

POWER ELECTRONICS

INTRODUCTION

Power Electronics can be described as “control of power through electronic circuits and components.” Semiconductor devices with ratings above 1 kV and 1 kA can be manufactured today as a result of technological developments in the last thirty years. Power electronics has advanced in parallel with the semiconductor technology. It is possible today to control power from a few watts to several megawatts level.

Some of the areas where power electronics is utilized are listed below.

- Household applications: Air conditioning, lighting, computers and other electronic equipment.
- Commercial: Heating, air conditioning, cooling, ventilation, lighting, computers, uninterruptible power supplies, reactive power compensation.
- Industrial: Pumps, compressors, CNC systems, robot manipulators, induction furnaces, arc welding machines, uninterruptible power supplies, reactive power compensation.
- Traction: Electrical vehicles, battery charging, electrical trains.
- Power Systems: High Voltage DC (HVDC) systems, reactive power compensation, renewable energy source integration.
- Space: Satellite attitude controllers, solar power systems, power supplies.
- Communication: Battery chargers

Available power sources can have alternating current (AC) or direct current (DC). Power converters are used to convert the available voltage into other forms. They can be classified as follows:

- AC-DC Converters (Rectifiers)
- DC-DC Converters
- DC-AC Converters (Inverters)
- AC-AC Converters

Interdisciplinary nature of power electronics:

Power electronics is an interdisciplinary area. One needs to have knowledge in the following areas to be a successful power electronics engineer:

- Electronics: Semiconductor devices and their protection, gate drive circuits, power supply design.
- Control: Closed loop control system design
- Electrical Machines: Motor drives

- Power Systems: Reactive power compensation, active and passive filters, flexible ac transmission line systems, smart grids and renewable energy sources.
- Magnetics: High frequency transformer and inductor design, EMI and EMC issues.
- Software: Microprocessors, Digital Signal Processors,

Four Principles of Power Electronics Circuit Analysis

Two energy storage components, capacitors and inductors play an important role in power electronic converters. These components and their defining equations are shown in Figure 1.1.

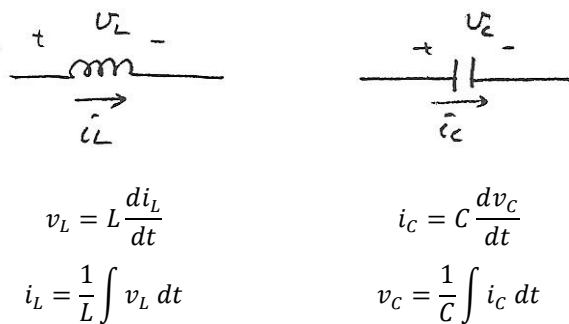


Figure 1.1 Energy storage components and their defining equations

Four conclusions can be drawn from these equations:

1. Inductor current cannot change instantaneously: $i_L(t = 0_-) = i_L(t = 0_+)$
2. Capacitor voltage cannot change instantaneously: $v_C(t = 0_-) = v_C(t = 0_+)$
3. Average value of inductor voltage at the steady state over one full period is zero: $\langle v_L \rangle = 0$
4. Average value of capacitor current at the steady state over one full period is zero: $\langle i_C \rangle = 0$

These four principles can be used as a starting point in analyzing power converters.

Power Devices Commonly Used in Power Converters

Power semiconductor devices can be classified in terms of their controllability into three groups:

1. Uncontrolled devices (Diodes): They cannot be turned-on or off. They turn-on or turn-off when certain conditions arise in the circuit.
2. Semi-controlled devices: They can be turned on, but their turn off is not controlled. Turn-off is achieved either naturally when the current decays to zero, or by forcing the current to deviate to another component. Thyristors are semi-controlled devices.
3. Controllable Devices: These devices can be turned-on and off by a gate control signal. Transistors are controlled devices.

Diodes

Current-voltage characteristics of diodes are shown in Figure 1.2. An ideal diode has no voltage drop across the junction when it is forward biased. When reverse biased, there is no current flow. Ideal diode can conduct any amount of current in the forward direction and it can block any amount of voltage in the reverse direction.

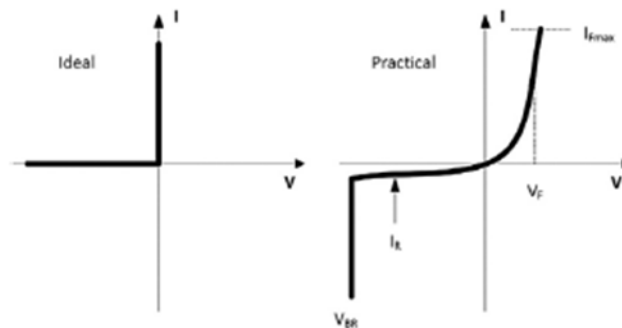


Figure 1.2 Ideal and real diode characteristics

A real diode can conduct only after forward bias voltage is at least equal to a threshold voltage. This threshold voltage is about 0.7 V in silicon devices. Forward voltage drop of a diode is equal to the sum of the threshold voltage and voltage drop term which is proportional with the forward current. This can be viewed as a resistive voltage drop. Forward voltage drops of silicon diodes can be between 1 V and 2 V. There are some special diodes with smaller voltage drops.

When the voltage between the anode and cathode is negative, diodes are called to be reverse biased and they do not conduct current. Only a negligibly small amount of current called leakage current exists in this case. However, if the reverse voltage exceeds a specific level called breakdown voltage, a large amount of short circuit current flows through the diode in the reverse direction causing its destruction.

Diodes can turn-on very quickly but their turn-off is slower. In the turn-off period the current first decays to zero, then reverses. The peak reverse current can be as high as the forward current. After reaching this reverse peak value the current turns back towards zero. This process is called reverse recovery. The time length of this is called reverse recovery time (t_{rr}). Reverse recovery transient is shown in Figure 1.3. The reason for reverse recovery is that diode current is due to both minority and majority carriers, and it takes time for the minority carriers to recombine with reverse polarity carriers and neutralize.

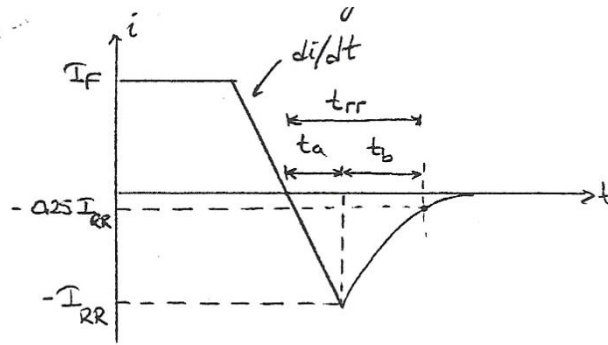


Figure 1.3 Reverse recovery of diodes

Following parameters are used to define the reverse recovery process:

t_a : Time difference between the zero cross point of the current and the time when the current reaches its peak value.

t_b : Time needed for the reverse current to drop from the peak value to 25% of the peak value.

t_{rr} : reverse recovery time $t_{rr} = t_a + t_b$

s : softness factor $s = \frac{t_b}{t_a}$

A low softness factor represents very sharp (abrupt) reverse recovery. A high softness factor on the other hand means that the recovery is very smooth.

If the slope of the current during turn-off is di/dt

$$I_{RR} = t_a \frac{di}{dt}$$

The stored charge at the p-n junction during the reverse recovery (Q_{RR}) can be found by calculating the area under the current waveform. The waveform can be approximated to a triangle to simplify the calculations as seen in Figure 1.4.

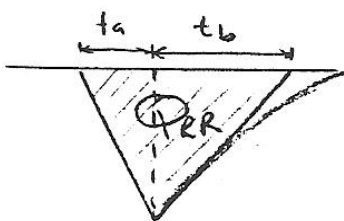


Figure 1.4. Reverse recovery charge calculation

$$Q_{RR} \cong \frac{1}{2}I_{RR}t_a + \frac{1}{2}I_{RR}t_b = \frac{1}{2}I_{RR}(t_a + t_b)$$

$$Q_{RR} \cong \frac{1}{2}I_{RR}t_{RR}$$

$$I_{RR} = \frac{2Q_{RR}}{t_{RR}}$$

$$t_{RR} = t_a + t_b = t_a + st_a = t_a(1 + s) \rightarrow I_{RR} = \frac{t_{RR}}{1 + s} \frac{di}{dt}$$

$$Q_{RR} \cong \frac{1}{2}t_{RR} \frac{t_{RR}}{1 + s} \frac{di}{dt} = \frac{1}{2(1 + s)} t_{RR}^2 \frac{di}{dt}$$

$$t_{RR} = \sqrt{\frac{2Q_{RR}(1 + s)}{di/dt}}$$

or

$$I_{RR} = \sqrt{\frac{2Q_{RR}(di/dt)}{1 + s}}$$

As seen from these equations, t_{RR} and I_{RR} depend on the stored charge and reverse di/dt . Q_{RR} depends on forward diode current I_F . Typical values of I_{RR} , Q_{RR} and s can be found at the data sheets of diodes.

Diodes also need some time for the recovery of majority carriers before conducting. This is called forward recovery.

Power Diode Types

Power diodes can be divided into three groups based on their reverse recovery characteristics:

- 1) General purposed diodes:
- 2) Fast recovery diodes:
- 3) Schottky diodes:

General purposed diodes: These diodes are typically used in low frequency (a few Hertz to one kHz) applications. Typical value of reverse recovery time is 25 μ s. They are slow but since the operating frequency is low, reverse recovery characteristic can be ignored. Their ratings can be up to 6 kV and 4.5 kA.

Fast recovery diodes: These diodes have low reverse recovery times, typically less than 5 μ s. Since the reverse recovery time is shorter they can be used at higher frequency applications such as dc-dc and dc-ac converters, with voltage ratings up to 3 kV and current ratings up to a few hundred amps. There faster diodes with less than 100 ns reverse recovery time but they cannot be used above 400 V.

Schottky diodes: These diodes have a different p-n junction structure, and as a result, they have almost none reverse recovery. Therefore, they can be used at very high frequencies. Their voltage drop is also lower compared to other diode types. However, they are available only up to 100 V although current ratings can go up to a few amps.

Thyristors

Thyristors are three-junction (four-layer) devices. Even if a positive voltage is applied between the Anode and Cathode terminals, it cannot conduct since one of the p-n junctions is still reverse biased.

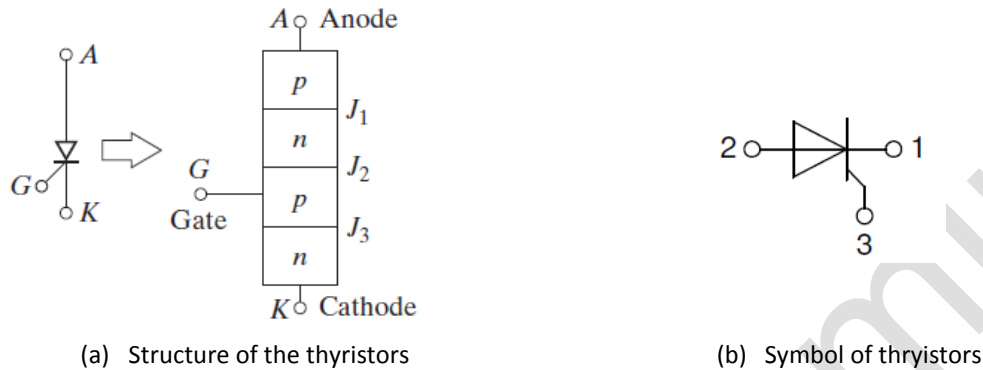


Figure 1.5. Thyristor structure and symbol

Thyristors are semi-controlled devices. They can be turned-on but their turn-off cannot be controlled. Once they are on, they behave like diodes. Thyristor characteristic is shown in Figure 1.6.

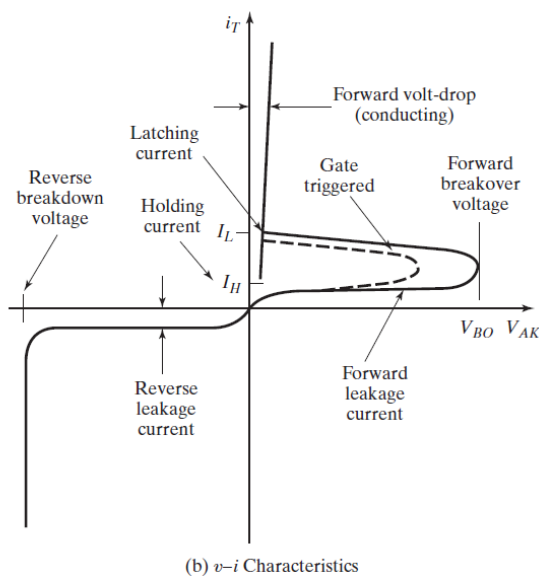


Figure 1.6 Thyristor $i-v$ characteristic

Thyristors can be turned on by applying a positive pulse between the third terminal (gate) and cathode while the anode-cathode voltage is positive. If the applied forward voltage is over a certain limit (breakover voltage) thyristor fails.

Thyristors, like diodes, can withstand negative voltages up to reverse breakdown voltage.

Thyristors turn-off when their current drop to zero. This may take place in two different ways:

- 1) **Natural turn-off:** A sinusoidal-like current waveform naturally goes through zero. As soon as it is zero, thyristor turns-off.
- 2) **Forced turn-off:** Certain conditions are met and another device is forward biased, taking over the current, so that thyristor current drops to zero.

Gate Circuits

Thyristors are turned on by applying a pulse between the gate terminal and cathode terminal. This pulse is generated by a circuitry called gate circuit. Typically it includes a synchronization circuitry to synchronize the signal with the voltage applied across the device. There is also a logic circuit that determines the instant of turn-on. Signal generated by the gate circuit is also called triggering signal or firing signal. Gate circuits may also include some protection circuitry. The pulses are short, typically a few microseconds.

Some Concerns about Thyristors

- 1) **Time rate of voltage (dv/dt):** There are three p-n junctions in the thyristor structure. Each junction has stray capacitance due to stored charges on both sides. If the voltage across a thyristor changes too fast (high dv/dt), there may be enough amount of stray currents flowing through the device due to these capacitance ($C_{stray} dv/dt$). This current may cause unexpected turn-on of the device, resulting in a possible destruction. Snubber circuits are used to prevent this situation. This is actually a concern for all semiconductor devices.
- 2) **Time rate of current (di/dt) during turn-on:** If the current rises too quickly when the device is turning on, rather than it is spreading all over the cross-section of the device, it concentrates on a smaller portion. This causes over-heated sections (hot-spots) causing the failure of the device.
- 3) **Isolation:** If thyristors are utilized in high-voltage circuits an isolation may be required between its high-voltage exposed terminals and gate circuitry. This could be done by using a transformer (pulse transformer) or an opto-coupler.

Some Thyristor Types:

Some of the commonly used thyristors are listed below:

- 1) **Phase controlled thyristors (Silicon Controlled Rectifiers):** These devices are typically used at line frequencies. They could handle up to 4 kV voltage and 5-6 kA current. On-state voltage drops are between 1.1 V to 2.5 V, depending on the current.
- 2) **TRIACs:** TRIAC is a back-to-back connected thyristor pair. It is used to adjust the rms value of the ac voltage. This feature is useful for soft starting the motors, adjusting the light intensity, etc.

- Gate Turn-off Thyristors (GTO): These devices can be turned off by applying a negative signal between the gate and cathode terminals. They are especially preferred at high power applications.

Review Questions for Part-1

- List three household devices which include power electronic application.
- List three industrial applications which use power electronics.
- What are the turn-on and turn-off conditions for diodes?
- What are the turn-on and turn-off conditions for thyristors?
- What are the turn-on and turn-off conditions for transistors?
- What is the difference between abrupt reverse recovery and soft reverse recovery?
- Which type of diodes has the highest voltage rating?
- Which type of diodes is the fastest?
- What type of diode would you choose in a 50-Hz converter?
- What type of diode would you choose in a d-dc converter operating with a switching frequency of 20 kHz with a 600 V peak voltage?
- What type of diode would you choose a d-dc converter operating with a switching frequency of 200 kHz with a 50 V peak voltage?

Answer Questions 12-19 based on the graphs given below for the DPG10I200PA diode (Product of IXYS). The data sheet describes this device as 200 V, 10 A, 35 ns diode.

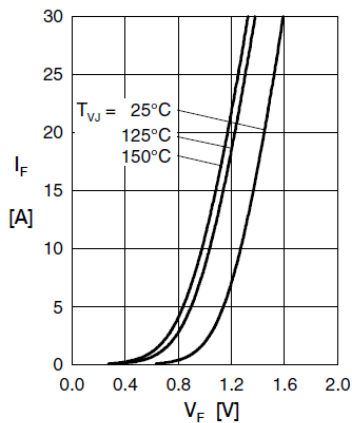


Fig. 1 Forward current I_F versus V_F

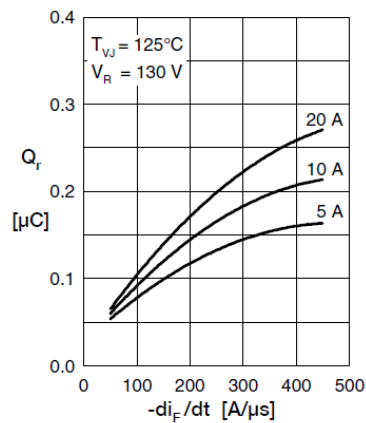


Fig. 2 Typ. reverse recov. charge Q_r versus $-di_F/dt$

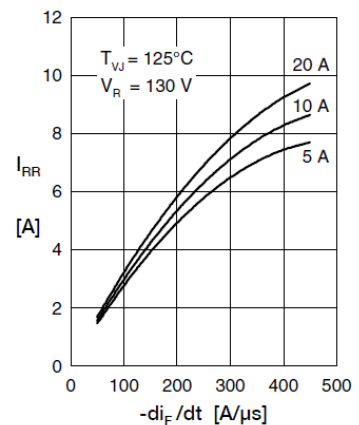


Fig. 3 Typ. reverse recovery current I_{RR} versus $-di_F/dt$

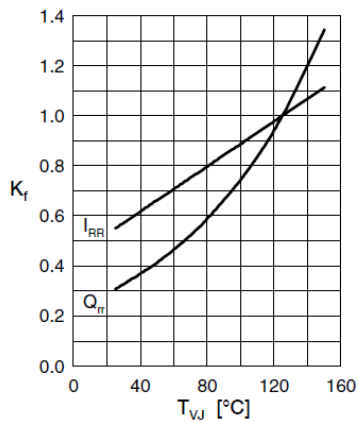


Fig. 4 Typ. dynamic parameters Q_{rr} , I_{RR} versus T_{VJ}

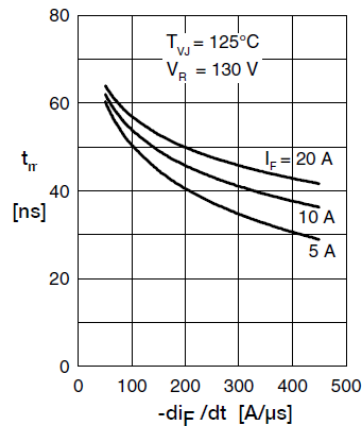


Fig. 5 Typ. reverse recov. time t_{rr} versus $-di_F/dt$

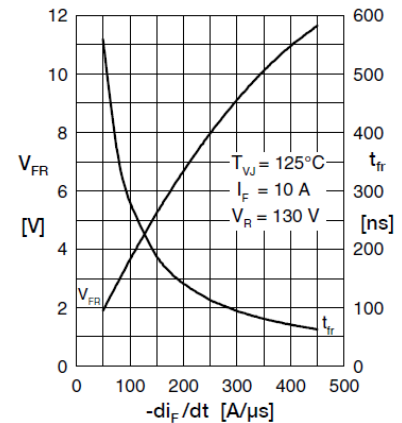


Fig. 6 Typ. forward recovery voltage V_{FR} and t_{rr} versus di_F/dt

- 12) What is the forward voltage of this diode if it is operating with 10 A current at 125 °C?
- 13) What is the forward voltage of this diode if it is operating with 10 A current at 75 °C?
- 14) The diode turns off while 10 A is flowing in the forward direction. The operating temperature is 125 °C and the reverse voltage across the diode after turn-off is 130 V. The current falls with a slope of 200 A/μs. What is the amount of reverse recovery charge?
- 15) The diode turns off while 10 A is flowing in the forward direction. The operating temperature is 125 °C and the reverse voltage across the diode after turn-off is 130 V. The current falls with a slope of 200 A/μs. What is the peak value of reverse recovery current?
- 16) Calculate the reverse recovery time of the diode by using the results obtained in Questions 14 and 15.
- 17) Calculate the reverse recovery time of the diode by using the graph in Fig. 5.
- 18) Compare the results obtained in Questions 14 and 15? Is it close to 35 ns?
- 19) What type of diode is this?
- 20) What are the conditions to turn-on a thyristor?
- 21) What is the condition to turn-off the thyristor?
- 22) Why is dv/dt protection important?
- 23) Why is di/dt protection important?

Answer Questions 24-25 based on the graph given below for the CLA16E1299PN thyristor (Product of IXYS). The data sheet describes this device as 1200 V, 10 A thyristor with 1.07 V on-state voltage drop.

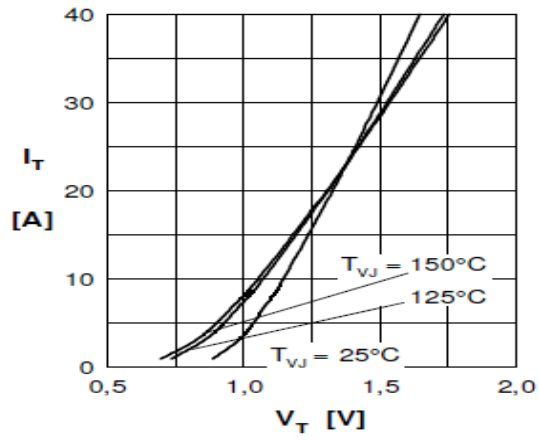


Fig. 1 Forward characteristics

24) What is the forward voltage of this thyristor if it is operating with 10 A current at 125 °C?

25) What is the forward voltage of this thyristor if it is operating with 10 A current at 75 °C?