3.General Switching Characteristics

3.1 The Ideal Switch

It is always desired to have the power switches perform as close as possible to the ideal case. Device characteristically speaking, for a semiconductor device to operate as an ideal switch, it must possess the following features:

1. No limit on the amount of current (known as forward or reverse current) the device can carry when in the conduction state (*on*-state).
2. No limit on the amount of the device-voltage ((known as forward or reverse blocking voltage) when the device is in the non-conduction state (*off*-state).
3. Zero *on*-state voltage drop when in the conduction state.
4. Infinite *off*-state resistance, i.e. zero leakage current when in the non-conduction state.
5. No limit on the operating speed of the device when changes states, i.e. zero rise and fall times.
6. It dissipates zero power.
7. It uses little power to control its operation.
8. It is highly reliable.
9. It is small in size and weight.
10. It is low in cost and needs no maintenance.

Both during the switching and conduction periods, the power loss is zero, resulting in a 100% efficiency, and with no switching delays, an infinite operating frequency can be achieved. In short, an ideal switch has infinite speed, unlimited power handling capabilities, and 100% efficiency. It must be noted that it is not surprising to find semiconductor-switching devices that can almost, for all practical purposes, perform as ideal switches for number of applications.

3.2. The Practical Switch

The practical switch has the following switching and conduction characteristics:

1. Limited power handling capabilities, i.e. limited conduction current when the switch is in the *on*-state, and limited blocking voltage when the switch is in the *off*-state.

2. Limited switching speed that is caused by the finite turn-*on* and turn-*off* times. This limits the maximum operating frequency of the device.
3. Finite *on*-state and *off*-state resistance's i.e. there exists forward voltage drop when in the *on*-state, and reverse current flow (leakage) when in the off-state.
4. Because of characteristics 2 and 3 above, the practical switch experiences power losses in the on and the off states (known as conduction loss), and during switching transitions (known as switching loss).

4. Losses in real power switch

Unlike an ideal switch, an actual switch, such as a bipolar junction transistor, has two major sources of power loss : conduction loss and switching loss.

4.1. Conduction loss

When the transistor in figure (6-a) is off, it carries a leakage (I_{LEAK}). The power loss associated with leakage current is $P_{OFF} = Vs*I_{LEAK}$. Since the leakage current is quite small and does not significantly with voltage , it is usually neglected and thus the transistor power loss is essentially zero.
When the transistor is ON, figure (6-b), it has a small voltage drop across it. This voltage is called saturation voltage ($V_{CE(SAT)}$). The transistor's power dissipation or conduction loss due to the saturation voltage is

$$PON = V_{CE(SAT)} * Ic \qquad \text{……} \quad (1)$$

Where

$$Ic = (Vs - V_{CE(SAT)})/ R_L \approx Vs / R_L \qquad \text{……….}$$
(2)

Equation (1) gives the power loss due to the conduction if the switch remains ON indefinitely. However, to control the power for a given application, the switch is turned ON and OFF in a periodic manner. Therefore, to find the average power loss we must consider the duty cycle (d) :

$$P_{ON}(avg) = V_{CE(SAT)}* Ic * T_{ON}/ T = V_{CE(SAT)} * Ic * d$$

Similarly,

$$P_{OFF}(avg) = V_S* I_{LEAK} * T_{OFF}/ T$$

Where : d is the duty cycle = T_{ON}/T

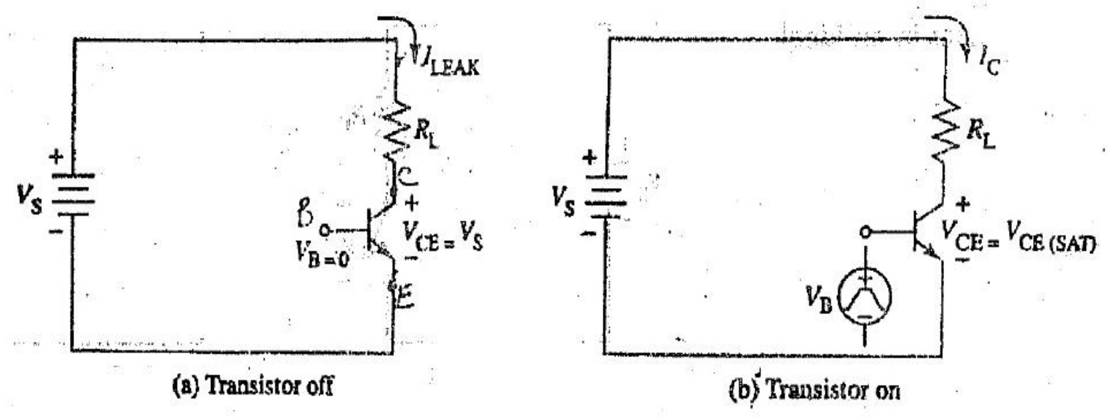

Figure (6) Power losses in a transistor.

4.2. Switching loss

In addition to the conduction loss, a real switch has switching losses because it cannot change from the ON state to OFF state (or vice versa) instantaneously. A real switch takes a finite time $t_{sw(ON)}$ to turn ON and a finite time $t_{sw(OFF)}$ to turn OFF. These times not only introduce power dissipation but also limit the highest frequency possible. $t_{sw(ON)}$ and $t_{sw(OFF)}$ are not equal with $t_{sw(ON)}$ generally being larger.

In our discussion we will assume that $t_{sw(ON)}$ is equal to $t_{sw(OFF)}$. Figure (7) shows switching waveforms for (a) the voltage across the switch and (b) the current through it. When the switch is OFF, the voltage across it is equal to source voltage. During turn-ON, which takes a finite time, the voltage across the switch decreases to zero. During the same time, the current through the switch increases from zero to Ic. The transistor has a current through it and a voltage across it during the switching time; therefore it has a power loss.

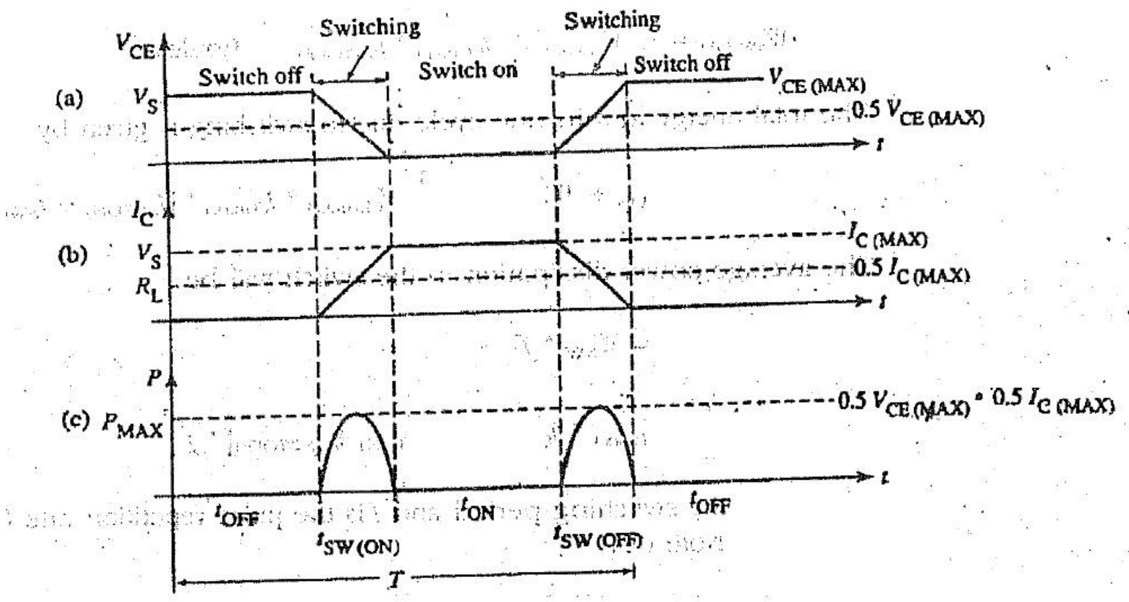

Figure (7) Waveform during switching operation: (a) voltage across the switch (b) current through the switch (c) power dissipated in the switch.

To find the power dissipated in a transistor during the switching interval, we multiply the instantaneous value of Ic and the corresponding value of V_{CE}. This power is illustrated in figure (7-c). The energy dissipated in the switch is equal to the area under the power waveform. Note that the maximum power is dissipated when both the current and voltage are passing their midpoint values. Therefore, the maximum power loss when switching from the OFF state to the ON state is :

$$P_{SW\ ON(max)} = 0.5\ V_{CE(max)} * 0.5\ I_{C(max)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

It is interesting to note that the power curve looks like essentially like a rectified sine wave. The average value of this waveform is

$$P_{SW\ ON(avg)} = 0.636 * P_{SW\ ON(max)} = 0.636 * 0.5\ V_{CE(max)} * 0.5\ I_{C(max)}$$

$$= (1/6) * V_{CE(max)} * I_{C(max)}$$

The energy loss (power * time) during turn-ON will be $P_{SW\ ON(avg)} * t_{SW\ ON}$

$$W_{SW\ ON} = (1/6)\ V_{CE(max)} * I_{C(max)} * t_{SW\ ON} \qquad \text{(Joules)}$$

A similar analysis gives the energy loss during turn-OFF ;

$$W_{SW\ OFF} = (1/6)\ V_{CE(max)} * I_{C(max)} * t_{SW\ OFF} \qquad \text{(Joules)}$$

The total energy loss in one cycle due to switching is given by

$$W_{SW}= W_{SW\ ON} + W_{SW\ OFF} = (1/6)\ V_{CE(max)} * I_{C(max)} * (t_{SW\ OFF} + t_{SW\ ON})$$

The average power dissipation in the switch will be

$$P_{SW} = W_{SW} / T = W_{SW} * f \qquad ; \ f = 1/T$$

$$P_{SW} = (1/6)\ V_{CE(max)} * I_{C(max)} * (t_{SW\ OFF} + t_{SW\ ON}) * f$$

Where T is the switching period and f is the pulse repetition rate (frequency of switching). Note that

$$T= t_{ON} + t_{SW(ON)} + t_{OFF} + t_{SW(OFF)}$$

If we let

$$t_{SW(ON)} = t_{SW(OFF)} = t_{SW}$$

Then

$$P_{SW} = (1/6)\ V_{CE(max)} * I_{C(max)} * (2\ t_{SW}) * f$$

The total power loss in the switch is

$$P_T = P_{ON(avg)} + P_{OFF(avg)} + P_{SW} \approx P_{ON(avg)} + P_{SW}$$

$$= V_{CE(SAT)} * I_{C(max)} * d + V_{CE(max)} * I_{Leak} * T_{off}/T + (1/3)\ V_{CE(max)} * I_{C(max)} * t_{SW} * f$$

EX.3

Referring to figure (6) if Vs=50 V, R_L=5 ohms, and the switch is ideal with no switching loss. If the on state voltage drop is 1.5 V and the leakage current is 1.5 mA, calculate the power loss in the switch when it is (a) ON (b) OFF,.

SOL.

a) Conduction current = (50-1.5)/5 = 9.7 A
   Power loss during ON state = 1.5 * 9.7 = 14.55 W

b) Power loss during OFF state P_{OFF} = 50 V * 1.5 mA = 75 mW.

For normal load condition the power dissipation during OFF state can be neglected in comparison to the power loss during ON state.

EX.4

Calculate the maximum and average power loss for the switch in previous example if the switching frequency is 500 Hz with duty cycle of 50%.

SOL.

Switching period T = 1/f = 1/500 = 2 ms.

Duty cycle d = 0.50

Then t_{ON}=1 ms and t_{OFF} = 1 ms

Average power loss during ON state = P_{ON} * t_{ON}/T = 14.55*0.5 = 7.27 W

Average power loss during OFF state = P_{OFF} * t_{OFF}/T = 0.075*0.5=0.037 W

Average power loss in one cycle = $P_{ON(avg)}$ + $P_{OFF(avg)}$ = 7.27+0.037=7.3 W

Remember that the maximum power dissipated is 14.55 W.

EX.5

Assume Vs=120 V, RL=6 ohms, and the transistor is ideal for conduction loss. If $t_{SW(ON)}$=$t_{SW(OFF)}$ = 1.5 μs, calculate the average switching power loss at the switching frequency of 1 KHz.

SOL.

$I_{C(max)}$ = 120/6 = 20 A

$P_{SW\ ON(avg)}$ = (1/6) * $V_{CE(max)}$ * $I_{C(max)}$ = 120 * 20 / 6 = 400 W

The energy loss is

$W_{SW\ ON}$ = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * $t_{SW\ ON}$ = 400 * 1.5X10^{-6}=0.6 mJ

$W_{SW\ OFF}$ = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * $t_{SW\ OFF}$ = 400 * 1.5X10^{-6}=0.6 mJ

W_{SW} = $W_{SW\ ON}$ + $W_{SW\ ON}$ = 1.2 mJ

P_{SW} = W_{SW} / T = W_{SW} * f = 1.2 mJ * 1000 = 1.2 W

OR

P_{SW} = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * (2 t_{SW}) * f = (1/6)*120 * 20 *2*1.5X10^{-6} *1000

= 1.2 W

It is clear from the examples that when we select a power switch, it is necessary to select the adequate frequency of switching in order to minimize the losses in the switch and obtain a good waveform on the load.