CHAPTER 5
POWER SEMICONDUCTOR DEVICES

5.1 DIODES

Diodes are also known as 'passive' semiconductors as opposed to 'active' semiconductors such as switches because diodes are not turned on or off by external controls. Diodes always turn on for positive current, i.e. diodes always conduct positive current. Diodes never turn on for negative current, i.e. diodes never conduct negative current. By convention the diode terminal into which current enters is called the anode and the diode terminal from which the current exits is called the cathode.

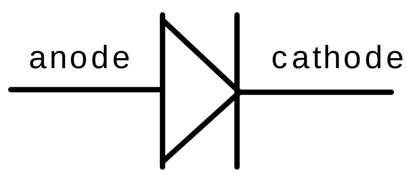


Figure 5.1 Diode Symbol

An ideal diode is a short circuit when it is conducting, or forward biased, and an open circuit when it is not conducting, or reverse biased. Real diodes, however, have a forward voltage drop when conducting. This forward voltage drop is represented by V_f , where:

$$V_f \propto \frac{\log I}{A}$$

And A is the conducting area of the semiconductor. Also V_f decreases with increasing device temperature. For most power diodes $V_f \approx 0.6 — 1.0\ V$.

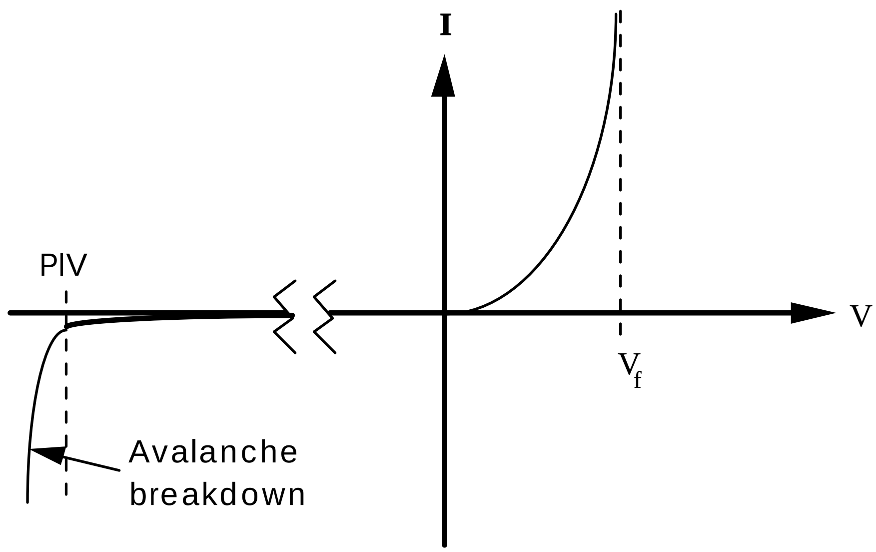


Figure 5.2 V I Characteristics for a Diode

5.1.1 Power Diodes

Of course for power diodes the major considerations are power handling capability. The power *handling* capability of a power diode is given by various ratings:

I_{rms} - the steady state RMS current that the device can tolerate without damage

$\hat{I}$ - steady state peak current that the device can tolerate without damage
(Note that $\hat{I} = \sqrt{2}\, I_{rms}$ *only for sinusiodal currents*)

$\hat{I}_S$ - the single-cycle peak current; this is the single pulse of 50 or 60 Hz current that the device can tolerate and is actually a single *half* cycle rating.

I^2t - "fuse current rating", required for fuse coordination in DC applications

PIV - Peak inverse voltage, the maximum reverse voltage that the device can withstand.

The above device parameters refer to the power *handling* capability of a power diode. The power *dissipated* in the device, P_D is given by the general expression:

$$P_D = P_C + P_S$$

Where P_C represents the conduction losses which are the losses due to the forward voltage drop across the diode, and is given by:

$$P_C = \frac{1}{T}\int_0^T V_f\, i(t)\partial t \approx \frac{V_f}{T}\int_0^T i(t)\partial t = V_f\, I_{Average}$$

Where V_f represents the forward voltage drop across the diode when it is conducting. For most power diodes $V_f \approx 0.6 - 1.0$ V and is dependent on the current as shown in **Figure 5.1.** As a first approximation it is convenient to assume a constant value for V_f .

Of course for an ideal (lossless) diode $V_f = 0$.

P_S represents the switching losses which are the losses due the the diode turning on and off. The actual expressions for this parameter are complex but in general they can be simplified to:

$$P_S = (W_{on} + W_{off})f$$

Where f is the switching frequency, and W_{on} represents losses, in Joules, at each turn on, and W_{off} represents the losses at each turn off.

For low frequency operation such as 50 or 60 Hz, the switching losses are relatively small and the power dissipation is dominated by the conduction losses. At high switching frequencies such as 20 KHz and higher the switching losses become significant and special high frequency diodes with correspondingly low switching losses must be used.

The main source of turn off switching losses in a power diode is associated with the charge carriers in the PN junction. These have to be swept out by a negative current before the diode actually switches off. Before turning off the positive current in a diode actually reverses for a short period of time, it is then called the reverse recovery current, $i(t)_{rr}$. It takes a finite time for the charges to be swept out, this time is called the reverse recovery time, t_{rr} . The reverse recovery charge, Q_{rr} , can then be determined by the expression:

$$Q_{rr} = \int_{I=0}^{t=t_{rr}} i_{rr}(t)\partial t \approx \tfrac{1}{2} I_{rr} t_{rr} .$$

Once the reverse recovery charge carriers are swept away the reverse recovery current abruptly snaps off and goes to zero as shown in **Figure 5.3**

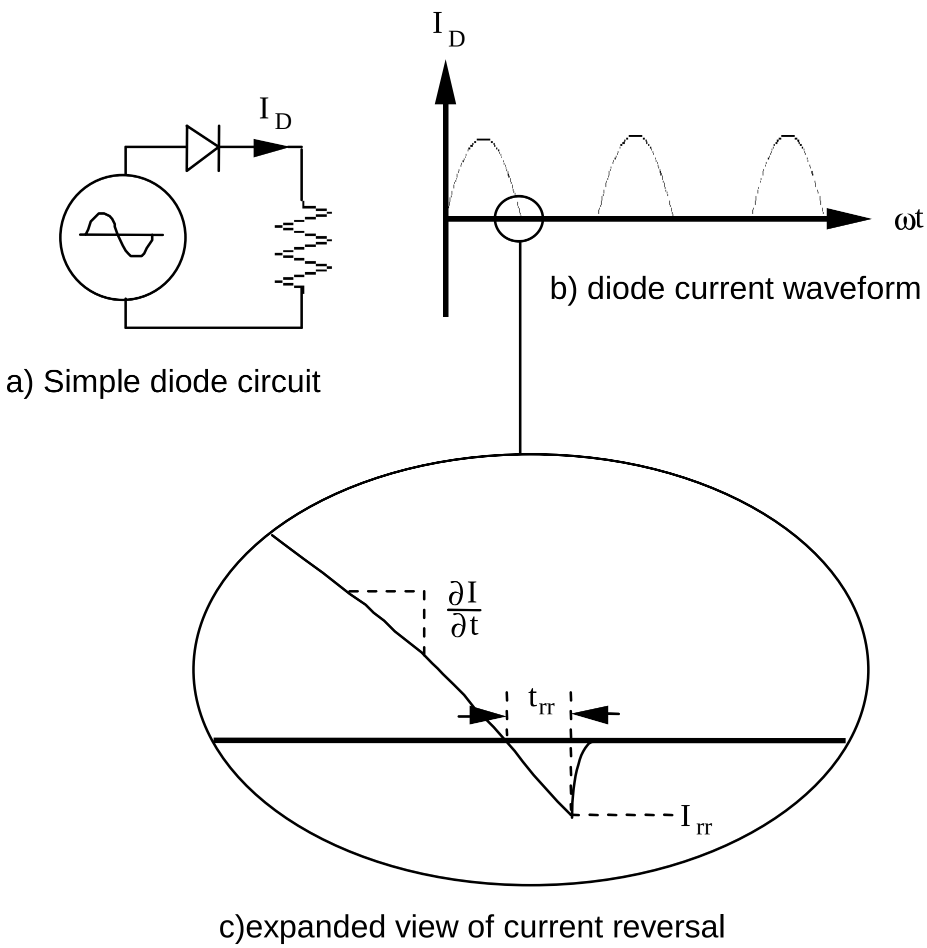


Figure 5.3 Reverse Recovery Current in a Diode

The peak value of $i_{rr}(t)$ is referred to as the reverse recovery current, I_{rr} , and is a function of the initial forward current through the diode, the t_{rr} for the device, and the $\partial I/\partial t$ at the time the diode current changes polarity.

During this current snap off any inductance, L, in the circuit will have stored energy given by the equation:

$$W = \frac{1}{2} L I_{rr}^2$$

This stored energy will have to be dissipitated during each diode turn off somewhere in the circuit or ’recovered’ into some other device such as a capacitor.

For high frequency applications I_{rr} and t_{rr} become increasingly important and thus fast recovery diodes and "ultra fast" recovery diodes were developed that have very low t_{rr} and Q_{rr} .

Thus, using an incorrect diode in a power electronics circuit could result in excessive temperatures and premature failure or even immediate self destruction.

5.1.2 Schottkey Diodes

Schottkey diodes are basically the same as regular pn diodes except that they consist of a semiconductor/metal junction. This results in the following differences in performance:

	Schottkey Diode	PN Diode
V_f	0.3 -0.4 V	0.6 - 1.0 V
PIV	25 - 50V	up to kV's
t_{rr}	nanoseconds	microseconds
I_{rr}	nanoamps	2 - 20% of $\hat{I}$
I_r	milliamps	microamps

The reverse leakage current, I_r , is the current through the device when peak inverse voltage PIV is applied.

The major disadvantages of Schottkey diodes are the high reverse leakage current, I_r , and the low PIV ratings.

Nevertheless their low V_f , and low t_{rr} and I_{rr} make them very useful for high frequency and low voltage applications.

5.1.3 Zener Diodes

Zener diodes act like regular diodes in the forward direction but act somewhat like a voltage source in the reverse direction. This is because when the reverse voltage reaches a certain level, (the Zener voltage), the diode goes into avalanche breakdown and won’t sustain any higher reverse voltage. The Zener diode won’t distruct in this breakdown mode as long as the reverse current does not exceed the device limitations and the power dissipated in the device is limited to within its ratings.

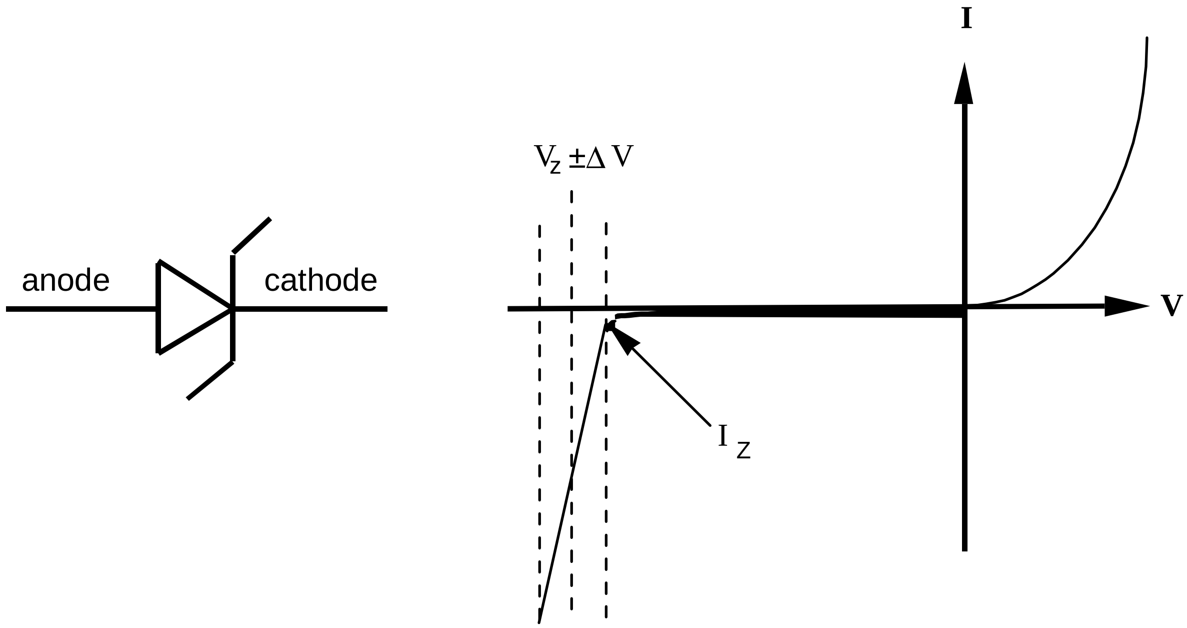


Figure 5.4 Zener symbol and V I curve

Important Zener diode characteristics are;

V_z - zener voltage (almost any value is available)

% - % variation in zener voltage from minimum to maximum current, and over temperature variations, typically 2%, 5% or 10%.

I_z - minimum current required to get Zener voltage

W - maximum wattage rating of the Zener.

Note: maximum current rating, $\hat{I}$, can be determined from

$$W = V_z \hat{I}$$

$$\text{or} \quad \hat{I} = W/V_z$$

Zener diodes are commonly used in non-power applications as voltage references, voltage subtractors, and for threshold settings. Their main applications for power circuits are as voltage regulators and overvoltage clamps.

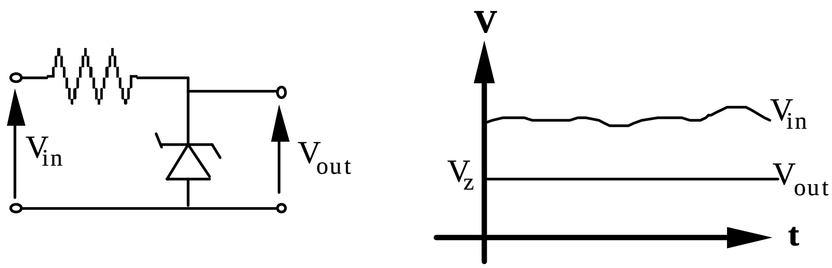


Figure 5.5 Basic Zener Voltage Regulator

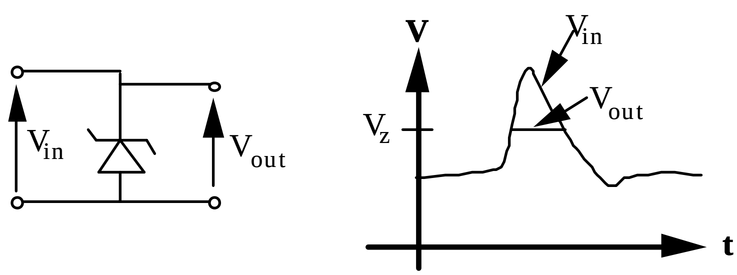


Figure 5.6 Basic Zener Overvoltage Clamp

For operation as an overvoltage clamp, it is important that the Zener diode be capable of surviving an overvoltage condition at least long enough for a protective device, such as a circuit breaker or fuse, to operate and disconnect the offending circuitry.

5.2 Semiconductor Switches

5.2.1 General Characteristics

Semiconductor switches are sometimes called 'active' semiconductors because they are actively turned on by an external signal. Some devices are also actively turned off by external signals or circuitry.

All semiconductor switches have to be turned on or gated by applying voltage or current to a gate or base.
The device usually does not start to turn on until after a short delay time, t_d , after which time the device goes through the turn on transition which also takes a finite time. The total of delay time and turn on transition time is refered to as t_{on} , the turn on time. Different devices have various values for t_d and t_{on} .
All devices also require a finite time to turn off this is called the turn off time, t_q , or t_o ,

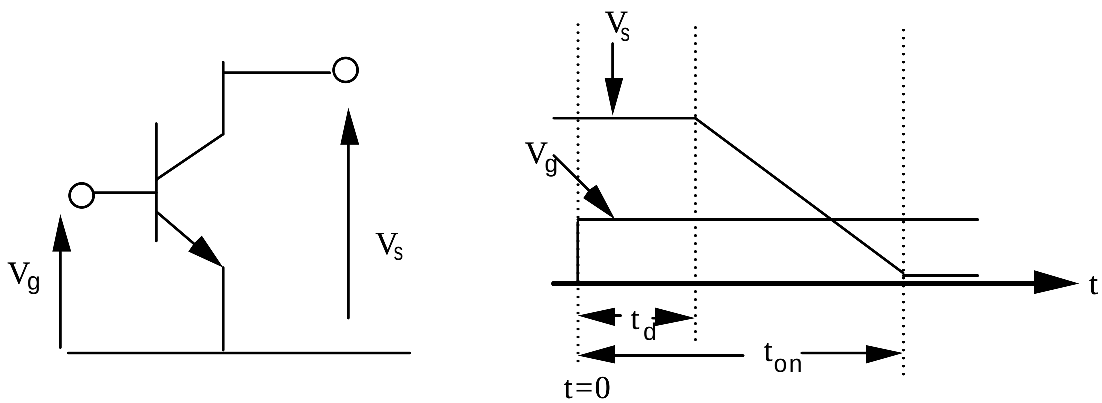


Figure 5.7 Semiconductor Voltages During Turn On

A major consideration in power circuits are the power losses that occur each time a switch turns on or off. This is especially important for high frequency operation.

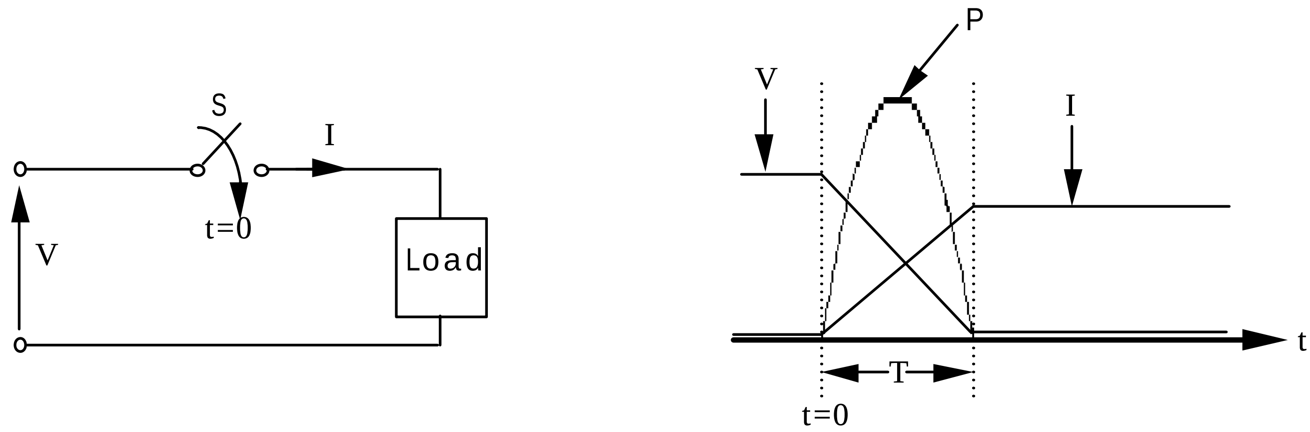


Figure 5.8 Switching losses during turn on

The power dissipated during the turn on of the switch in **Figure 5.8** can be approximated as follows:

$$P = v(t) \times i(t) = \left(V - \frac{Vt}{T}\right) \times \left(\frac{It}{T}\right)$$
$$= VI\frac{t}{T} - VI\frac{t^2}{T^2}$$

Where T is the transition time during which voltage across the device is falling and current through the device is rising.
Thus the energy dissipated in the switch during this on transition can be determined by integrating the expression for power:

$$W = \int_{t=0}^{t=T} P\partial t = \int_{t=0}^{t=T} \left[VI\frac{t}{T} - VI\frac{t^2}{T^2}\right]\partial t = \frac{VI}{T}\left[\frac{t^2}{2} - \frac{t^3}{3T}\right]_0^T$$

$$= \frac{VIT}{6} \text{ joules}$$

This is the energy dissipated in the switch during each turn on transition. A similar analyis can be performed for the turn off transition to yield an expression for P_s , the total power dissipated in the switch;

$$P_s = \frac{fVI}{6}(T_{on} + T_{off})$$

Where f is the switching frequency and T_{on} ,T_{off} , represent the turn on and turn off *transition times* respectively.

Thus it can be seen that switching losses are proportional to frequency and transition times. Devices with low transition times are said to be "fast" devices and these would have lower switching losses than "slow devices". Thus fast devices are required for high frequency operation because their fast switching times result in lower switching losses.

5.3 SILICON CONTROLLED RECTIFIERS

5.3.1 Basic Characteristics

Silicon Controlled Rectifiers (also known as SCR's and Thyristors) are the most common high power semiconductor in use today.

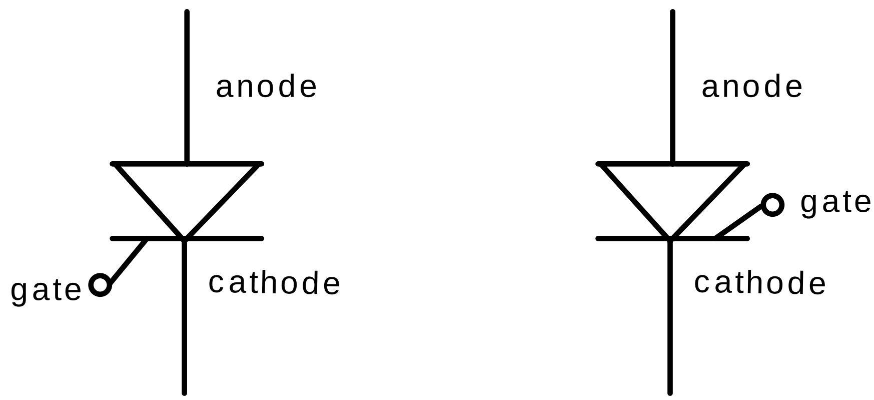


Figure 5.9 SCR symbols

This device is an open circuit until a positive current pulse is applied to the gate. This turns on the device, after which it operates like a diode.
The device turns off only when the current goes to zero *and* a reverse voltage is applied.
When the device is on it has similar characteristics to a power diode i.e. there is a forward voltage drop, V_f, which is about double that of a diode of the same size and current rating. The SCR power handling capability is determined by the same characteristics as for power diodes:

I_{rms} - the steady state RMS current that the device can tolerate without damage

$\hat{I}$ - steady state peak current that the device can tolerate without damage
(Note that $\hat{I} = \sqrt{2}\, I_{rms}$ *only for sinusiodal currents*)

$\hat{I}_s$ - the single-cycle peak current; this is the single pulse of 50 or 60 Hz current that the device can tolerate and is actually a single half cycle rating.

I^2t - "fuse current rating", required for fuse coordination in DC applications

PIV - Peak Inverse Voltage, the maximum reverse voltage that he device can withstand.

5.3.2 SCR Turn on Characteristics

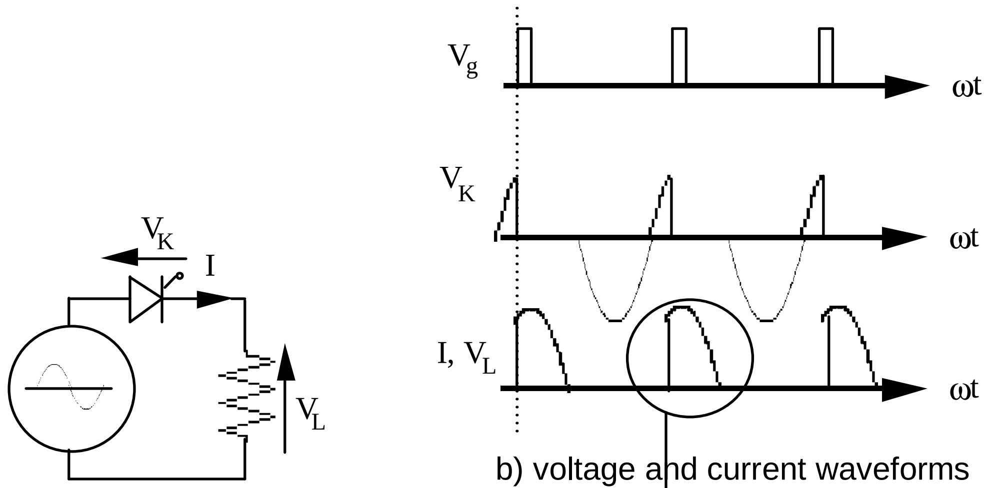
a) Rate of current rise
In order to turn on, an SCR must be forward biased, i.e. anode must be at a positive voltage with respect to the cathode, *and* a gate current, I_g , must be injected into the gate terminal. Typically only a few milliamps are required and I_g is independent of the size of the SCR or its current rating.

When the gate is initially turned on only a small part of the conducting area of the SCR is on. The "on" area expands at a finite rate, i.e. the $\partial A/\partial t$ is finite. Therefore, to avoid destroying the device, the rate of rise of current through the SCR (the $\partial I/\partial t$) must not exceed the rate at which the conducting area is turning on. Thus there is a maximum rating for the rate of current rise;

$$\frac{\partial I}{\partial t} \leq K$$

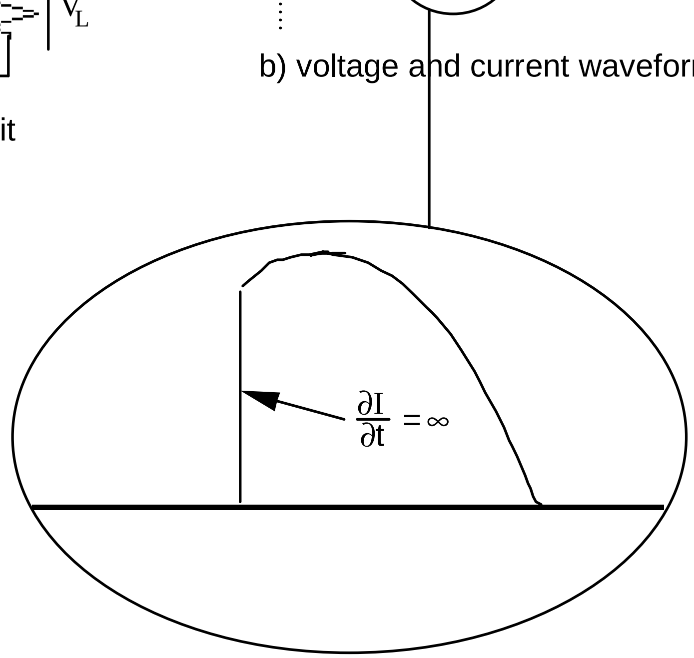
Where K is a constant determined by the rate at which the conducting are expands and is typically less than 100 A/µS for slow (60Hz) devices but up to several hundreds of amps per microsecond for fast switching devices. Of course this $\partial I/\partial t$ limitation only applies during turn on and not during turn off.

Figure 5.10 shows a typical circuit in which the turn on $\partial I/\partial t$ would be a concern.



a) Simple SCR circuit

b) voltage and current waveforms



c)expanded view of $\partial I/\partial t$ during turn on

Figure 5.10 $\partial I/\partial t$ concern during SCR turn on

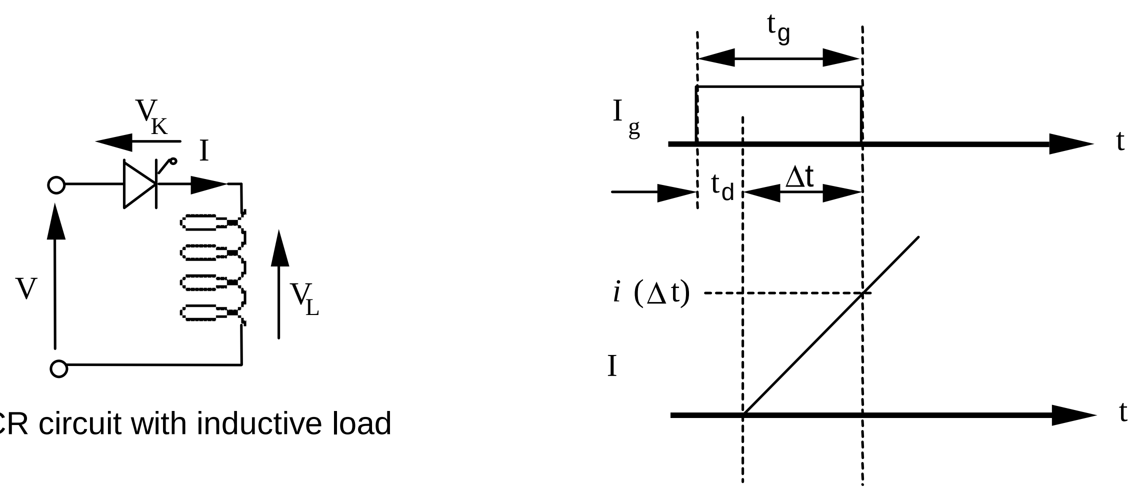
In this circuit the $\partial I/\partial t$ is "unlimited". In actual circuits $\partial I/\partial t$ is limited by stray circuit inductances or parasitic load inductances or by actually incorporating a physical inductor, L, in series with the SCR such that

$$L = \frac{V}{\partial I / \partial t_{max}}$$

b)Short Gate Pulses Considerations
Once the gate current is turned off, the SCR will stay on only if its current is greater than a minimum "holding current", I_h ;

$$i(t) = I_h \qquad \text{when } I_g = 0$$

If there is inductance in series with the SCR (as may be required to limit $\partial I/\partial t$) then this inductor will also limit the SCR current at the time the gate pulse is turned off, as shown in **Figure 5.11**.



a) Simple SCR circuit with inductive load

b) SCR current at end of gate pulse

Figure 5.11 SCR current after a short gate pulse

Thus there would be two constraints on this inductance value;

$$\frac{V\Delta t}{I_h} = L = \frac{V}{\partial I/\partial t_{max}}$$

Where Δt is the duration of the gate pulse minus the turn on delay

$$\Delta t = \Delta t_g - t_d$$

c) Turn on delay

There is always some delay between the application of a gate signal and the turn on of the device. This is always the case for all devices: SCR's and transistors for both power and signal applications.

For an SCR this delay time t_d is typically 2 to 5 μs for slow (60 Hz) devices and 1 to 2 μs for fast (inverter-grade) devices.

d) Spurious turn on

An SCR (like all semiconductor junctions) has internal parasitic capacitance and this can also turn on the device as shown in **Figure 5.12.**

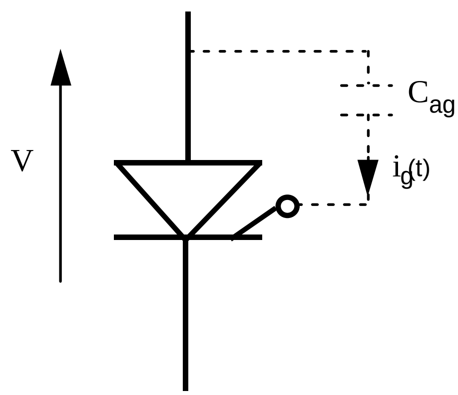


Figure 5.12 Simplified Equivalent circuit for an SCR including parasitic anode-gate capacitance

If C_{ag} is the internal parasitic capacitance between the anode and gate, then an expression for gate current, $i_g(t)$, can be obtained:

$$i_g(t) = C_{ag}\frac{\partial V}{\partial t}$$

Thus the SCR can 'inadvertently' turn on if:

$$\frac{\partial V}{\partial t} = I_g / C_{ag}$$

Where I_g is the minimum gate current required to turn on the SCR.

This is only a consideration when V is +ve. There is no turn on problem as long as V is -ve. Typical values of $\partial V/\partial t$ for slow (60Hz) SCR's are 25V/µS and up to 1000V/µS for fast (inverter grade) SCR's.

Example:

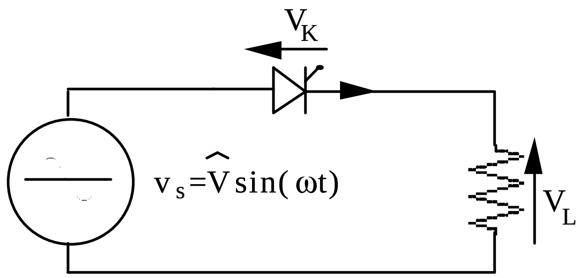


Figure 5.13 SCR phase control circuit with variable frequency source

In the circuit shown in Figure **5.13** the voltage across the SCR prior to turn on is given by the equations:

$$v_k(t) = V_s = \hat{V}\sin(\omega t)$$

and;

$$\frac{\partial v_k(t)}{\partial t} = \omega\hat{V}\cos(\omega t)$$

Thus the peak $\partial v_k/\partial t$ can be determined:

$$\text{peak } \frac{\partial v_k(t)}{\partial t} = \omega\hat{V} \quad \text{at } t = o, \frac{\pi}{\omega}, \frac{2\pi}{\omega}, \ldots$$

As an example: if the SCR is rated at 25V/µS, (a slow SCR), and the source voltage is 600 Vrms then the maximum operating frequency for this SCR will be determined by;

$$\omega_{max} = \frac{\partial v_k/\partial t}{\hat{V}} = \frac{25\times10^6}{600\sqrt{2}} = 29.5 \text{ r/s} = 4.7 \text{ kHz}$$

5.3.3 Turning Off An SCR

An SCR will turn off when its current goes to zero. It will not conduct in the reverse direction (except for the reverse recovery current) and will block reverse voltage.

However, in order to block reapplied forward voltage the SCR must remain reverse biased for a minimum "turn off time", t_q . This t_q can be as high as 50 to 250 microseconds for slow (60Hz) SCR's or as low as 5 to 50 microseconds for fast (inverter grade) SCR's.

The process of forcing an SCR current to zero and applying reverse voltage is called "commutation". The circuitry used to do this is called the commutation circuit. There are four major types of commutation: natural line commutation, natural load commutation, forced soft commutation and forced hard commutation.

a) Natural line commutation
In this type of commutation the SCR current goes to zero because the source voltage and current go to zero. This occurs in AC driven circuits, an example of which is shown in Figure **5.14**.

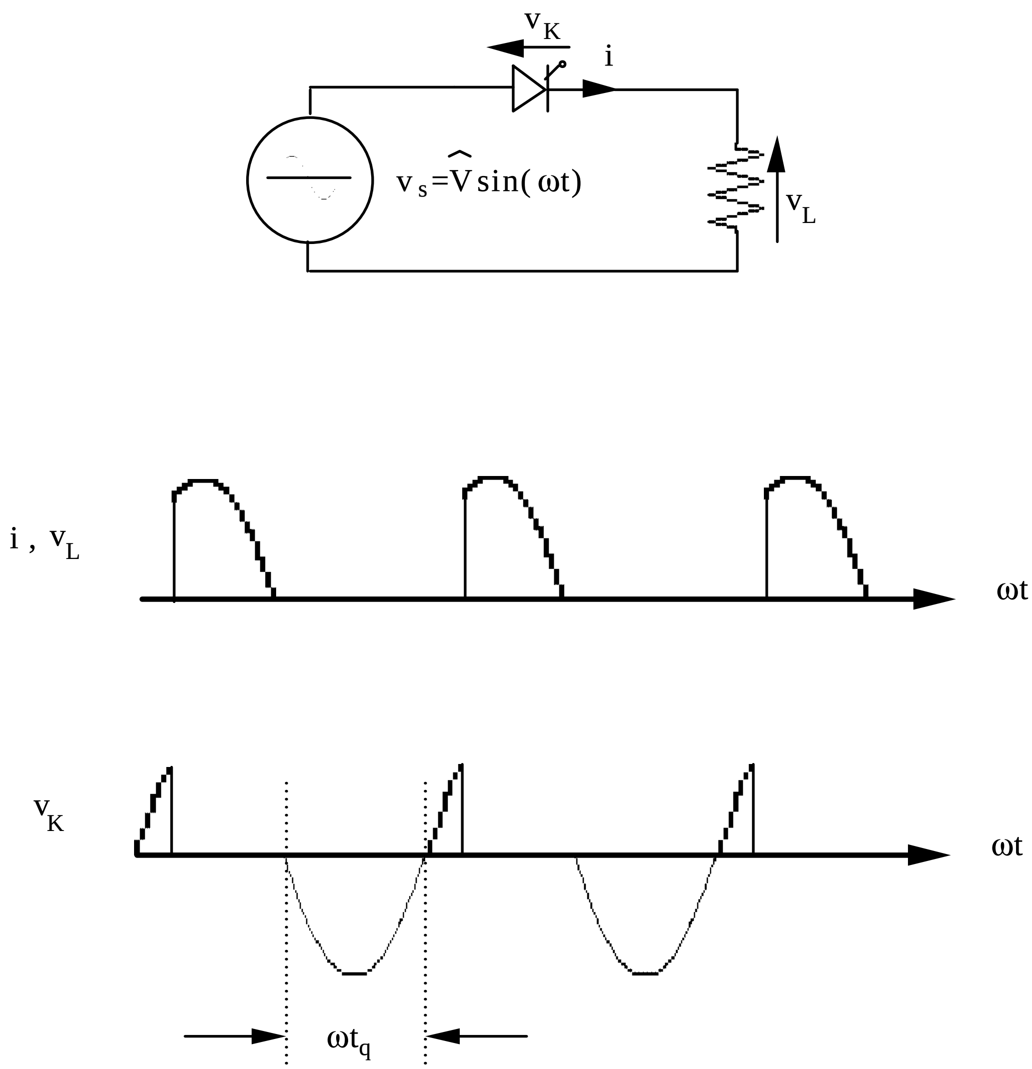


Figure 5.14 Example of an SCR circuit with natural line commutation

In the circuit in Figure **5.14** the available turn off time is the entire negative half cycle of the input voltage waveform;

$$\omega t_q = \pi$$

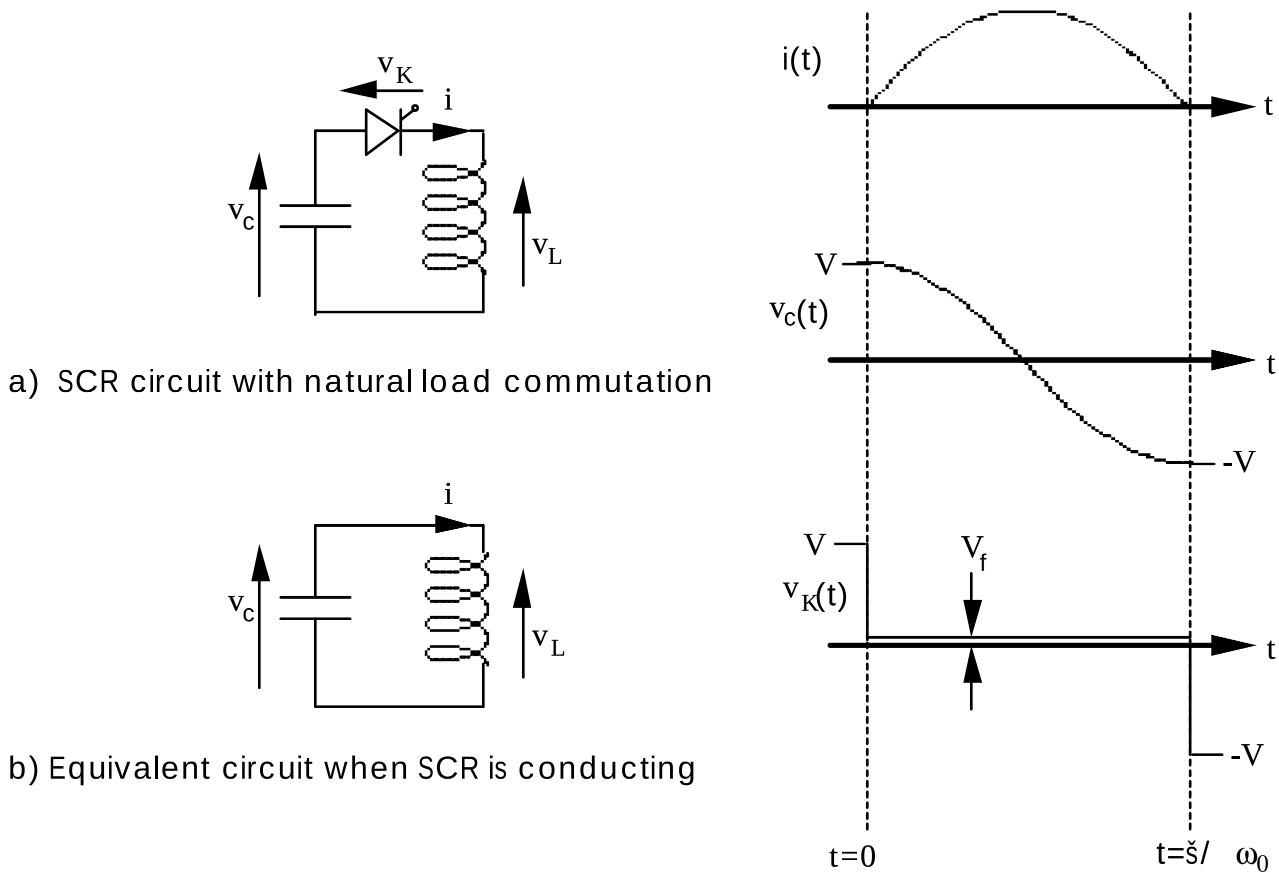
and;

$$t_q = \frac{\pi}{\omega} = \frac{1}{2f}$$

Where f is the supply frequency in Hz.

b) Natural load commutation

In natural load commutation the SCR current goes to zero because the load current goes to zero regardless of the supply voltage, or in some cases there is no supply voltage. An example of the latter is shown in Figure **5.15**



a) SCR circuit with natural load commutation

b) Equivalent circuit when SCR is conducting

c) Voltage and current waveforms

Figure 5.15 Example of SCR circuit with natural load commutation

The SCR is turned on at t = o, at which time the capacitor voltage is +V.
The SCR current is given by the equation:

$$i(t) = \frac{V}{Z_o} \sin(\omega_o t)$$

Where:

$$Z_o = \sqrt{\frac{L}{C}}$$

and:

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

The SCR current, i(t), will go to zero at;

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

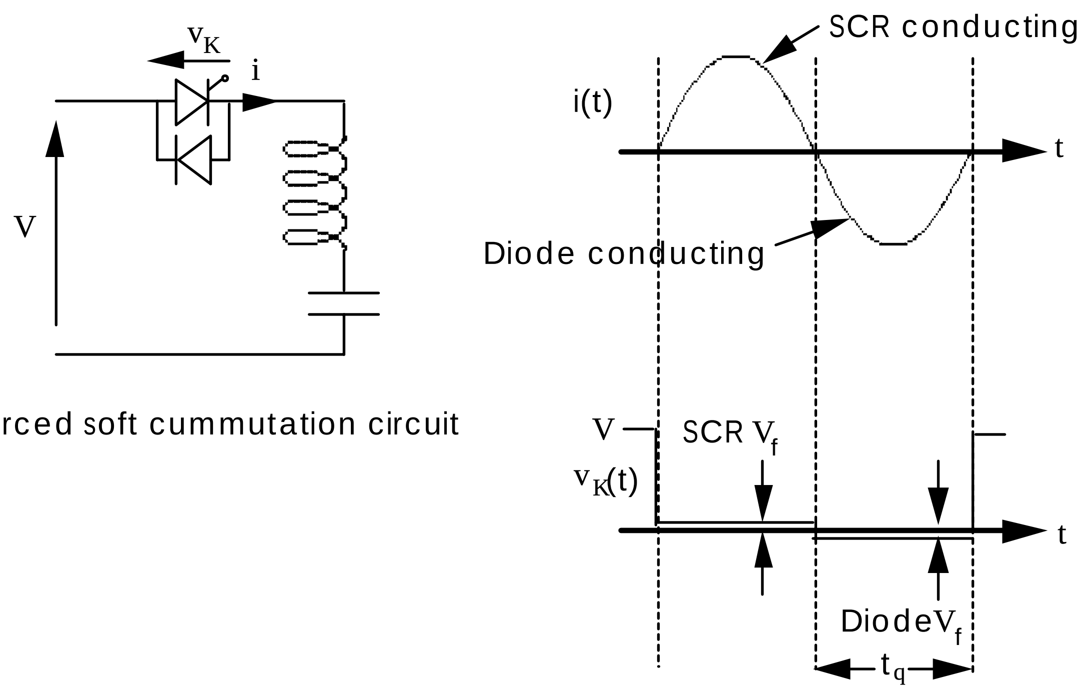
At which time the SCR turns off. The voltage applied to the SCR is the capacitor voltage, $v_c(t)$, which is given by the equation:

$$v_c(t) = V\cos(\omega t) = V\cos(\pi) = -V$$

Thus the SCR has a negative voltage applied to it and will turn off. The available turnoff time is determined by how long the capacitor voltage remains negative.

c)Forced Soft Commutation

In forced commutation the SCR is turned off by external circuitry. Forced commutation can be classified as either 'soft' or 'hard'. In hard commutation the reverse voltage applied to turn off the SCR is high, usually close to the PIV rating of the SCR. In soft commutation the reverse voltage applied to turn off the SCR is relatively low, usually no more than the V_f from an antiparallel diode, as shown in **Figure 5.16.** In general the higher the reverse voltage the shorter the time required to turn off the device, but the relationship between reverse voltage and turnoff time is non-linear.



a) forced soft cummutation circuit

c) Voltage and current waveforms

Figure 5.16 Forced Soft Commutation Circuit and Waveforms

In the circuit of Figure **5.16 t**he SCR is turned on at t = 0,
and V_c = 0 at t = 0.
The SCR current is given by the equation:

$$i(t) = \frac{V}{Z_o} \sin(\omega_o t)$$

Where:

$$Z_o = \sqrt{\frac{L}{C}}$$

and:

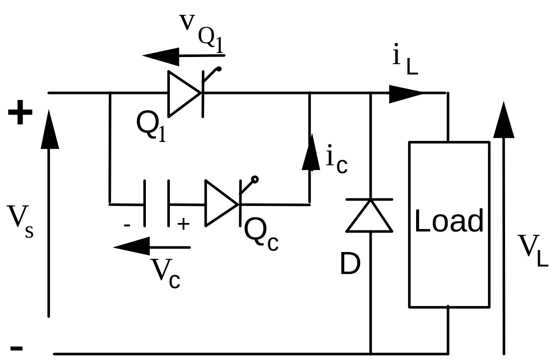
$$\omega_o = \frac{1}{\sqrt{LC}}$$

In this case, even though the SCR current goes to zero at $\omega t = \pi$, the load current, i(t), will go negative during $\pi < \omega t < 2\pi$ at which time it will flow through the diode. During this negative current part of the waveform the forward voltage drop across the diode appears as a negative voltage across the SCR and, if it lasts long enough, will be sufficient to turn off the SCR. The available turn off time is the time during which the diode is conducting, which is:

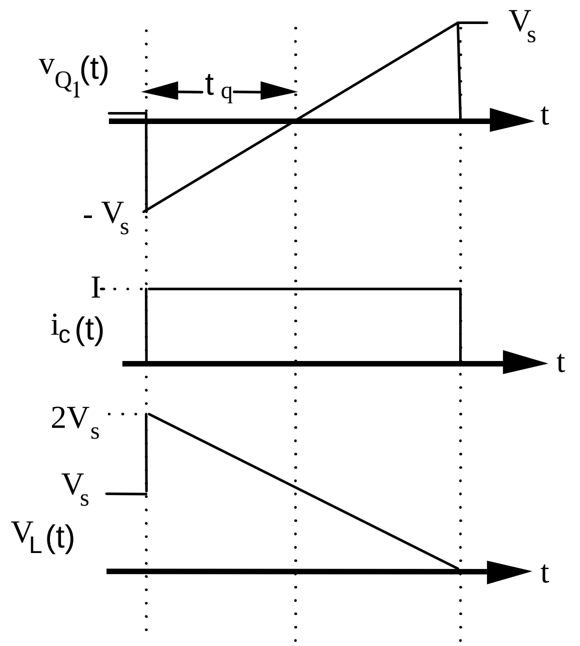
$$t_q = \frac{\pi}{\omega}$$

The same SCR will typically require 50% more t_q under "soft" commutation vs "hard" commutation c)Forced Hard Commutation

In forced hard commutation an auxiliary SCR is used to turn off the main SCR. as shown in Figure **5.17** This additional SCR is often referred to as the commutation SCR.



a) forced hard cummutation circuit



c) Voltage and current waveforms

Figure 5.17 A circuit demonstrating forced hard commutation

The initial conditions for the circuit of Figure **5.17** are:

a) at t = 0^- ;

$v_C = -V_S$,

i_L = I which is assumed to remain constant,

the main SCR, Q_1 , is conducting

the commutation SCR, Q_C , is off.

b) at t = 0^+ ;

Q_C is turned on,

i_L = I is assumed to remain constant for the duration of the commutation interval.

As soon as Q_C is turned on the capacitor voltage appears as a reverse voltage across the main SCR, Q_1 . This reverse biases Q_1 and it stops conducting. The load current can no longer go through Q_1 and instead the load current goes through the commutation circuit consisting of C and Q_C .

The governing equation during this commutation interval is:

$$i_C(t) = i_{Q_c}(t) = i_L(t) = I$$

$$v_{Q_1}(t) = v_C(t) = v_C(0) + \frac{1}{C}\int_0^t i_c(t)\partial t = -V_S + \frac{It}{C}$$

The the commutation interval ends at $t = t_q$ when the reverse SCR voltage goes to zero, or:

$$v_{Q_1}(t_q) = 0 = -V_S + \frac{It_q}{C}$$

Solve for;

$$t_q = \frac{V_S C}{I}$$

Note that in this circuit the available turn off time, t_q , decreases with increasing load current, I.

5.3.4 Other Thyristor Devices

Some other power semiconductors in the SCR/Thyristor family are;

- Asymmetrical SCR's (also known as ASCR's)
- Gate Turn Off SCR's (also known as GTO's)
- Light activated SCR's
- FET activated SCR's
- TRIAC's

a)Asymetrical SCR's, also known as ASCR's;
These are the same as normal SCR only their reverse blocking voltage is very low, about 10V. Therefore they can only be "soft" commutated, i.e. with an antiparallel diode. The main advantage or ASCR's is that they require very little turnoff time, typically 3 to 5 µS.

b)Gate Turn Off SCR's, also known as GTO's;
A GTO is similar to an SCR but it can be turned-off by a negative gate pulse. However, the gate current requirement is high to turn off a GTO, typically about 20% of load current. Also the forward voltage drop, V_f , is high, typically about 3V.

c)Light activated SCR's;
These devices are turned on by a pulse of light. They are used for ultra-high voltage applications >10KV where high gate drive isolation is required. The direct access of light into the gate region of the SCR results in very fast turn on times, typically less than a microsecond.

d)FET activated SCR's;
These devices are turned on by a Field Effect Transistor (FET) that is integrated as part of the gate structure. This results in a very low gate drive requirement and a relatively fast turn on. These are not very common because of the added cost of the FET circuitry usually costs more than can be saved from the reduced gate drive circuitry.

e) TRIAC'S;
A TRIAC consists of two antiparallel SCR's as shown in Figure **5.18**. This is the second most common type of Thyristor, after the basic SCR itself. It operates exactly like two back to back SCR's and it can thus provide phase control in both positive and negative directions. These are most commonly used in providing a phase controlled AC output, and as such are sometimes referred to AC controllers. A common example of an AC controller is the "solid state light dimmer".

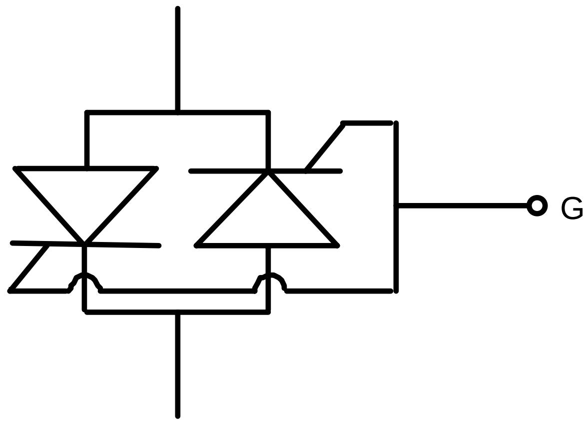


Figure 5.18 Basic Schematic symbol for a TRIAC

5.4 POWER TRANSISTORS

The most common power transistor devices in use today are bipolar transistors, Darlingtons, and FET's (Field Effect Transistor's). Each of these devices are used in two general types of applications: Linear applications and Switching applications. The characteristics of each of these devices is quite different for Linear vs Switching applications

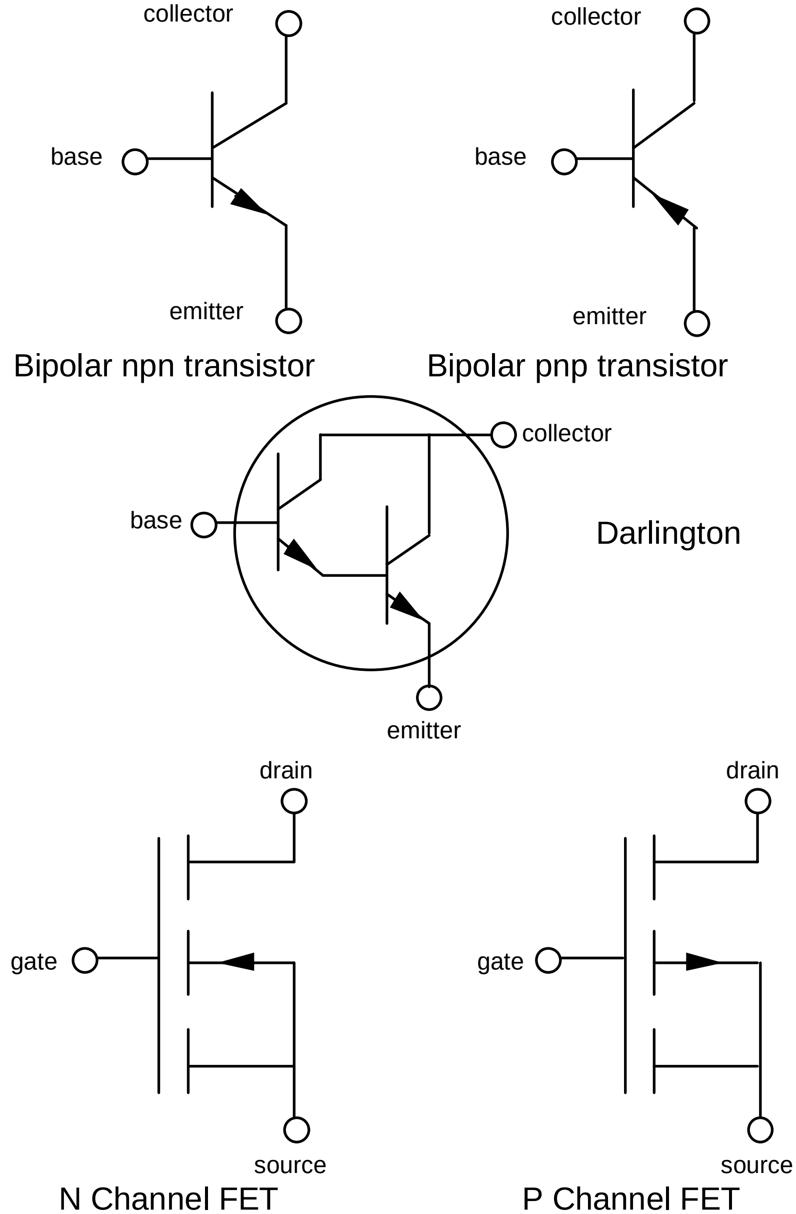
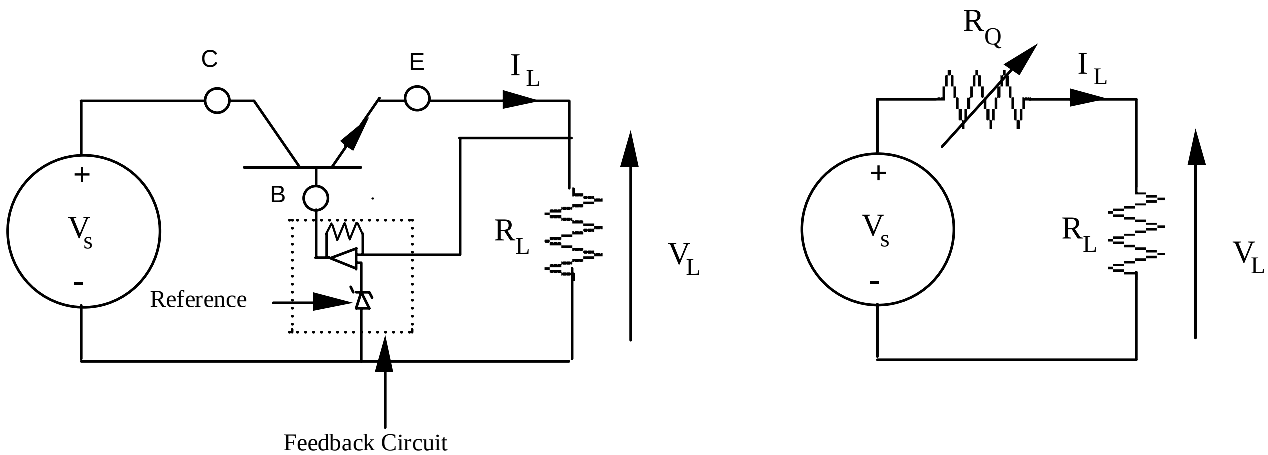


Figure 5.19 Power Transistors

5.4.1 Bipolar Power Transistors

a) Linear Applications of Bipolar Power Transistors
The most common Linear application of power transistors is as a linear regulator. (The power amplifier application will not be discussed in this text because that is basically an amplifier applications and is not peculiar to power electronics.) In a linear regulator application the power transistor, is used as an electronically controllable power resistor as shown in **Figure 5.20**:



a) Basic linear regulator circuit

b) Simplified equivalent circuit

Figure 5.20 Linear regulator circuits - A linear application of a power transistor

R_Q is the equivalent series resistance of the transistor between collector and emitter and can be controlled by controlling the transistor base voltage.

higher base voltage $\Rightarrow$ lower R_Q

lower base voltage $\Rightarrow$ higher R_Q

In this and other Linear applications the power *handling* capability of the bipolar transistor is determined by the following characteristics:

$\hat{I}_C$ = maximum current capability.

Typical values are up to tens of amps.

$\hat{V}_{CE}$ = maximum voltage withstand capability.

Typical values are up to hundreds of volts.

β = the current gain for the device = $\frac{I_C}{I_B}$

typical values of β for power transistors are between 5 and 20

Note that β drops of with increasing I_B .

$V_{CE_{min}}$ = the minimum value of V_{CE} without going into saturation, where saturation is defined as the minimum V_{CE} below which increasing base drive will not affect V_{CE} .

For power bipolars the V_{CE} can be as low as 0.5V or less.

P = the maximum power dissipation for the device
$= I_C V_{CE}$

b) Linear Regulators

Complete linear regulator circuits are available as single package integrated circuits that contain the power transistor, feedback circuitry, op-amp, reference and base drive circuitry all on one piece of silicon. As a first approximation these linear regulators can be treated as a simple transistor. These linear requlators come in different types that may use a bipolar or Darlington or FET as the power transistor. The main differences between a linear regulator and a discrete bipolar transistor are:

Base drive: the linear regulator does not require any additional base drive circuitry. The base drive circuitry for the internal transistors is included inside the package.

Minimum V_{CE} : the minimum V_{CE} for a linear regulator, often referred to as ΔV_{min} , is usually much higher than for a discrete bipolar transistor typically 2 to 3 V. Though low dropout regulators are available at a premium price.

Linear regulators are available in either series regulator or shunt regulator configurations.

c) Switching Applications of Bipolar Power Transistors

In a switching application the power transistor is used as an on-off switch. In the on mode the transistor is fully saturated, assuming the base drive is adequate. In the ideal case the transistor can be represented by a short circuit. In more realistic cases the transistor may be represented by a voltage drop equal to V_{CE} . In the off mode the transistor is open circuit and can be represented by an open circuit.

Important characteristics for a switching power transistor are:

$\hat{I}_C$ = maximum current capability, subject to the constraints described under SOA.

$\hat{V}_{CE}$ = maximum voltage withstand capability, subject to the constraints described under SOA.

β = the current gain for the device = $\frac{I_C}{I_B}$ For a switching transistor it is also important to increase/decrease the base current very quickly in order to switch the transistor on/off quickly and thus minimize switching losses.

$V_{CE_{Sat.}}$ = the minimum value of V_{CE} when the device is driven fully into saturation.

t_{on} = turn on time, this is dependent on I_C , base drive, and temperature, and is typically less than 1 µs.

t_{off} = turn off time, this is also dependent on I_C , base drive, and temperature. In particular it is important to apply negative base drive current to get minimum possible turn off time, which is also typically less than 1 µs.

d) Safe Operating Area (SOA)
SOA (Safe Operating Area), is the area under the I_C vs. V_{CE} curve in which the switching transistor must operate in order to prevent destruction, as shown in **Figure 5.21.**

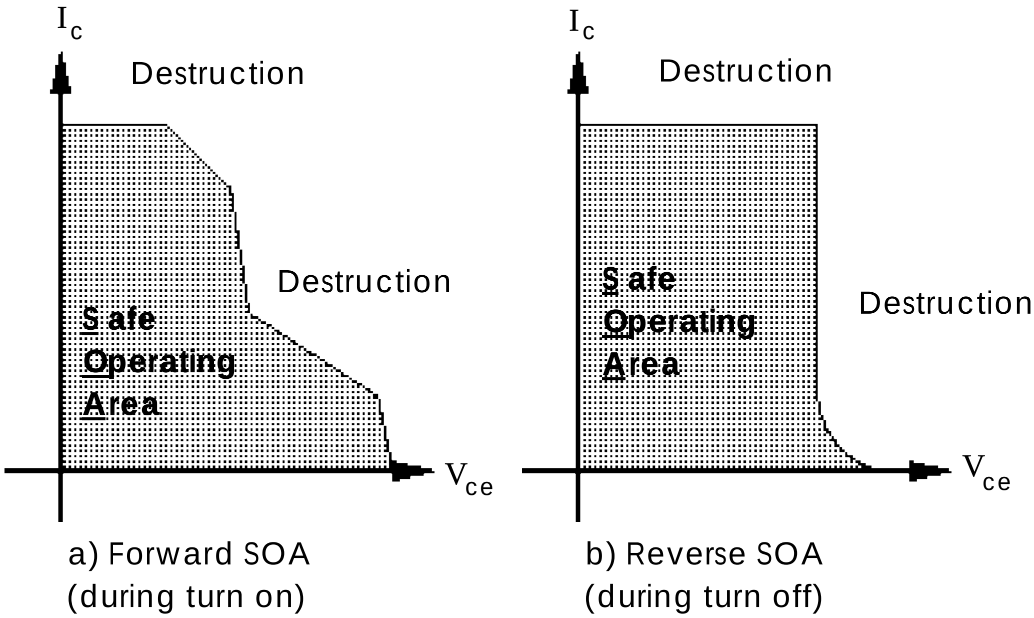


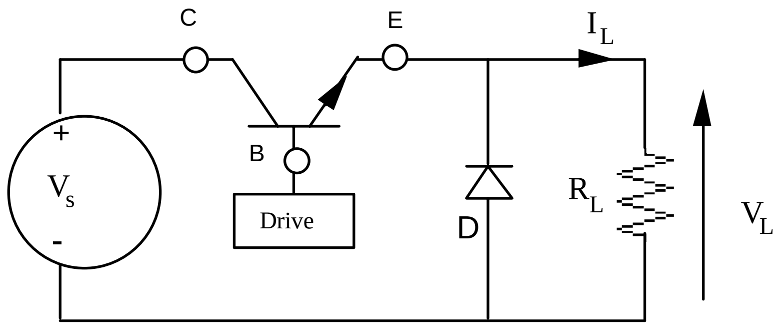
Figure 5.21 Safe Operating Area for a switching bipolar transistor

The SOA for any particular bipolar power transistor is very dependent on:

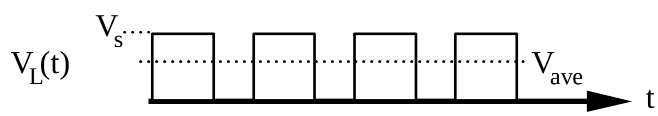
- device characteristics, such as doping, manufacturing quality, manufacturing process
- base drive rise and fall times
- temperature, SOA decreases with increasing temperature.
- external circuit elements such as inductance and capacitance which will tend to speed up or slow down I_C and/or V_{CE} during the switching interval.

Note: Bipolar power transistors are very "delicate" a lot of device and circuit parameters must be taken into account in order to use them properly, otherwise they will "blow up". "You have to read the fine print on a bipolar."

Example switching considerations for bipolar transistors.



a) Basic switching regulator circuit



b) Output voltage waveform

Figure 5.22 A Common Switching Application for a Power Transistor

The circuit shown in **Figure 5.22** is an example of a common circuit in which a power transistor has to switch voltage and current. When transistor Q is turned on it will reverse bias the diode and start to assume all the load current I_L instantaneously, even before V_{CE} has fully collapsed. Therefore it is necessary to turn on the device quickly and limit the $\partial i/\partial t$ so as not to exceed the SOA. Similarly when the device is turned off it is necessary to reduce the current to zero quickly (using reverse base-emitter voltage) and limit the $\partial v/\partial t$ so as not to exceed the SOA.

5.4.2 Darlington Transistors

A Darlington transistor consists of two transistors on one silicon die. The transistors are internally connected as shown in **Figure 5.23**

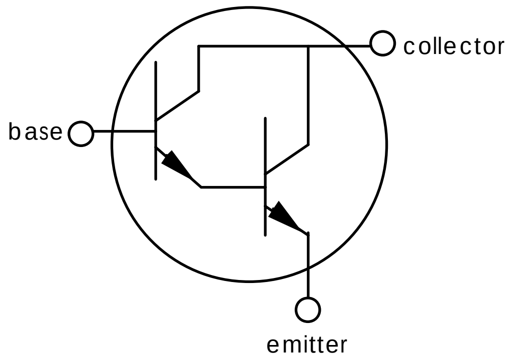


Figure 5.23 Darlington Transistor

This connection has the effect of multiplying the β's of the two transistors, i.e.

$$\beta_D = \beta_1 \times \beta_2$$

However, it also has the effect of adding the delay, turn on and turn off times, i.e.

$$t_d = t_1 + t_2$$

Also the $V_{CE_{Sat.}}$ of a Darlington transistor will always be higher than that for a transistor that has direct base drive. The main requirement for Darlington transistors was in high current applications where high gain was required. FET's are now available at higher currents and have higher gains than Darlingtons and thus Darlingtons are not used much any more.

5.4.3 Important drawbacks of Bipolar power transistors (Single and Darlington)

a) SOA considerations: exceed the SOA, even for an instant, and they're gone. Bipolar power devices are not forgiving. They are not 'user friendly'.

b) Reverse voltage: a bipolar will destruct if V_{CE} is reversed.

c) High drive current: for a typical β of 10 to 20 a bipolar requires much more drive circuitry than a FET (field effect transistor).

d) Low switching speeds: bipolars switch much slower than FET's and dissipate more power per switch transition. This makes them unsuitable for frequencies above 100KHz.

e) Secondary breakdown: a localized area of the base-emitter junction may get slightly hotter than the rest of the junction (probably because it is drawing slightly more current). The effective β for that area goes up producing more collector current into that area — raising its temperature more, etc., etc. This type of vicious circle is also known as *thermal runaway* and it will destroy a bipolar transistor.

The net result is that bipolars are not being used for new applications in Power Electronics.

5.4.4 Field Effect Transistor (FET)

The basic symbols for a FET are shown in **Figure 5.24**.

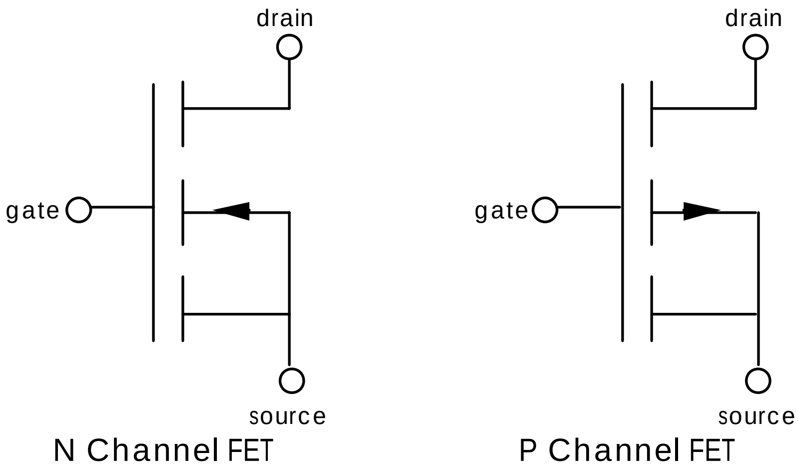


Figure 5.24 Basic Symbols for a FET

Most power FET's are N channel enhancement type, though there are some P channel enhancement type. The gate of a FET is comparable in function to the base of a bipolar transistor except that in a FET it is the gate voltage that determines the effective resistance between drain and source. Whereas in a bipolar transistor it is the base current that determines the current between collector and emitter. In general a FET is much closer to an "ideal switch" than a bipolar transistor.

The basic power handling capability of a FET is determined by the following parameters;

V_{DS} - Maximum source to drain voltage
I_D - Maximum drain current
$R_{DS(on)}$ - Drain to source resistance

FET's also inherently have a 'body diode' as shown in **Figure 5.25**.

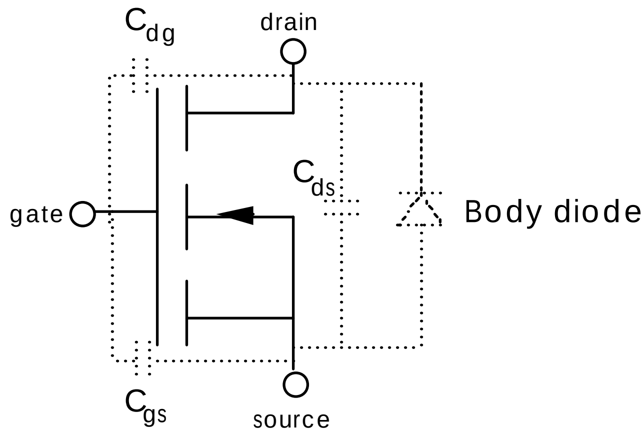


Figure 5.25 FET showing body diode and other 'parasitics'

This diode is an unavoidable byproduct of FET fabrication and is generally a 'lousy' diode in that it has a relatively high forward voltage drop, V_f , and high reverse recovery time, t_{rr} , and recovery charge, Q_{rr} . For most applications the standard transistor symbol is adequate, and the body diode is often ignored.

In addition to the body diode a FET has other 'non-ideal' characteristics. These are called parasitic parameters or just 'parasitics'. Gate capacitance is most significant especially at high frequencies because this capacitor has to be charged and discharged at each on/off cycle and its stored energy has to be provided/dissipated. Therefore, even though the effective current gain for a FET is extremely high in the on mode, nevertheless several amps of gate drive may be required for short intervals in order to turn on a FET quickly because the gate capacitance requires high pulses of current to reach sufficient voltage to turn on the device quickly. i.e.

$$I_G = C_{gs} \frac{\partial V}{\partial t}$$

Also the turn on time and turn off time for a FET are much less than for bipolar power transistors (several nanoseconds vs. hundreds of nanoseconds). Furthermore, FET's are not subject to secondary breakdown, thermal runaway and thus are not limited by Safe Operating Area considerations. Thus FET's are much more forgiving and 'user friendly' than bipolars. However, like all semiconductors, FET's will destruct if they are subjected to excessive heat dissipation or overvoltage conditions.

5.5 Worst Case Analysis

In general, it is the ratings of electronic components that determine the maximum operating conditions, (max. V, I or f), for power circuits.
For example in the simple circuit shown in Figure 5.26 the maximum voltage for the circuit is determined by the minimum of each of the component peak voltage ratings.

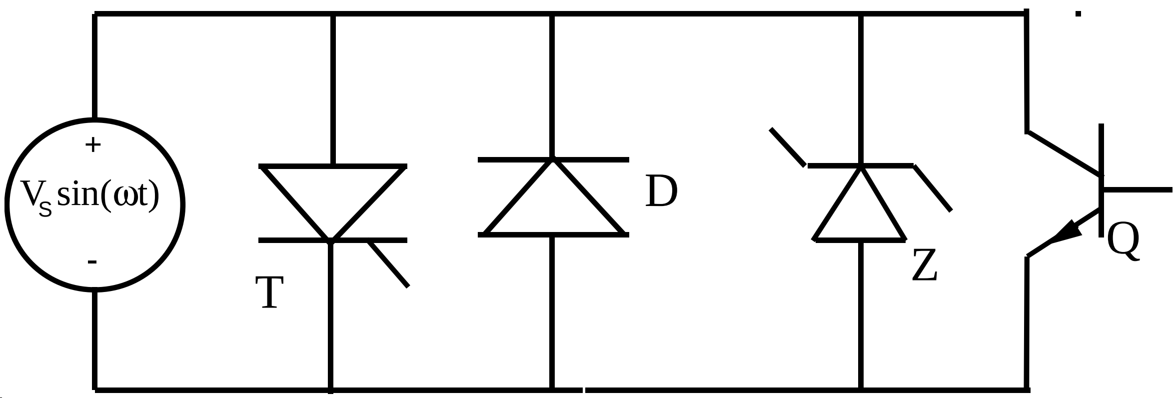


Figure 5.26 Simple Circuit Using Components of Different Ratings

Therefore if:

$$\hat{V}_T = 100 \text{ V}, \ \hat{V}_D = 350 \text{ V}, \ \hat{V}_Z = 150 \text{ V, and } \hat{V}_Q = 85 \text{ V}$$

Then the maximum value for V_S would be 85V determined by $\hat{V}_Q$.
In this case it is intuitively obvious that the maximum operating value of V_S is determined by the minimum component rating.

Similar principles apply in all worst case analysis.

For example, if the component ratings were given by the following:

$$\hat{V}_T = \hat{V}_D = \hat{V}_Z = \hat{V}_Q = 200(1 - \delta) \text{ V}$$

Where:

$$0.5 > \delta > 0.0$$

Then the maximum value for V_S would be 100V determined by $\delta = 0.5$.
Similarly, if the components had different minimum frequency requirements, such as:

$$\omega_{T_{min}} = 1.5 \text{ kHz}, \ \omega_{D_{min}} = 0, \ \omega_{Z_{min}} = 0, \text{ and } \omega_{Q_{min}} = 50 \text{ kHz}$$

Then the minimum frequency for this circuit would be 50 kHz determined by $\omega_{Q_{min}}$.
Thus the minimum operating value for frequency is determined by the maximum of each of the component minimum frequency requirements.