Power Electronics and Special Machines

Lecture 4: Cooling

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The sources of loss in power semiconductor devices may be listed:

1- The loss during forward conduction.

2- The loss associated with the leakage current during the blocking state.

3- The switching loss, that is, the energy dissipated in the device during turn-on and turn-off which is high when the switching is occurring at a relatively high frequency.

The losses will lead to heat generation within the device, and consequently a rise in temperature until the rate of heat dissipation matches the loss. Most of heat transfer takes place by convection, to air in the case of the metal-finned heat sink illustrated in Figure 1a, where the level of heat dissipation is very high, the heat sink can be cooled by a compact water-cooled assembly as shown in Figure 1b. Heat transfer will take place from a higher-temperature region to a lower temperature region. The heat transfer equation is:

$$P = \frac{T_1 - T_2}{R} \tag{1}$$

where P is the power losses in watt, T_1 and T_1 are temperatures of the hot and cold bodies respectively which are measured in °C, and R is the thermal resistance in °C/W.

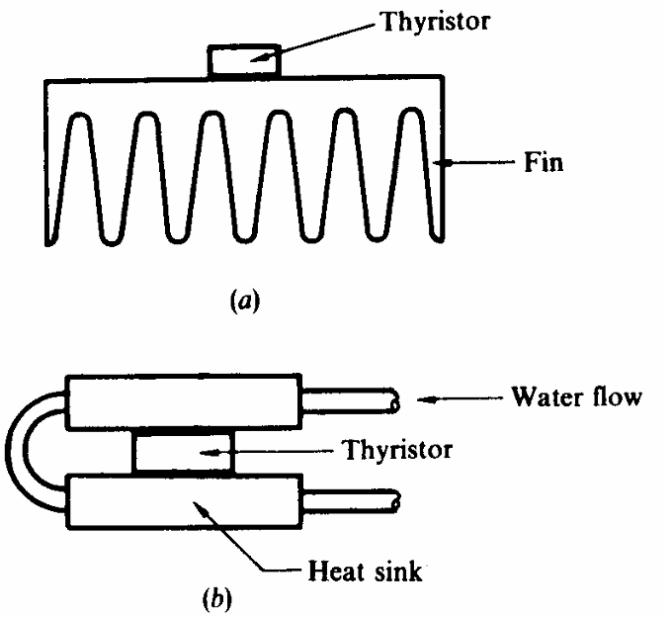

Figure 1: Typical cooling arrangements: **(a)** Air cooled, **(b)** Water cooled.

The heat flow is from the junction to the base, to the heat sink, to the surrounding air, and the total thermal resistance will be the series addition of the individual thermal resistances of each section. The total thermal resistance from the junction to the ambient (R_{ja}) is given by:

$$R_{ja} = R_{jb} + R_{bh} + R_{ha} \tag{2}$$

where R_{jb}, R_{bh}, and R_{ha} are the thermal resistances from junction to base, base to heat sink, and heat sink to ambient.

The virtual junction T_{vj} is:

$$T_{vj} = T_a + P\ R_{ja} \tag{3}$$

where T_a is the ambient temperature. Figure 2 illustrates the circuit equivalent to heat transfer, enabling the intermediate temperatures of base and heat sink to be determined. The virtual junction is used to avoid defining exactly what is the junction in multi-layer device.

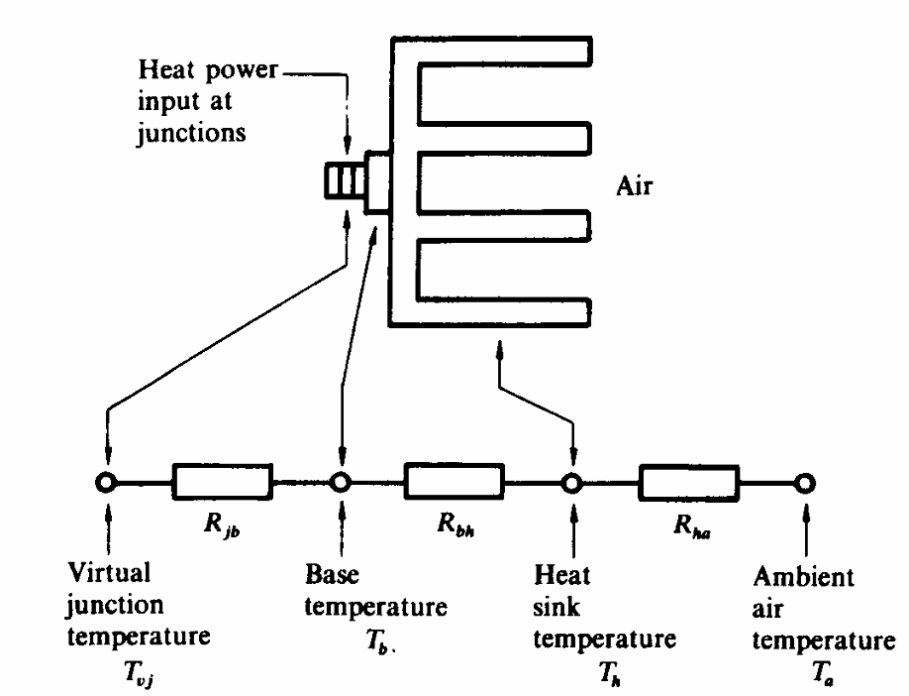

Figure 2: Heat flow and temperature distribution.

The temperature changes will occur over the period of a cyclic change. With the steady-state conditions at 50 Hz, the thermal resistance values quoted at the rated mean power loss will be such as to ensure the maximum allowable temperature is not exceeded during cyclic period.

During short-period transients, such as overload or fault conditions, the temperature rise of the junction must be calculated using a transient thermal impedance for the specified period of time which is given by manufacturer and the Equation-1 is used.

Example 1: A thyristor of thermal resistance 1.8 °C/W is mounted on a heat sink of thermal resistance 2.0 °C/W. Calculate the maximum power loss of the thyristor if the junction temperature is not exceeded 125 °C in an ambient of 40 °C.

Solution:

Total Thermal Resistance R_{ja}:

$$R_{ja} = R_{jb} + R_{bh} + R_{ha}$$

$$R_{ja} = 1.8 + 2.0 = 3.8\ °\text{C/W}$$

Maximum Power Loss P:

Using the virtual junction temperature equation:

$$T_{vj} = T_a + P\ R_{ja}$$

Rearranging to solve for P:

$$P = \frac{T_1 - T_2}{R} = \frac{T_{vj} - T_a}{R_{ja}}$$

$$P = \frac{125 - 40}{3.8} = 22.37\ \text{W}$$

Example 2: A thyristor with a steady power-loss of 30 W has a junction to heat sink thermal resistance of 0.7 °C/W. Determine the maximum value of the thermal resistance the heat sink can have if the ambient temperature is 40 °C and the junction temperature is limited to 125 °C. Give the heat sink temperature at this condition.

Solution:

Given Data:

Power loss (P) = 30 W

Junction-to-heat sink thermal resistance R_{jb} = 0.7 °C/W

Maximum junction temperature T_{vj} = 125 °C

Ambient temperature T_a = 40 °C

1. Maximum Total Thermal Resistance (R_{ja}):

Using the steady-state thermal equation:

$T_{vj} = T_a + P\,R_{ja}$

$125 = 40 + 30\,R_{ja}$

$R_{ja} = 2.833$ °C/W

2. Maximum Heat Sink Thermal Resistance (R_{ha}):

$R_{ja} = R_{jb} + R_{bh} + R_{ha}$

$2.833 = 0.7 + R_{ha}$

$R_{ha} = 2.133$ °C/W

3. Heat Sink Temperature (T_h):

$T_h = T_a + P\,R_{ha} = 40 + 30 * 2.133$

$T_h = 104$ °C

Example 3: A thyristor has with its heatsink a thermal resistance of 0.2 °C/W steady state and a 100 ms value of 0.05 °C/W. What power loss can the thyristor tolerate for 100 ms if the junction temperature is not exceeded 125 °C following a steady power loss of 300 W, the ambient temperature being 30 °C?

Solution:

Given Data:

Steady-state thermal resistance (R_{ja}) = 0.2 °C/W

Transient thermal impedance at 100 ms, Zth = 0.05 °C/W

Initial steady power loss (P_{steady}) = 300 W

Maximum allowable junction temperature (T_{vj}) = 125 °C

Ambient temperature (T_a) = 30 °C

1. Initial Steady-State Junction Temperature (T_j):

Before the overload/transient pulse, the junction temperature is determined by the steady-state power loss:

$T_j = T_a + P_{Steady}.R_{ja}$

$T_j = 30 + 300 * 0.2 = 90$

$T_j = 90$ °C

2. Allowable Temperature Rise (ΔT):

The maximum permitted rise from the initial steady state up to the maximum junction limit is:

$\Delta T = T_{vj} - T_j = 125 - 90 = 35$ °C

3. Maximum Tolerable Power Loss (P_{pulse}) for 100 ms:

Using the transient thermal impedance for the specified duration:

$\Delta T = P_{pulse}.Z_{th}$

$35 = P_{pulse}.0.05$

$P_{pulse} = 700\ \text{W}$

Total overload power=300+700=1000 W