not change much
[Ans. (b)]
Q. 14 In case of normal thyristors, turn off time is
(a) equal to turn on time
(b) less than turn on time
(c) more than turn on time
(d) 4 times turn on time
[Ans. (c)]
Q. 15 If we use UJT for triggering an SCR, the wave shape of the voltage obtained from the output of UJT will be
(a) square wave
(b) sine wave
(c) wave shape can not be decided
(d) saw tooth wave
[Ans. (d)]
Q. 16 In case of an UJT, we require maximum value of charging resistance at
(a) valley point
(b) peak point
(c) after the valley point
(d) anywhere between valley and peak point
[Ans. (b)]
Q. 17 The forward voltage drop across thyristor
(a) increases slightly with the increase in the load current
(b) in independent of load current
(c) decreases slightly with the increase in the load current (d) varies linearly with the load current
[Ans. (a)]
Q. 18 The sharing of the voltages between thyristors operating in series is influenced by their
(a) $\frac{d i}{d t}$ capabilities
(b) $\frac{d v}{d t}$ capabilities
(c) junction temperatures
(d) static v-i characteristics and leakage current
[Ans. (d)]
Q. 19 When cathode of a thyristor is made more positive than its anode
(a) all the junctions are reverse biased
(b) outer junctions are reverse biased and central one is forward biased
(c) outer junctions are forward biased and central one is reverse biased
(d) all the junctions are forward biased
[Ans. (b)]
Q. 20 When a thyristor is in forward blocking state, the thyristor has
(a) low current, low voltage
(b) low current, high voltage
(c) high current, low voltage
(d) high current, high voltage
[Ans. (b)]
Q. 21 In UJT, if $V_{B B}$ is the voltage across two base terminals and $V_{D}$ is voltage across pn junction, the emitter potential at peak is given by
(a) $\eta V_{D}+V_{B B}$
(b) $\eta V_{B B}$
(c) $\eta V_{D}$
(d) $\eta V_{B B}+V_{D}$
[Ans. (d)]
Q. 22 Which of the following provides $\frac{d i}{d t}$ protection for a thyristor?
(a) L in series with thyristor
(b) R in series with thyristor
(c) C in series with thyristor
(d) RL in series with thyristor
[Ans. (a)]

## TRUE/FALSE QUESTIONS

Q. 1 Average power distribution in a thyristor is function of the average and RMS value of the forward current.

## (True/False)

Q. 2 Turn on time in case of a thyristor is more than its turn off time.

## (True/False)

Q. 3 Thyristor has higher switching losses and gate power requirements compared to IGBT.

## (True/False)

Q. 4 Whatever may be the value of $\frac{d v}{d t}$ across the thyristor, it will not turn on.
(True/False)
Q. 5 Latching current of a thyristor is more than holding current.
(True/False)
Q. 6 Turn off time for converter grade thyristors is less than turn off time of inverter grade thyristors.
(True/False)
Q. 7 Circuit turn off time should be more than thyristor turn off time.

## (True/False)

Q. 8 Hard firing of a thyristor does not affect its turn time.
(True/False)
Q. 9 Snubber circuit is connected in series with the thyristors.

## (True/False)

Q. 10 UJT relaxation oscillator is preferred for thyristor triggering as it maintains constant frequency with the variation in supply voltage.
(True/False)
Q. 11 The higher the load current, the higher will be the circuit turn off time in case of resonant pulse commutation.

## (True/False)

1. T 2.F 3. T 4.F 5.T 6.F 7.T 8.F 9.F 10. T 11.F.
