

POWER ELECTRONIC SWITCHING DEVICES

by K. C. Daly

School of Electrical Engineering
UNSW

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Functions of Power Electronic Equipment

The functions performed by power electronic equipment can be grouped as follows:

- 1) conversion of electrical energy from one form to another i.e. AC to DC (rectification), DC to AC (inversion) etc.,
- (2) source/load connection/disconnection i.e. electronic relay function
- (3) power conditioning; reactive power control, harmonic filtering etc.,

These functions are all achieved by the use of power semiconductor devices entirely in switch-mode, i.e. the devices are either in the conductive state or the non-conductive state. So in one sense, power electronics is the application of digital electronics for power control.

The Ideal Switch

The analysis of power electronic circuits is usually carried out by assuming that the power electronic devices are behaving as ideal switches, and the assumptions underpinning an ideal switch are useful because they focus attention on the non-idealities of real semiconductor switches. The assumptions for an ideal switch are;

- (1) when closed, zero voltage drop occurs across the terminals no matter what current flows; i.e. it is a perfect short circuit
- (2) when open, no current flows and any voltage can be supported across the terminals; i.e. it is a perfect open circuit
- (3) able to make the transition from closed to open and from open to closed in zero time

As a result of these assumptions, the ideal switch is lossless. Like the ideal transformer, the ideal switch doesn't exist, but it gives a yardstick against which real switches can be measured.

Differences between Power Electronic Switches and Mechanical Switches

The main difference between power electronic switches and mechanical switches is that power electronic switches have almost no capability to dissipate power compared to mechanical switches, both in steady state operation and in a one-off (surge) situation.

They have a low continuous power dissipation and a low one-off, or surge, capability.

When a semiconductor device turns off, it is always necessary to ensure that the current diverted from it has somewhere to go, probably through another semiconductor.

2.2 Categories of Semiconductor Switches

A fundamental division is between those switches which have a control terminal to allow them to operate independently of the external circuit and those which just respond to the circuit.

Uncontrolled : diodes - these conduct whenever current is flowing in the forward direction and block current at other times.

Controlled:

- (a) can only be turned on from the control terminal - this group contains the thyristor and its variants. These devices can be triggered into conduction when the switch terminal voltage is positive and can only conduct current in one direction.
- (b) can be turned on and off from a control terminal - this is by far the largest group and contains -

transistors, which can conduct current in one direction and block voltage in one direction. They are turned on by the application of a continuous current to the control terminal (base).

MOSFET's, which effectively have a diode in inverse parallel and so they can control current flow in only one direction. They are gated on by the application of a voltage to the control terminal (gate) but draw no steady state gate current because the gate is insulated from the other 2 terminals.

Insulated Gate Bipolar Transistors (IGBT's) which attempt to combine the low on-state voltage and high voltage blocking capability of a transistor with the simplified gating characteristics of a MOSFET. They conduct in one direction and only block in one direction as well.

Gate Turnoff Thyristors (GTO's), which as their name implies are thyristors which can be turned off from the gate - however not without some difficulty. Some types can block voltage in both directions and some can't. They only conduct in one direction.

MOS Controlled Thyristors (MCT's) which have a thyristor structure and a MOS-style gate which allows them to be turned on and off from the gate. They can block voltage in both directions and conduct only in one direction.

3.0 Important Semiconductor Switch Ratings

Power semiconductor switches are physically very small and are not designed to be able to dissipate large amounts of power either in transient or continuous operation. Rather they are meant to be able to dissipate the power which arises from their own non-ideal switch behaviour and not from any associated circuitry.

The current technology for semiconductor switch fabrication is doped silicon and so the fundamental limitation in the operation of the device under all circumstances is the temperature at which the doping materials start to react chemically with the silicon. Once this begins, it is irreversible and the junctions cease to perform as designed.

3.1 Surge and Transient Ratings

Semiconductor switches aren't designed to be withstand much in the way of non-repetitive surge currents. Nevertheless, for devices such as thyristors and diodes, which

are the most rugged of the available devices, manufacturers usually give an I^2t rating for a single half sine wave of 20 ms or 16.7 ms duration.

3.2 Current and Voltage Ratings

The maximum current a device can handle and the maximum voltage it can block without breaking down are the most important parameters for a device as far as applications are concerned. Exceeding the maximum voltage rating isn't in itself fatal for the device, provided the resulting current flow and power dissipation is limited. Overcurrent causes the wire bonding the semiconductor crystal to the terminal outside the package to melt.

3.3 Power and Temperature Ratings

The maximum junction temperature a device can withstand is the fundamental rating. From it can be calculated the maximum power dissipation within the device provided the thermal conductivities from within the device to the heatsink and the cooling medium (usually air but sometimes water) are known.

3.4 Series and Parallel Connections of Switching devices

For some applications, the voltages or currents involved are such that no single semiconductor switch can satisfy the requirements and so parallel or series connections are needed.

To achieve a higher voltage rating, switching devices can be connected in parallel. Care needs to be exercised at switching transitions to ensure that differences in the switching behaviour of individual devices in the series connected string don't lead to one device being subjected to excessive voltage before the other devices switch.

Parallel connection can be used to achieve a higher current rating for the switch, but in this case care is needed to ensure that the parallel connected devices share current. Transistors are notoriously unreliable in this regard because as a transistor gets hotter its current gain increases which means for the same base current it can carry more current and so get hotter still - the "current hogging" phenomenon. MOSFET's on the other hand, increase their on-state resistance as their temperature rises, which tends to decrease the current in the device.

4.0 Losses in Power Semiconductor Switches

For semiconductor devices which are used in switch-mode, it is convenient to characterize their power dissipation in terms of the 4 states which they cycle through, viz the on and off states and the transitions between on and off states. Typical waveforms for the current and voltage in a thyristor through a full cycle of operation are shown in figure 4.1

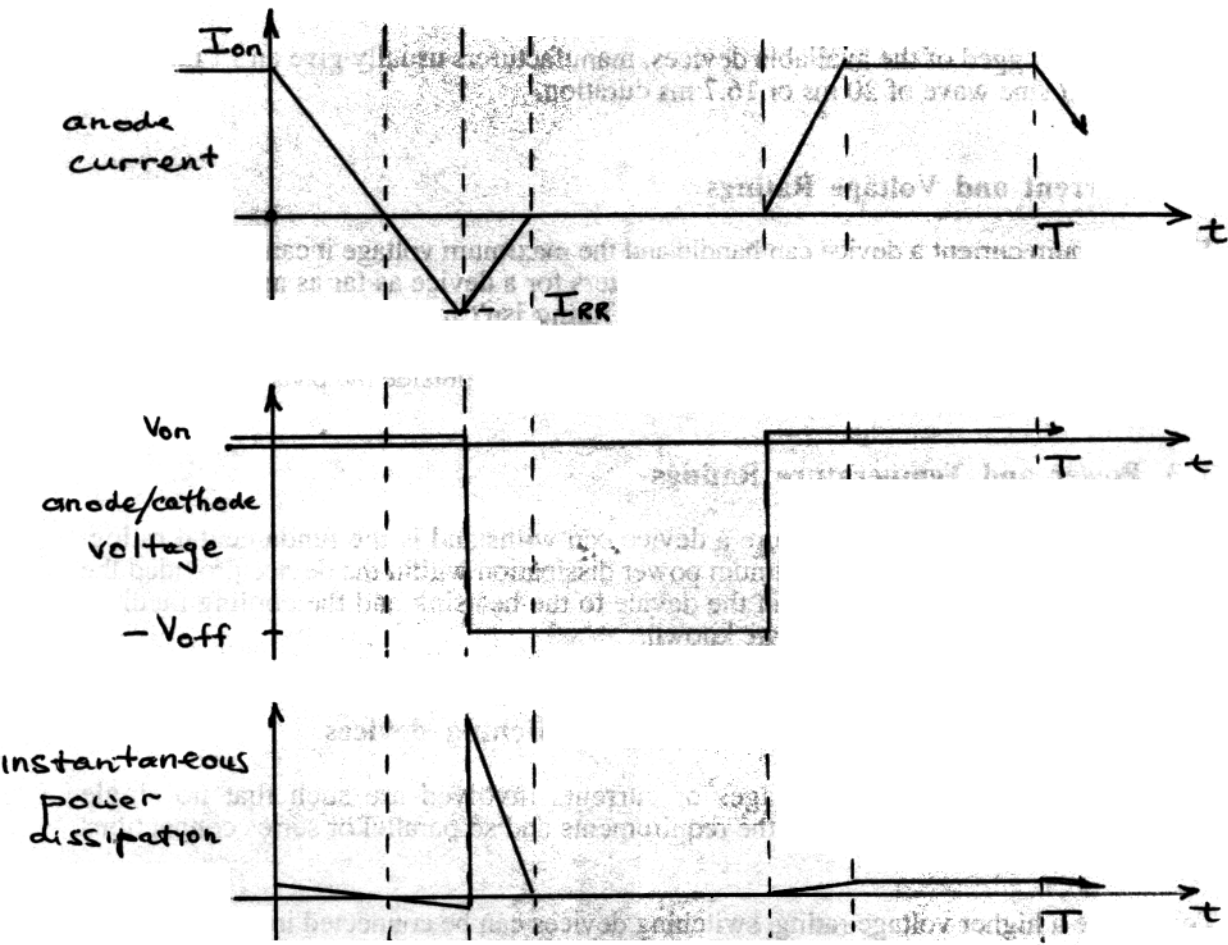


Figure 4.1 : Thyristor Switching Waveforms

For some devices it is also convenient to represent these switching characteristics in an I-V plane with time a parameter along the trajectory. In figure 4.2 below, this is illustrated for a transistor

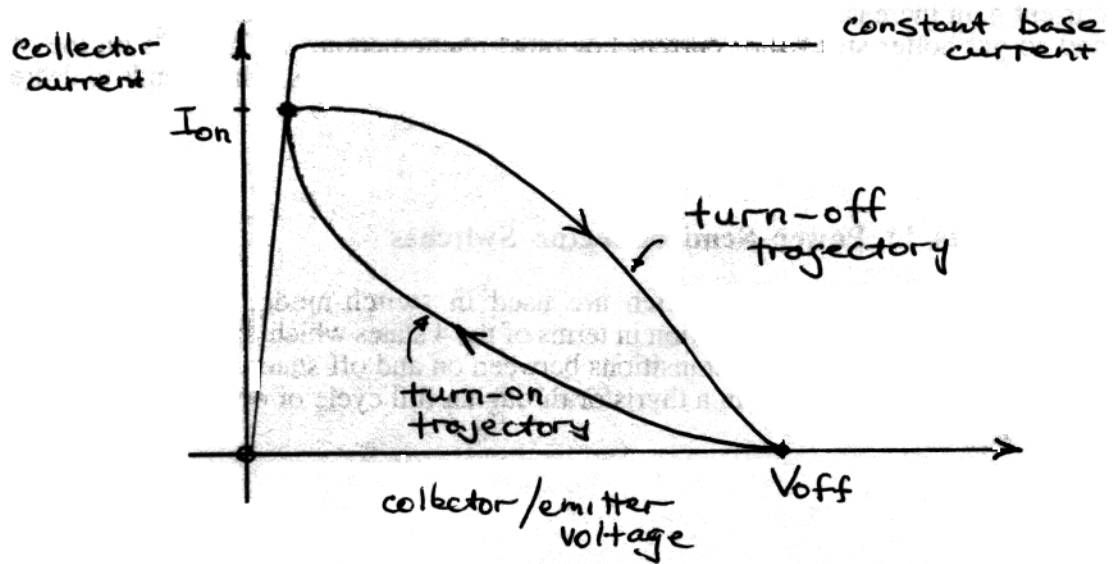


Figure 4.2 : Transistor Switching Trajectory in I-V Plane

The loss associated with the transition between on and off is called the turn-off loss while that between the off and on states is called the turn-on loss. The total loss due to the transitions (off to on and on to off) is often referred to as the switching loss.

Each of the 4 loss components is calculated by averaging the instantaneous power loss for the corresponding time interval over a complete switching period. For example, if the current and voltage for a particular device are $i(t)$ and $v(t)$ during the on-time when $0 \leq t \leq t_1$ and the total switching period is T , then the on-state loss is given by

$$P_{on} = \frac{1}{T} \int_0^{t_1} i(t) v(t) dt$$

4.1 On-state Losses

In an ideal switch the on-state loss would be zero. However in a semiconductor switch there is always a small voltage drop associated with the on-state due to the resistance of the semiconductor material and the voltages associated with the semiconductor junctions. The magnitude of the on-state voltage, V_{on} , usually increases with current, I_{on} , and is often modelled by

$$V_{on} = V_o + gI_{on}$$

where V_o and g are constants which differ for classes of devices (thyristors, transistors etc.) and for power levels within device classes. The product of the on-state voltage with the on-state current then provides the on-state losses. Since the on-state voltage is only weakly dependant on the on-state current, the on-state power loss is roughly proportional to the switching device duty cycle which is then dependant on the application.

4.2 Off-state Losses

When a semiconductor switch turns off, there is still some residual current flow, referred to as leakage current, usually due to thermal generation of carriers where they aren't wanted. The off-state voltage multiplied by the leakage current then provides the off-state power losses. In modern semiconductors, the off-state loss is so small that it is usually neglected, however care needs to be exercised as it is strongly temperature dependant.

4.3 Turn-on Losses

During turn-on, both the current and the voltage of the switching device change simultaneously and so their product can be much larger than the instantaneous power during on and off states. However, if the duration of the transition is very brief, then the average dissipation is small. At turn-on, the device current rises from the negligibly small leakage current to the on-state current while the device voltage falls from the off-state voltage to the small on-state voltage. The transition period, called the turn-on time is a function of the class of switching device, the circuitry driving the device and the associated power circuitry. The turn-on time is reasonably independent of the application and hence the turn-on losses are proportional to switching frequency

4.4 Turn-off Losses

During turn-off, both the current and the voltage of the switching device change simultaneously and so their product can be much larger than the instantaneous power during on and off states. However, if the duration of the transition is very brief, then the average dissipation is small. At turn-off, the device current falls from the on-state current to the negligibly small leakage current while the device voltage rises from the on-state voltage to the high off-state voltage. The transition period, called the turn-off time, is a function of the class of switching device, the circuitry driving the device and the associated power circuitry. The turn-off time is reasonably independent of the application and hence the turn-off losses are proportional to switching frequency.

5.0 Chopper Circuit / Force Commutated Device and Uncontrolled Device

The purpose of this chopper circuit is to control the flow of power from a DC voltage source to a load which consists of an RL circuit. This is achieved by using a forced commutated device (MOSFET, transistor, IGBT etc.,) which is turned on to allow current to flow from the voltage source into the load for a variable fraction of the switching cycle. The greater the fraction of a switching cycle that the load is connected to the voltage source, the greater the current in the load and consequently the greater the power dissipated in the load.

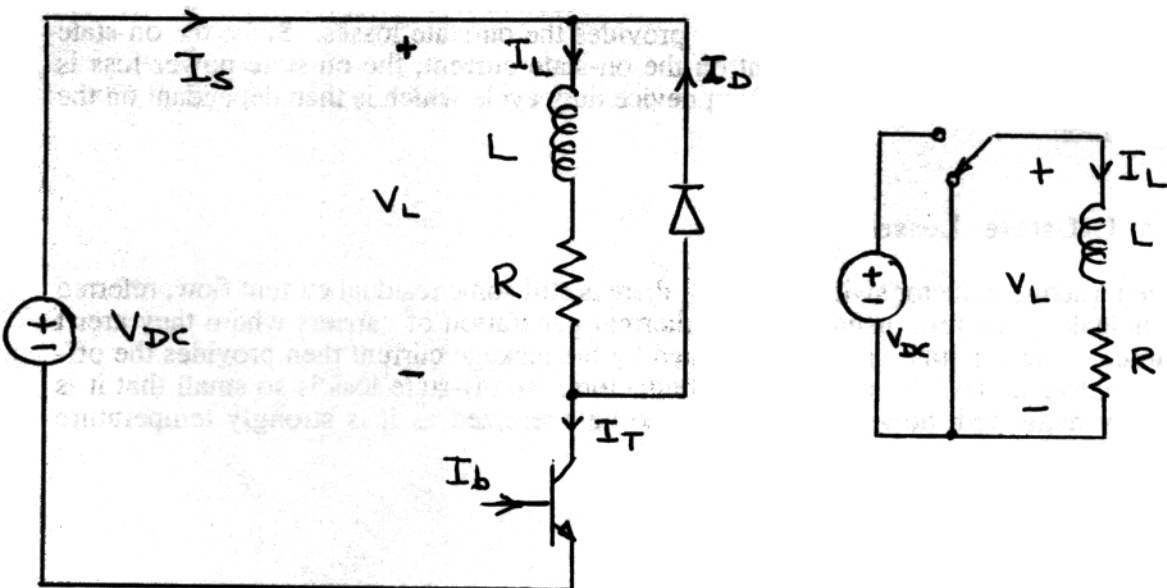


Figure 5.0.1 : DC Chopper Circuit

5.1 Circuit Operation

During the on time of the semiconductor switch, current builds up in the RL load and so when the device is turned off provision must be made to accommodate the current in the

inductance. Otherwise, if the current in the inductance falls to zero in a stepwise fashion, then the voltage across the inductance will be an impulse ($v = L di/dt$) and so the voltage across the terminals of the semiconductor switch will be very high, most likely in excess of the rating of the device.

The diode connected across the RL load prevents this happening by providing a current path for the load current when the main switching device turns off.

Treating the semiconductor switches as ideal switches and also assuming that the time constant of the RL circuit is very much greater than the switching period, the waveforms in the circuit would appear as shown in figure 5.1.1.

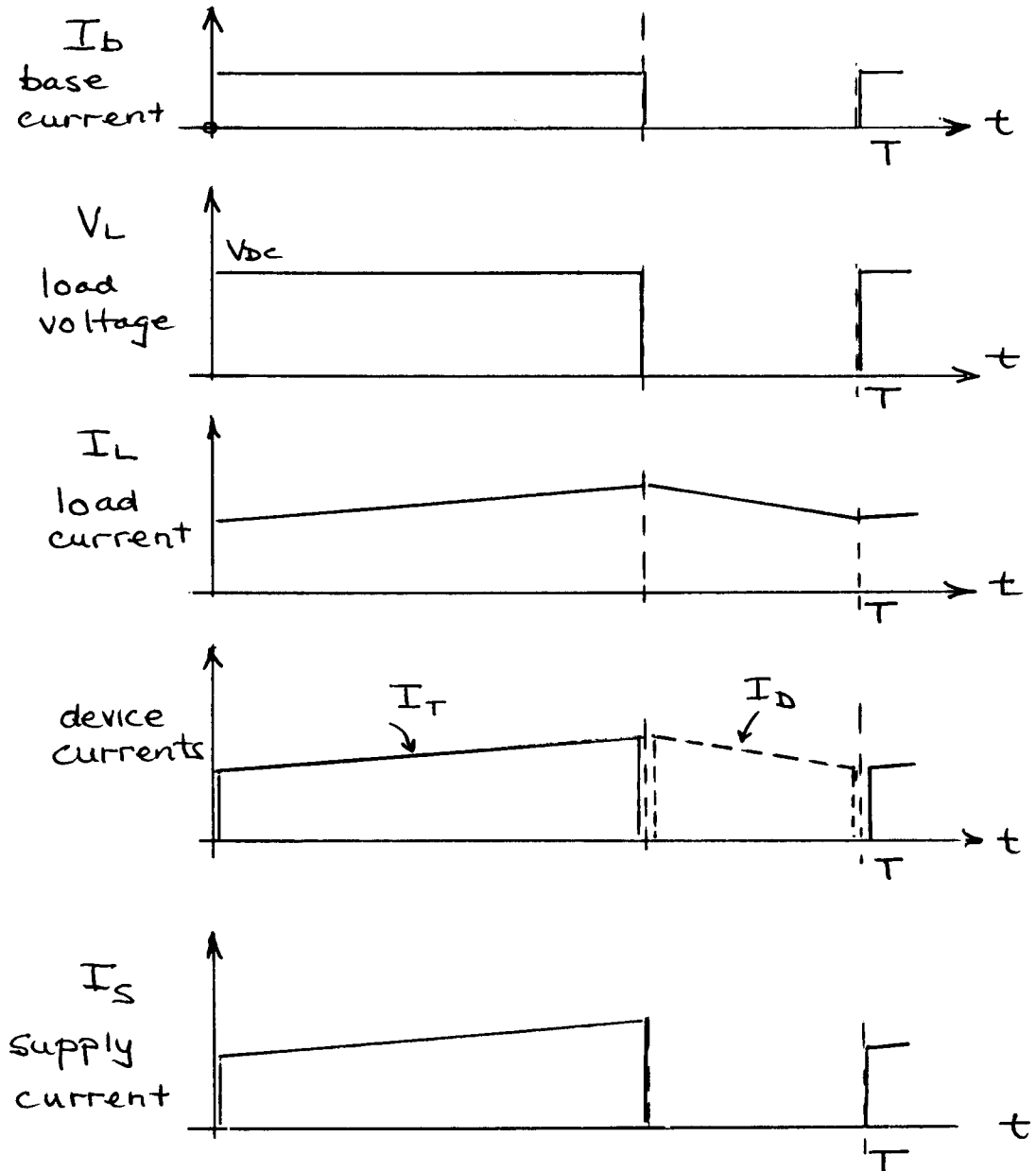


Figure 5.1.1 : Idealized Chopper Waveforms

Particular attention should be paid to the current, I_s , drawn from the source. Although the voltage source is DC, the current drawn is pulsating. This situation is typical of power electronic circuits ie. source voltage and current are seldom of the same type.

5.2 Diode Reverse Recovery Current

The waveforms of fig 5.1.1. allow the semiconductor on-state losses to be calculated provided their on-state voltages are known. However, to find the switching losses the fine detail of the on-off and off-on transitions of the devices is required. Figure 5.2.1 shows the transistor turn-on/diode turn-off transition.

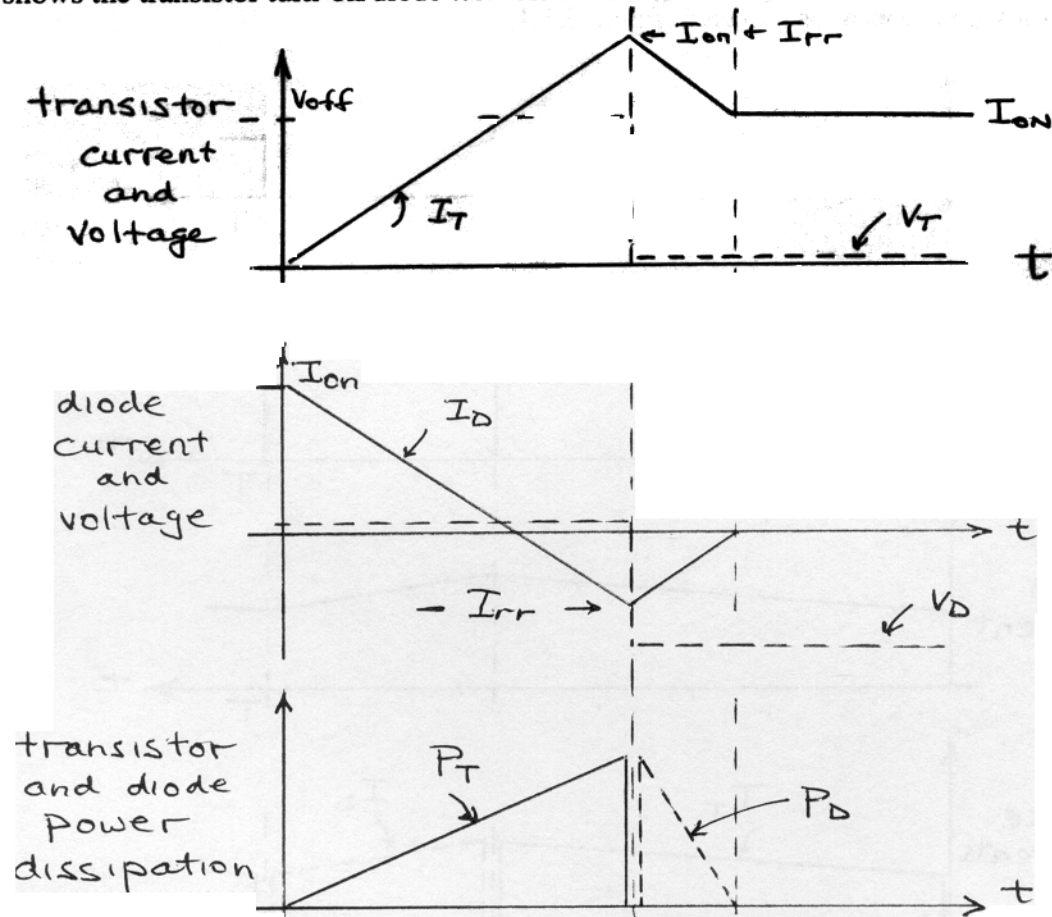


Figure 5.2.1 : Transistor Turn-on

When the transistor is turned on, the collector current ramps up according to the base drive applied. The diode current ramps down at the same rate because the sum of the diode and transistor currents equals the inductor current which is constant over an interval as short as a switching transition. As the diode current reaches zero it goes negative for a short time because of reverse recovery current which is needed to establish the blocking capability of the junction. Once this is achieved the diode current rises to zero.

At turn-off of the transistor, the diode can't begin to conduct until the transistor voltage has slightly exceeded the supply voltage. Under control of the transistor base current the transistor voltage ramps up while the current remains constant because of the load inductance. As the diode begins to conduct, the diode current ramps up while the transistor current ramps down. This is illustrated in figure 5.2.2.

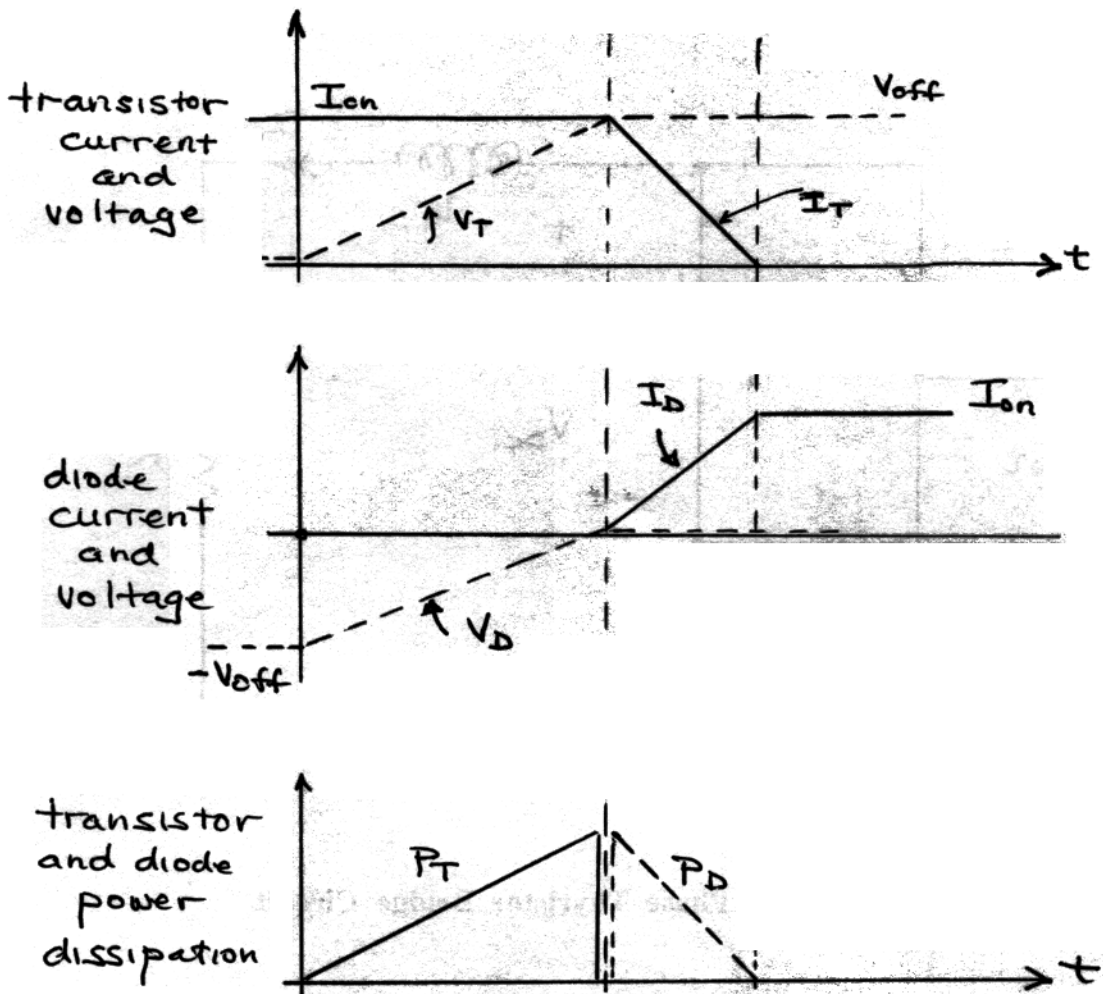


Figure 5.2.2 : Transistor Turn-off

6.0 Single Phase Thyristor Bridge/Naturally Commutated Devices

The purpose of this circuit is to convert fixed frequency AC to DC and vice versa i.e. from DC to fixed frequency AC. Practical applications of this circuit would normally be multi-phase rather than the single phase circuit shown here, but the principles are more easily illustrated in the single phase case and the extension to more phases is straightforward.

Multi-phase versions of this circuit are used in AC/DC (rectifier) applications. HVDC systems are comprised of one such unit at each end of the transmission line, one operating as a rectifier and the other as an inverter. Reversing the operating mode of each unit leads to a reversal of the direction of power flow in the transmission line.

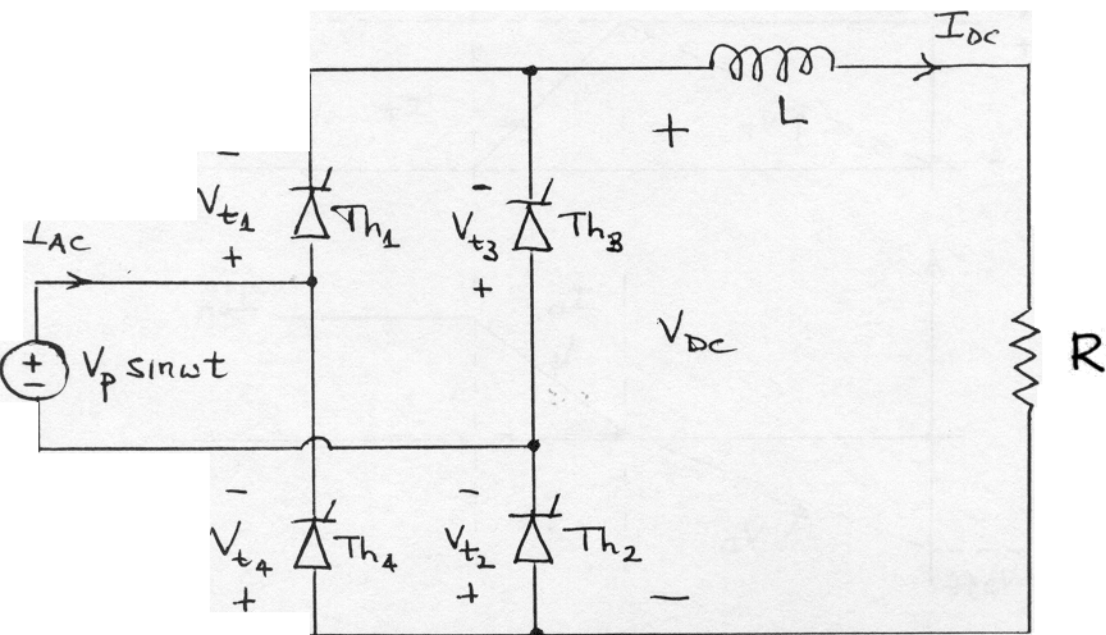


Figure 6.0.1 : Single Phase Thyristor Bridge Circuit

Circuits with low frequency (50 Hz) AC sources are ideally suited to thyristor applications because

- the inability to turn off the thyristor from the gate isn't a disadvantage - the voltages in the circuit reverse because of their AC nature and so turnoff of one thyristor can be achieved by turn-on of another in the circuit
- the low frequencies involved mean that the thyristor with its low switching speed and reverse recovery problems is able to get by.

6.1 Circuit Operation/Rectifier Mode

Operation of the circuit in rectifier mode can be explained with the assistance of the waveforms in figure 6.1.1. It is assumed that the time constant of the load viz., L/R is very much longer than the period of the AC voltage, $V_p \sin \omega t$. This means that the current flowing in the DC side of the bridge, I_{dc} , is constant.

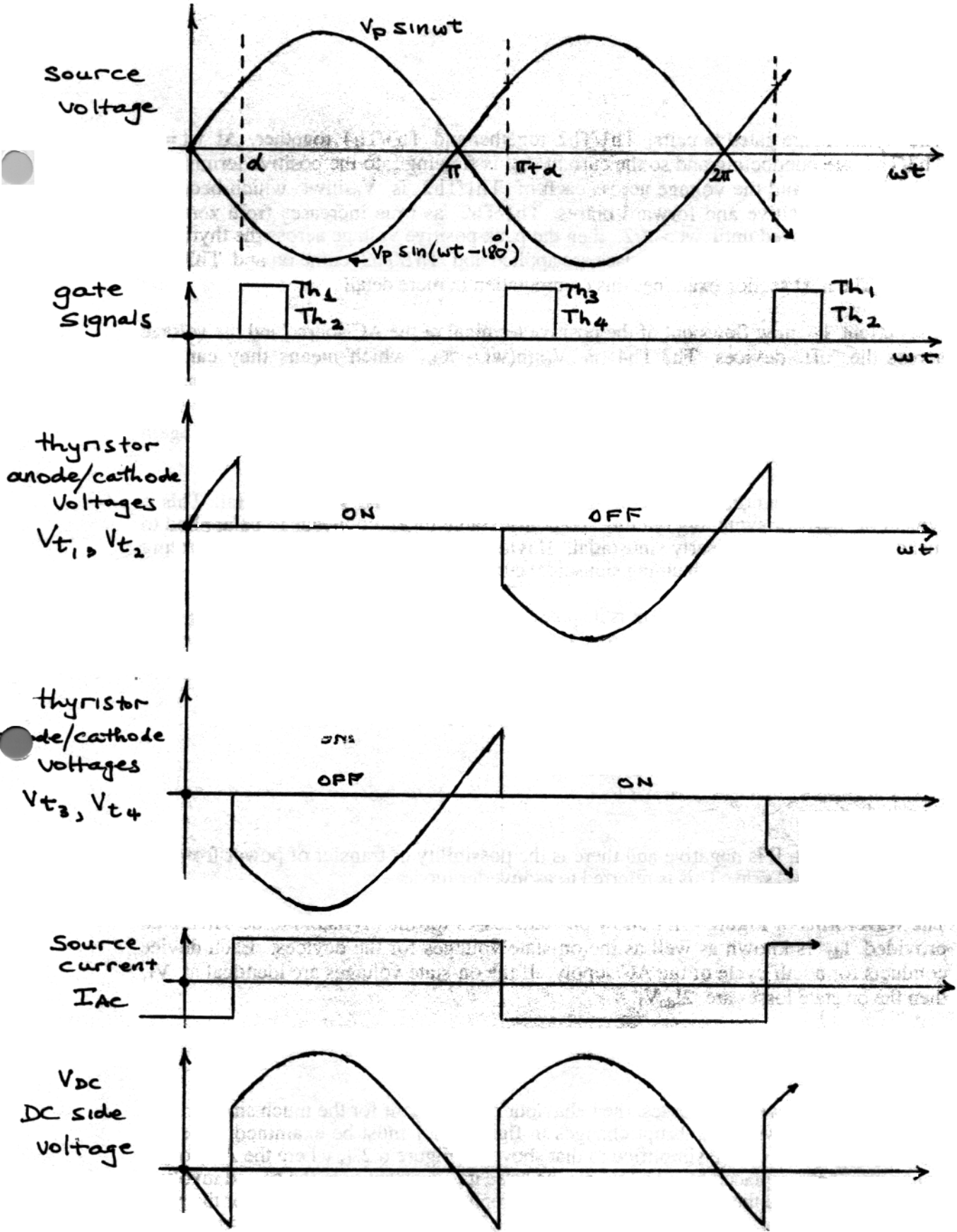


Figure 6.1.1 : Thyristor Bridge Circuit Waveforms

The thyristors are gated in pairs, Th1/Th2 together and Th3/Th4 together. At $\omega t = 0$, Th3/Th4 are conducting and so the current I_{dc} is flowing into the positive terminal of the AC source and the voltage across each of Th1/Th2 is $V_p \sin \omega t$ which becomes increasingly positive and forward biases Th1/Th2 as time increases from zero. If triggering is delayed until $\omega t > \pi/2$, then the peak positive voltage across the thyristors will be V_p . At $\omega t = \alpha$ trigger pulses are applied and Th1/Th2 come on and Th3/Th4 go off. The next section examines this commutation in more detail.

The current I_{dc} now flows out of the positive terminal of the AC source and the voltage across the "off" devices Th3/Th4 is $V_p \sin(\omega t - \pi)$, which means they can't be triggered into conduction from the gate. Observe that the peak negative voltage across the device is V_p and so the thyristors must be selected to be able to sustain this voltage. However, for $\omega t > \pi$, $V_p \sin(\omega t - \pi)$ becomes positive again and so Th3/Th4 are again able to be triggered. This occurs at $\pi + \alpha$ and so the cycle proceeds.

Note that the current drawn from the AC source is a square wave not sinusoidal. This is typical of thyristor switching circuits and considerable ingenuity needs to be applied to make the current more nearly sinusoidal. Having more phases available, or generating them in some way makes obtaining sinusoidal current easier.

The other aspect of the AC current is its phase shift with respect to the source voltage. If a Fourier analysis is applied to I_{ac} , then the fundamental lags the applied voltage by $\omega t = \alpha$. Since the source voltage is sinusoidal, real power transfer occurs only at the fundamental frequency and is given by

$$P = \left(\frac{V_p}{\sqrt{2}} \right) \left(\frac{4 I_{dc}}{\pi \sqrt{2}} \right) \cos \alpha$$

If $\alpha > \pi/2$, then P is negative and there is the possibility of transfer of power from the DC side to the AC side. This is referred to as inverter mode.

The waveforms of Figure 6.1.1 allow on-state losses for the thyristors to be calculated provided I_{dc} is known as well as the on-state voltages for the devices. Each device conducts for a half cycle of the AC supply. If the on-state voltages are identical at V_T , then the on state losses are $2I_{dc}V_T$.

6.2 Device Commutation

To calculate the switching losses, the behaviour of the circuit for the much smaller time frame associated with the abrupt changes in figure 6.1.1 must be examined. For this purpose the circuit can be simplified to that shown in Figure 6.2.1, where the AC source voltage has been replaced by a DC source, because it is constant over the period involved in commutation and the DC side of the circuit is replaced by a current source for the same reason. In addition, a small inductance is placed in series with the AC source. This could be due to the leakage inductance of a transformer or to di/dt limiting inductors placed in series with each thyristor.

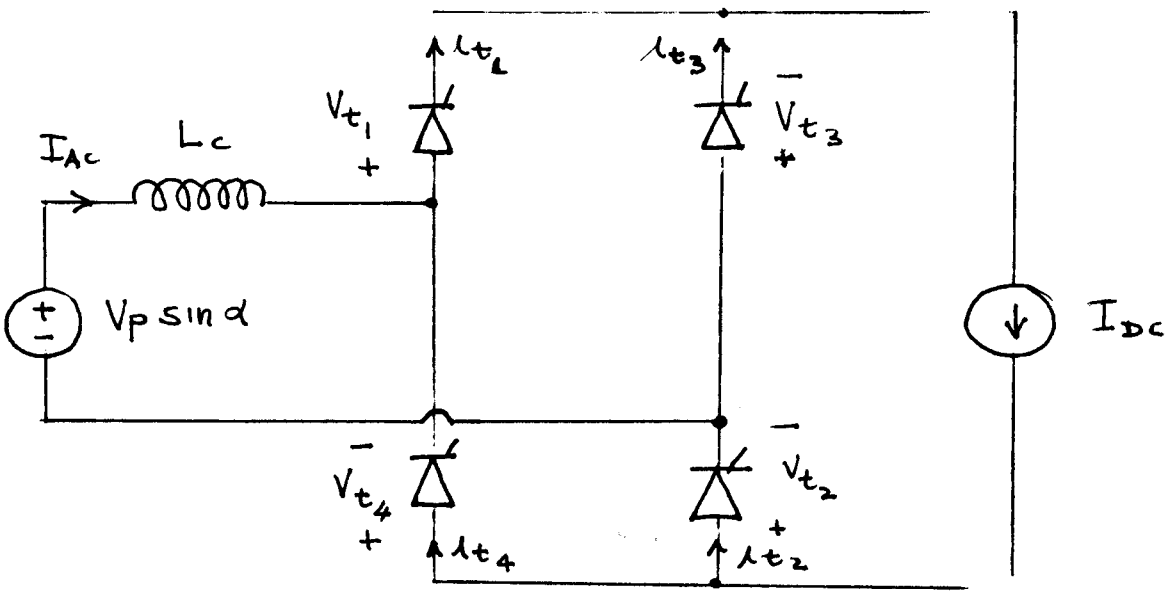


Figure 6.2.1 : Circuit during Commutation Time

Initially the current in the commutation inductance, L_c , is $I_{ac} = -I_{dc}$, but after the Thyristors Th_1/Th_2 come on the voltage across L_c becomes $V_p \sin \alpha > 0$ and so I_{ac} begins to increase. The current on the DC side is constant, so the current falls in Th_3/Th_4 at a rate determined by $V_p \sin \alpha / L_c$ and rises in Th_1/Th_2 at the same rate. The current in a thyristor can't become negative on a permanent basis, however it can briefly become negative because of the charge requirements for the junctions to be able to block voltage. Thereafter, the current drops rapidly to zero and the reverse voltage becomes equal to $V_p \sin \alpha$. This is illustrated in figure 6.2.2.

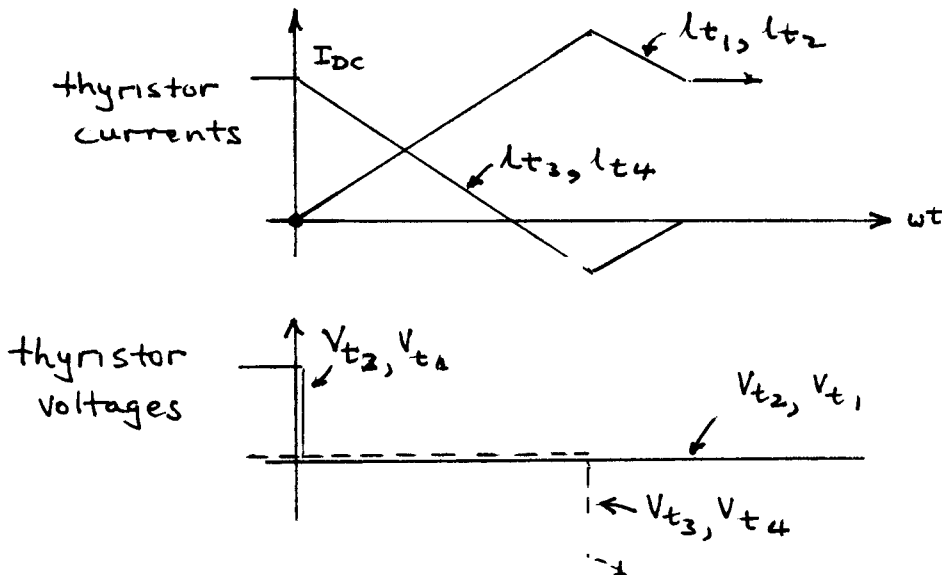


Figure 6.2.2 : Commutation Waveforms

In order to calculate the switching loss, the manner in which the current in the off-going thyristor returns to zero needs to be known. Since the on-coming devices have their voltage fall to zero before the current rises appreciably, turn on loss is zero. However, turn-off loss depends on the latter part of the reverse recovery interval.