# POWER SEMICONDUCTOR DEVICES

INTRODUCTION

Power Electronics is the technology of converting electric power from one form to another using electronic power devices.

Several types of solid state power semiconductor devices have been developed to control of output parameters, such as voltage, current or frequency.

In a static power converter, the power semiconductor devices function as switches, which operate statically, that is, without moving contacts.

The time durations, as well as the turn ON and turn OFF operations of these switches, are controlled in such a way that an electrical power source at the input terminals of the converter appears in a different form at its output terminals. In most types of converters, the individual switches in the converter are operated in a particular sequence in one time period, and this sequence is repeated at the switching frequency of the converter.

Figure shows a scheme for converting DC to AC. This type of power conversion is called inversion, and the circuit itself is called an inverter. Our inverter power circuit consists of four switches labeled S1-S4. The input is a DC voltage source of magnitude V (in V) connected to the input terminals of the inverter, which are P (positive) and Q (negative). The timing of the switches is shown in Fig. (d). For example, from instant $t = 0$ to instant $t = t1$, switches S1 and S4 are kept ON, the other two being kept OFF.

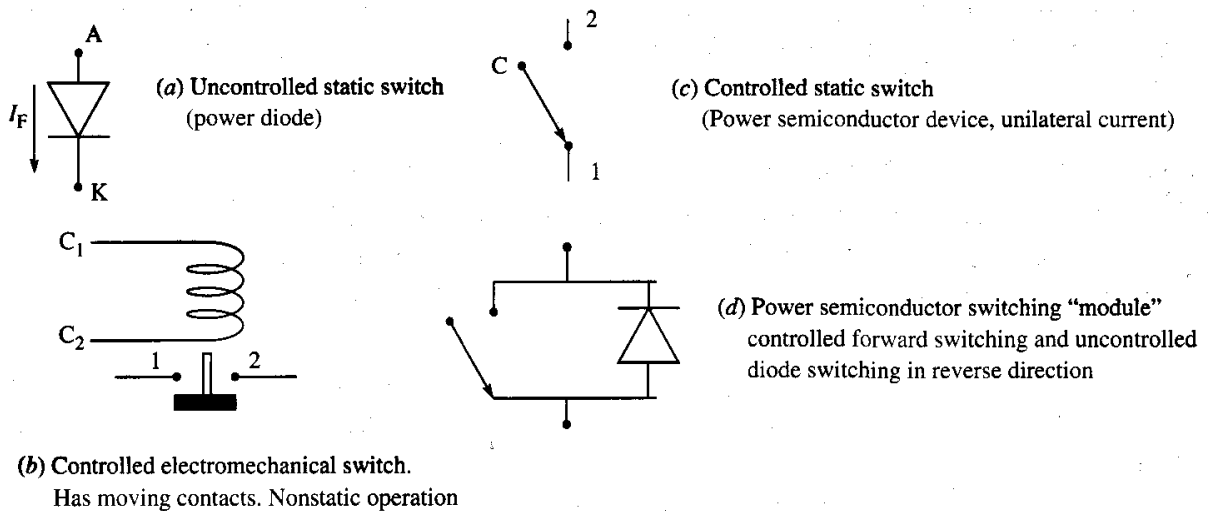(a) Inverter

(b) V_{PQ}

(c) V_{AB}
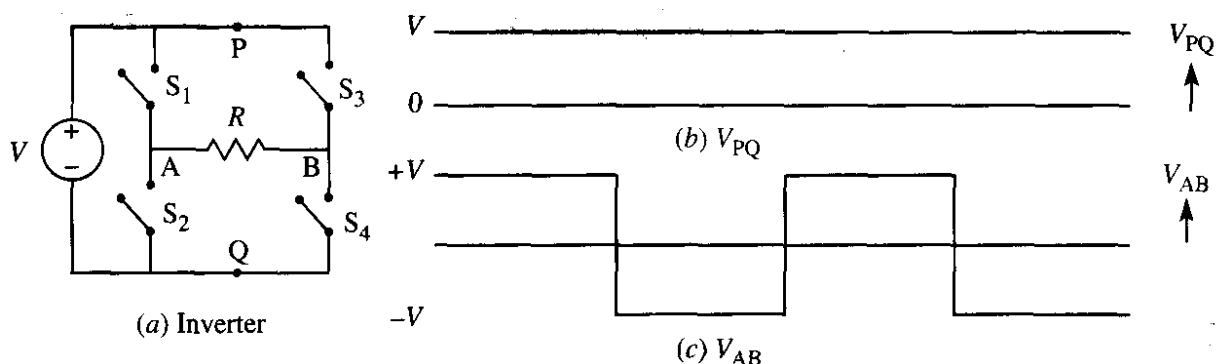
Therefore the input DC voltage appears at the output terminals with terminal A positive. During the next interval from S1 and S4 are kept OFF, but S2 and S3 are kept ON. Therefore, during this interval, the input DC voltage appears at the output terminals with reversed polarity (A negative). This sequence of switching is repeated, and in this way the input voltage V of fixed polarity shown in Fig.(b) is presented at the output terminals PQ as an AC square wave voltage as shown in Fig. (c).

Figure (e) shows how the same circuit configuration of four switches can be used to convert an AC voltage source connected at the terminals AB into a DC voltage at the terminals PQ. This type of power conversion is called rectification, and the circuit itself a rectifier. In our rectifier of Fig. (e), the switches S1-S4 are operated according to the same timing as indicated by Fig. (d). The input terminals of the rectifier are now A and B, to which the AC square wave voltage such as that shown in Fig. (c) is connected. The output terminals of our rectifier are P (positive) and Q (negative). The input AC voltage is now presented as a unidirectional voltage at the output terminals. Notice that the directions of current through the switches will be different in Figs (a) and (e).

(e) Rectification

(d) Switch timing diagram
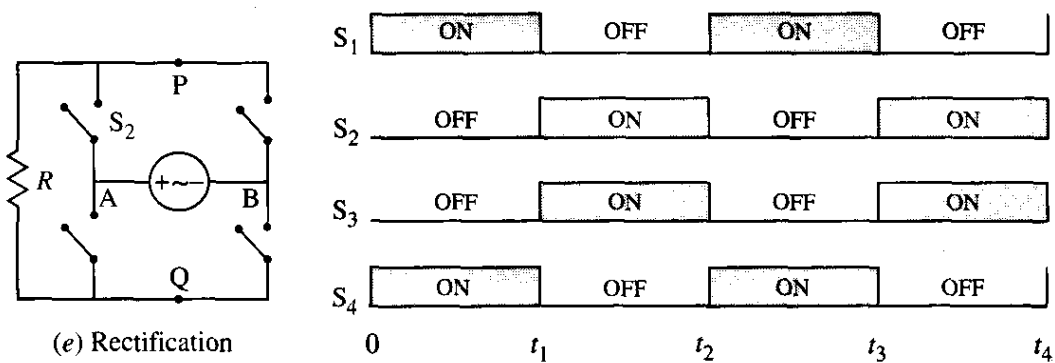
The objective of this course is to present the principles underlying power conversion by the use of static **switches** and the techniques employed for controlling output parameters such **as** voltage, current, power, frequency and waveform. We shall, in a progressive sequence, present all the important types of power converters that have proved useful in the application areas of electric power. We shall also present important application areas, and this will bring out how converter schemes and control strategies can be tailored to meet specific needs.

TYPES OF STATIC SWITCHES

(a) Uncontrolled static switch
(power diode)

(c) Controlled static switch
(Power semiconductor device, unilateral current)

(d) Power semiconductor switching "module"
controlled forward switching and uncontrolled
diode switching in reverse direction

(b) Controlled electromechanical switch.
Has moving contacts. Nonstatic operation

1. Uncontrolled Static Switch—The Power Diode

The simplest static switch is the diode. A power diode is a two-terminal device, whose circuit symbol is shown in Fig. (a). An ideal diode conducts when forward-biased, with negligible voltage drop across it and a forward current, I_F, flows through it. If, however, it is reverse-biased, ideally, it does not conduct. A real diode will have a small forward voltage drop across it when it conducts and a small reverse leakage current when it is reverse-biased.

The diode switch blocks reverse voltages, but has no capability to block forward voltages. We can describe the ideal power diode as an uncontrolled static switch that turns ON and turns OFF by itself, depending on the polarity of the voltage.

2 Controlled Switch

A controlled switch is one that could be turned ON and OFF by activating and deactivating a control circuit. Figure 1.2(b) shows a nonstatic (with moving contacts) switch of this kind. It has a control coil whose terminals are labeled C1 and C2. The power terminals of the switch are labeled 1 and 2.

To turn ON this switch, we send a current through the control coil, which will cause the plunger to move and connect the power terminals. The following aspects should be noted here.

1. The switch has four terminals—two for the power circuit and two for the control circuit.

2. The control circuit is electrically isolated from the power circuit.

The electrical isolation between the power terminals and the control circuit

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is very often a requirement in static power converters. Unfortunately, power semiconductor switching devices presently available do not provide any isolation at all between the power and control terminals. In fact, every power semiconductor switch is a three-terminal device. A typical example is the power transistor. The power terminals are the collector and the emitter. The third terminal, namely the base, and the emitter are the control terminals.

The circuit symbol that we shall use to represent an ideal three-terminal controlled unidirectional static switch is shown in Fig. (c). The power terminals of the switch are labeled 1 and 2. The arrow shows the direction of ON state current through it. The control input is across terminals C and 1.

3 Directional Properties of Static Switches—Current Direction

The power diode is a static uncontrolled switch with only one direction for current flow. The general circuit symbol that we have chosen and shown in Fig. 1.2(c) is for a controlled switch, which is also unidirectional.

The unidirectional the power semiconductor switches are,

1. the power diode,
2. the bipolar power transistor,
3. the insulated gate bipolar transistor (IGBT),
4. the thyristor, also known as the silicon controlled rectifier (SCR),
5. the asymmetrical silicon controlled rectifier (ASCR),
6. the gate turn off thyristor (GTO)
7. the MOS controlled Thyristor (MCT).

The switches with bi-directional current capability are:

1. the power MOSFET,
2. the reverse conducting thyristor,
3. the triac.

Of these, the power MOSFET and the reverse conducting thyristor function as controlled switches in the forward direction and as uncontrolled switches in the reverse direction Fig. (d). The triac works as a controlled switch in both directions.

4. Directional Voltage Capabilities of Static Switches

A distinction must be drawn between directional current flow capability and directional voltage blocking capability for a static power semiconductor switch.

The **bipolar power transistor** is a static switch that can only switch current in the "forward" direction. This does not mean that it has ability to block reverse voltages.

In contrast, **the thyristor**, which is also a *unidirectional* switch, has a symmetrical voltage blocking capability in that it can block approximately the same voltages in both forward and reverse directions.

TABLE 1 *Properties of power semiconductor switching devices*

	Capability to block F. Voltage	Capability to block R. Voltage	Reverse condition	Type of Forward ON switching Control		Is control available for switching OFF F. current?		Is control available for reverse conduction?	Is control available for switching OFF R. current?	
				C+	**L+**	**C**	**L**	**C L**	**C**	**L**
Power diode	No	Yes	No	No control						
Bipolar power transistor	Yes	No	No	Yes		Yes		Not		
Power MOSFET	Yes	No	Yes	Yes		Yes		No	No	
Insulated Gate Bipolar Transistor (IGBT)	Yes	No	No	Yes		Yes		N/A		
Thyristor (SCR)	Yes	Yes	No		Yes	No		N/A		
Asymmetrical SCR	Yes	No	No		Yes	No		N/A		
Reverse conducting thyristor	Yes	No	Yes		Yes	No		No	No	
Gate turn off thyristor (GTO), reverse blocking type	Yes	Yes	No		Yes		Yes	N/A		
GTO without reverse voltage blocking capability	Yes	No	No		Yes		Yes	N/A		
Triac	Yes	Yes	Yes		Yes	No		Yes	No	
MOS controlled thyristor	Yes	No	No		Yes		Yes	N/A		

5. Types of Switching Control — Continuous or Latching

There is a major difference between static switches in the manner in which the control terminal performs the switching operation.

In some devices, such as the **bipolar power transistor** and the power **MOSFET**, after the turn ON switching is implemented by an input to the control terminal, this input should continue to be present, to keep the switch in the ON state. If the control input ceases, the switch will turn OFF. With such a switch, both the turn ON and the turn OFF operations can be implemented by the same control circuit. This type of control may be described as "**continuous**".

In devices like the **thyristor**, the control input to implement turn ON need be only a pulse of very short duration. Once the switch has turned ON, there is no further need for the turn ON control pulse to be present. Another example of this type of control is the gate turn OFF thyristor (GTO). The GTO is turned ON by a short positive pulse and turned OFF by a short negative pulse on its control terminal. This type of control may be described as "**latching**", because the device is latched into the required state by a pulse of short duration.

The **thyristor**, which is a latching device, has a serious limitation. Its control terminal (gate) has the ability only to control the ON switching operation. Once the device has been latched into the ON state, the gate loses control and the device behaves like a diode. Its OFF switching has to take place by reverse bias of the main terminals like a diode.

Ideal and Real Switches

To assess the performance of a switch, we look at two aspects of its behavior—static and dynamic.

If the switch is either in its ON or OFF state, we call this a *static condition.* The *dynamic condition* is the transition from one static state to the other.

1. Static Performance

An ideal switch should have zero voltage across it in the ON state and zero current through it in the OFF state when it is blocking a voltage.

The product of current and voltage, which gives the power dissipated in the switch, is zero in both conditions.

This is the basic reason why a power conversion scheme based on switching is more efficient than other methods, because ideally, there is no internal power loss.

Power semiconductor switches depart to some extent from the ideal—there is a small but finite voltage drop in the ON state and a small but finite "leakage current" in the OFF state.

The power dissipated in a switch during its ON state is given (in W) by

$$p = i_f \cdot v_f$$

For an ON period duration t1 to *t2,,* during which *Vf* and *if* may vary, the total energy (in J) dissipated in it will be

$$J = \int_{t1}^{t2} i_f \cdot v_f \cdot dt$$

Energy dissipated in the switch causes its temperature to rise. The efficiency of power conversion is also lowered, because of the power dissipation in the switches.

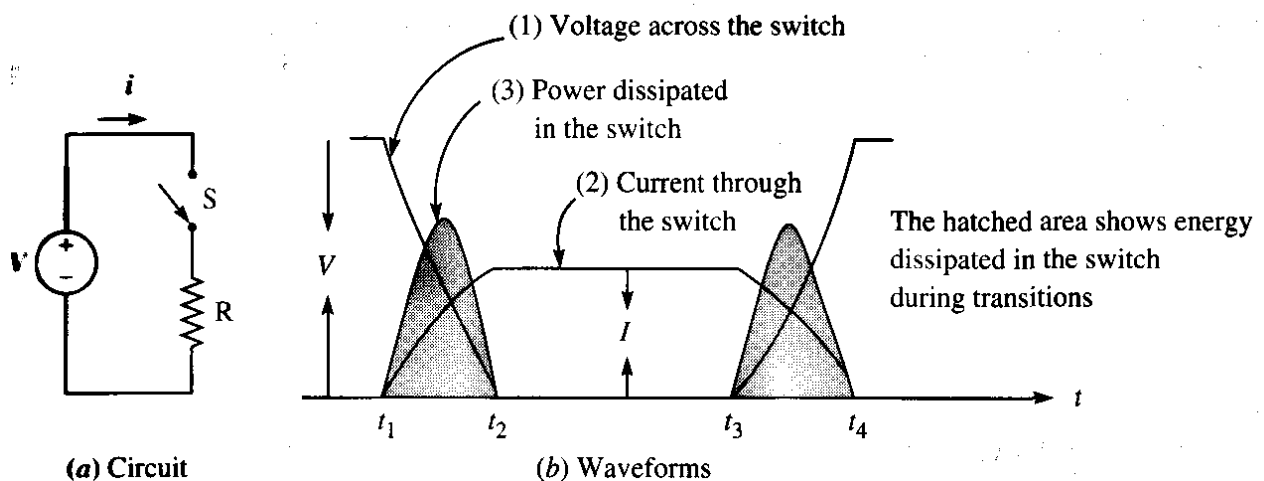The leakage current that flows in the OFF state causes the power dissipation in the device.

Usually the power dissipation due to this leakage current is small in comparison with the power dissipation in the ON state therefore the power dissipation due to OFF state leakage can be neglected.

2 Dynamic Performance

An ideal switch should change from the OFF state to the ON state, *instantaneously,* when the required switching control signal is applied to its control terminal. Similarly, the transition time for the turn OFF switching should also be zero. A real switch needs a finite t_{on} for ON switching and *tof* for OFF switching. These finite switching times have two major consequences.

1. They limit the highest repetitive switching frequencies possible.
2. They introduce additional power dissipation in the switches themselves.

Of these, the second phenomenon needs further explanation.

(1) Voltage across the switch

(3) Power dissipated in the switch

(2) Current through the switch

The hatched area shows energy dissipated in the switch during transitions

(*a*) Circuit   (*b*) Waveforms

Instantaneous voltages, currents and power in a static switch during the switching transitions.

Figure shows the waveforms of (1) the voltage drop across the switch and (2) the current *I* through it, when a turn **ON** switching is implemented at *t =t1* and a turn **OFF** - switching at *t = t2.*

We notice that during the transition there is power dissipation taking place inside the switch, whose instantaneous value is given by the product of voltage and current. The instantaneous power is also plotted (3) as a function of time in Fig. Depending on the nature of the current and voltage waveforms during the transition, the peak power can reach a relatively large magnitude. The energy dissipation in the switch is equal to the area shown hatched under the power waveform.

The total energy J (in J) dissipated in the switch in one switching cycle is given by the sum of the areas under the power waveform during t_{on} and t_{off}. The average switching power loss is therefore proportional to the switching frequency, and is given (in W) by

$$P_{switching} = f \cdot J$$

f being the converter switching frequency (in Hz).

3. Temperature Rise—Use of Heat Sinks

The immediate consequence of energy dissipation in a static switch is its temperature rise. The need for cooling arises to keep the switch temperature below its safe limit. The exact location where the heat is generated is in the silicon pellet that actually is the switch. Electrical contacts are made to appropriate areas of this thin wafer, and these constitute the terminals of the device, which are brought outside the casing in which the silicon pellet is housed. The power losses of the switch raises the temperature of the pellet. The temperature gradient thus created causes the heat power to flow outwards to the casing surface. To facilitate the easier flow of heat power to the ambient atmosphere outside, it is a common practice to mount the casing on a "heat sink." Heat sinks are made of metal, and provide a large surface area from which the heat power can pass by convection and radiation to the ambient atmosphere. The convection flow can be further enhanced, if needed, by using a fan to provide forced air cooling.

With the device mounted on a heat sink, the path of heat flow can be viewed as a series combination of the following individual paths: (1) from the junction (J) to the surface of the casing (C); (2) from the surface of the casing (C) to the outer surface of the heat sink (S); (3) from S to the ambient atmosphere (A), which we shall assume to be an external region sufficiently distant from the heat sink, at which the thermal gradient is negligible.

With constant power dissipation inside the pellet, thermal equilibrium conditions will be attained after a period of time. After this has happened, the temperatures and temperature gradients stay constant in such a way that all the power dissipated inside the device continually flows out into the ambient. Taking thermal power flow as proportional to temperature difference, we can represent this condition by an electrical analog in which electric current (in A) represents thermal power (in W) and potential difference (in V) represents temperature difference (in °C). Such an analogous electric circuit will consist of resistances (Ω = V/A) as the analog of "thermal resistance" (expressed as ^{o}C/W). On this basis, Fig. 1.8 shows the thermal power flow model for a static switch mounted on a heat sink. In this model, J represents the inside of the silicon pellet. Θ_{JC} is the thermal resistance (in °C/W) between J and the outer surface of the casing C. The other thermal resistances are labeled by appropriate subscripts.
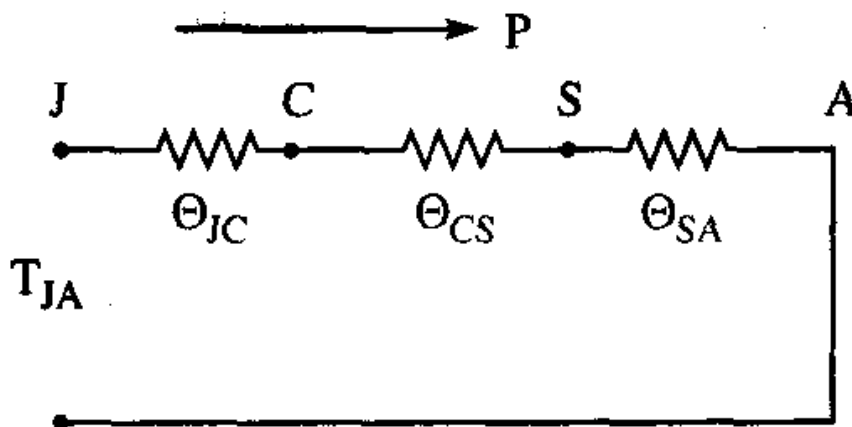
This model can be used to make estimates of the junction temperature rise when the power dissipation is known, or to estimate the maximum power dissipation possible for a specified junction temperature.

POWER DIODES
1 Available Ratings, Types

Diodes employed in static converters are essentially high power versions of conventional low power devices used in analog and digital signal processing circuits. Power diodes are manufactured in a wide range of current and voltage ratings.

Current ratings vary from a few amperes to several hundred amperes.

Voltage ratings extend from tens of volts to several thousand volts.

The important parameter is its "reverse recovery time." – a time after the forward conduction which is necessary to recover its ability to block reverse voltages. Based **on** this time, diodes are classified as "fast recovery" and "slow recovery" types. Certain types of converters require the use of fast recovery power diodes.
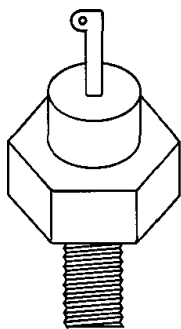
2. Junction Structure, Packaging

The diode consists of a silicon pellet with a single internal pn junction [Fig. (a)]. Typically, it is fabricated by diffusing p-type impurity atoms into one side of a n-type crystal wafer of silicon. It has two terminals, of which the anode (A) makes contact with the p side surface of the pellet and the cathode (K) with the n side. The forward direction of current flow is from A to K, as shown by the diode circuit symbol [Fig. (b)].
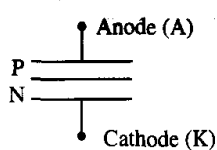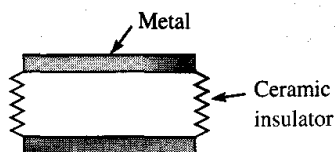
(a) Junction struture
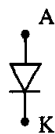
(b) Circuit symbol

(c) Stud-type package

(d) Disc-type (hockey puck) package

The power diode: junction structure, circuit symbol and package types.

The area of the pellet determines the current rating. For example, a large area device using a silicon wafer of 4 in. diameter may have a current rating of 1000 A.

The resistivity of the starting material and its thickness are mainly responsible for the voltage blocking capability of the device - its voltage rating will go up with the purity level of the starting wafer and its thickness.

The impurity profile in the silicon pellet has a major effect on both its ON state forward voltage drop and also on its reverse recovery time.

A trade off exists between **blocking voltage capability** and **reverse recovery time**. High resistivity silicon has a long minority carrier lifetime.

A trade off also exists between **blocking voltage capability** and **ON** state **forward voltage drop**. If a thicker and higher resistivity wafer is employed to achieve higher voltage rating, this will result in a higher forward voltage drop in the ON state.

There are two types of packages commonly used for housing the diode pellet. In the stud type package shown in Fig. (c), the casing, which is of metal, has a threaded stud for easy mounting on a heat sink. The metal casing and the stud constitute one terminal of the diode. The other terminal is brought out on the side opposite to the stud, with electrical insulation from the casing. Stud-type diodes are available with either polarity for the stud—anode or cathode. By choosing the stud polarity of the diode to match the casing terminal of the controlled switching device, both devices can be mounted on the same heat sink.

Diodes with very large current and voltage ratings employ the disc package, also known as "hockey puck," illustrated in Fig. *(d)*. Here, the two terminals are flat metallic surfaces separated by a ceramic insulator. Disc-type diodes are mounted with at least one side in contact with a flat heat sink surface. For better cooling, two separate heat sinks may be used—one on each side. Special mounting hardware, which provide for adequate contact pressure and insulation between the two sides is usually available from the manufacturer.

3 Reverse Recovery Characteristics

For most practical purposes, we can consider the turn ON switching of a diode as instantaneous. But the turn OFF switching behavior requires special consideration, because this has a significant effect on the performance of most types of static converters.

Let us assume that S has been ON for a long time, as a result of which a current has been established in the *R-L* circuit. After this, S в turned OFF. But the current in the *R-L* circuit cannot instantly fall to zero, because of the presence of the inductance *L*. When the current tends to fall, the induced e.m.f. in the inductance will forward-bias the diode, and the current, will "freewheel," that is, continue to flow through it due to the stored energy in the inductance, even though there is no voltage source present to drive this current. We shall assume that *L* is large, so that the decay of current is negligible during the short period of our next sequence of observations. In other words, / will be assumed to be constant.

(a) circuit   *(b)* Voltage and current waveforms
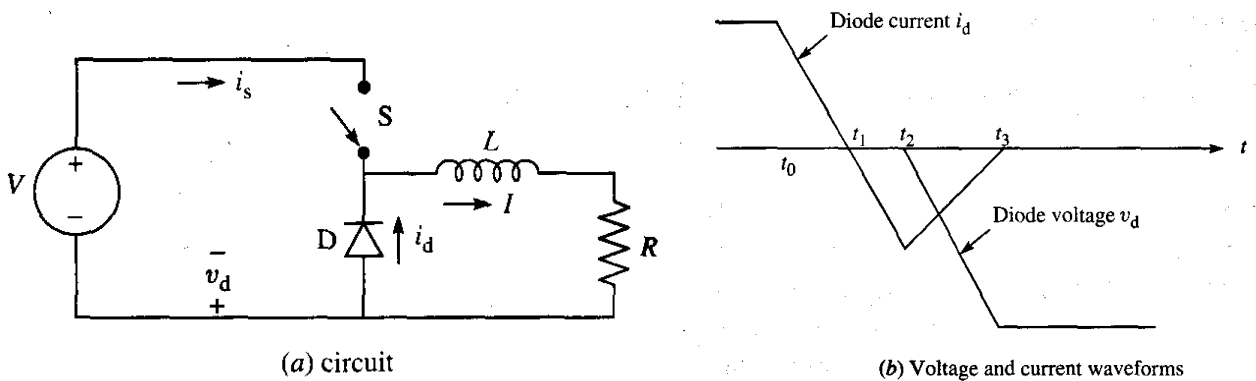
1. <u>From *t = t0* to *t = t1*</u> in Fig. (b), when S is turned ON again. This will cause a current *is* to build up in the DC source and through switch S. We will assume that the rate of increase of i_s is constant. This rate *di/dt* is determined by the residual inductance in the circuit mesh consisting of the source, the diode D and S. Since *I* is constant, the increase in i_s results in an equal decrease in the diode current i_d:

$$i_s + i_d = I \quad \text{Therefore}$$

$$\frac{i_d}{dt} = -\frac{i_s}{dt}$$

This linear fall of current in the diode is shown by the diode current waveform in Fig. (b).

2. <u>From $t = t1$ to $t = t2$</u>

If the diode is ideal in its dynamic behavior, it should stop conducting *at t =t1* and recover its reverse voltage blocking ability. But, because of the excess minority carriers it continues to conduct after $t = t1,$ now in the reverse direction. Therefore the diode continues to be a conducting switch and the current waveform continues unaffected, until the excess carriers are removed. This happens at $t = t2$.

3. <u>From $t = t2$ to $t = t3$</u>

After $t = t2$ the reverse current falls towards zero and the diode recovers its reverse voltage blocking capability. In the reverse blocking condition, the diode is charged to the reverse voltage. The diode current falls to zero at $t = t3,$ when this junction capacitance has been charged to the full reverse voltage. At this instant, the turn OFF switching transition of the diode is complete.

The "reverse recovery time" t_r is the time interval measured from the instant at which the forward current has fallen to zero to the instant at which the reverse voltage recovery is completed.

The specified reverse recovery time in the data sheet of a power diode is correct only for the specified test conditions. It does vary to some extent, depending on the test conditions, and is higher for a larger ON state current before the commencement of turn OFF.

If this time is very short, the diode is described as belonging to the "hard recovery" category. If this interval is relatively long, it is a "soft recovery" type. It follows that a soft recovery diode has a lower *di/dt* during reverse recovery. Soft recovery diodes are generally preferable in static power converters, because inductive voltage spikes resulting from the diodes' reverse recovery transients, are smaller.

EFFECTS OF REVERSE RECOVERY TRANSIENT

1 High Currents In The Controlled Switches.

In DC/DC converters and DC/AC inverters, when S is repetitively turned **ON** and turned **OFF** in each switching cycle, there is a current transfer taking place at each switching, between S and the diode.

If the diode were ideal, with no reverse recovery current, S would have to carry only the output current in the *R-L* circuit.

In the real situation S has to handle the sum of the output current and the reverse recovery current immediately after it is turned **ON**. This means that it should be capable of carrying a pulse current of very large amplitude and of dissipating the additional power due to this current spike. Alternatively, the amplitude of the current pulse itself should be limited by inserting additional inductance in series with the source.

2 Over-Voltage Spike Across Diode.

Any inductance present in the loop causes a voltage spike to appear across the diode, during the decay of the reverse current. The magnitude of this reverse over-voltage spike depends on the loop inductance value and the slope *di/dt* of the reverse current. In a real diode, the *di/dt* value during the decay of reverse current is not constant, as we have assumed by the approximated straight line from *t2* to *t3*. Therefore, the reverse over-voltage varies and has a peak value during this interval.

3 Limitation Of Converter Switching Frequency.

In a static converter, if the switching frequency is increased, the recovery time t_r of the diodes will constitute an increasing fraction of the total cycle time. This will generally decrease the efficiency of the converter. Therefore the reverse recovery time sets an upper limit to the converter switching frequency.

Schottky Diodes

Schottky diodes do not have a pn junction. Instead, they employ a metal-to-silicon barrier. In a Schottky diode, the current flow is due to the flow of majority carriers. Therefore they are suitable for use at very high frequencies. The barrier does have a capacitance, which accounts for a certain amount of reverse current, to charge this capacitance to the reverse voltage. Current ratings of Schottky diodes available are well below 100 A. Reverse voltage ratings are well below 100 V. They are very widely used in "switch mode power supplies," which work at high switching frequencies.

Snubber Circuits (Switching Aid Circuits)

A snubber circuit for a diode serves to protect it from damage that can arise due to an over-voltage spike during reverse recovery. During the decay of the reverse recovery current, the capacitor serves to limit the voltage spike.
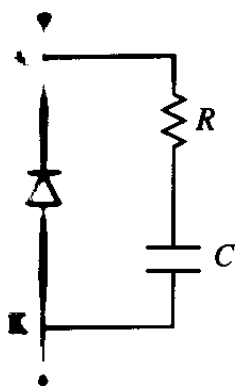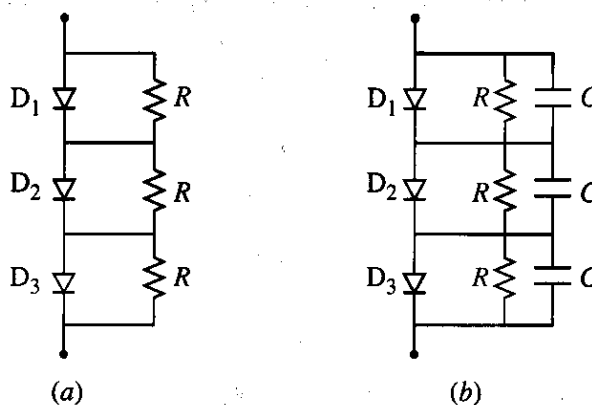

Snubber Circuits   Series Operation of Diodes

Series and Parallel Operation of Diodes

When the voltage rating of an available diode type is not high enough for a high voltage application, several such diodes connected in series can be used to achieve the required voltage capability. If this is done, it is necesssary to ensure that each diode in the series chain shares the total reverse voltage nearly equally.

To achieve high current capability, several diodes of one type can be connected in parallel. The recommended practice is to choose diodes that are matched as regards forward voltage drop.

CURRENT AND VOLTAGE RATINGS OF POWER DIODES

1 **Current Ratings.** The data sheet of a power diode usually gives three separate types of current ratings: (1) the average current, (2) the r.m.s. current and (3) the peak current. It is important to ensure that none of these ratings is exceeded in actual operation. To explain the significance of each of these ratings, we shall use the current waveform shown bellow.
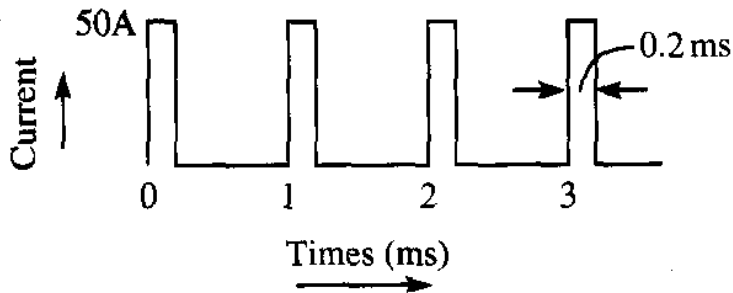

$$I_{average} = 50 \times 0.2/1 = 10A$$

$$I_{rms} = \sqrt{\left[50^2 \times 0.2/1\right]} = 22.4A$$

$$I_{peak} = 50A$$

2 **VOLTAGE RATINGS.** For high power diodes, the data sheets usually specify two voltage ratings: (1) the repetitive peak reverse voltage and (2) the nonrepetitive peak reverse voltage. The non-repetitive peak is specified to indicate the capability of a diode to withstand an occasional over-voltage surge that may occur due to a circuit fault.

(*a*) Source voltages

(*b*) Diode voltage v_{D_1}
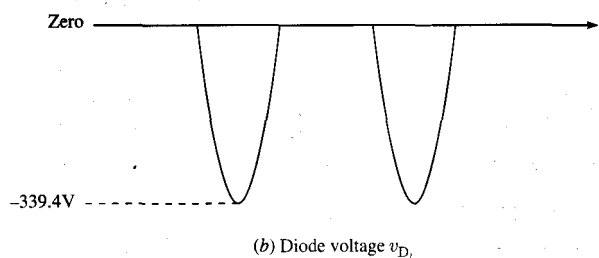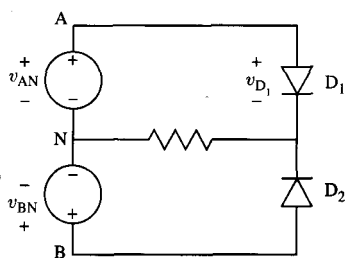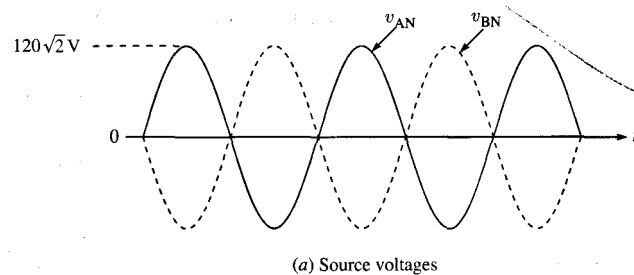
$$V_{ANpeak} = V_{BNpeak} = 120V_{rms}\sqrt{2} \approx 170V$$

Total peak reverse Voltage is 2 x 170V= 340V