INTERNATIONAL RECTIFIER IOR

CALCULATION OF CURRENT RATING

AN-305

APPLICATION NOTE

CALCULATION OF RECTANGULAR WAVEFORM CURRENT RATING OF THYRISTORS

Most data sheets for reverse blocking, triode, power thyristors (silicon controlled rectifiers) give current ratings only for the case of a single phase (half wave) resistive load. These ratings are usually given in the form of curves showing the maximum allowable current vs. case temperature for various conduction angles such as 180, 120, 90, 60 and 30 degrees. These current waveforms are shown in Figure 1. It should be noted that the highest value of average current shown on the data sheet curves for each current waveform has an RMS value equal to the maximum RMS rating of the thyristor in question.

The designer quickly finds that in a great many applications current flow is nearly rectangular so that the above published ratings do not apply. For a given conduction period and average current value, the heating effect of a rectangular current wave is less than that of a multilated sine wave of equal conduction time, because the peak current is less. This can be seen from Figure 2. Thus, the thyristor current ratings for rectangular waveform current are greater for any given conduction period, and advantage should be taken of this.

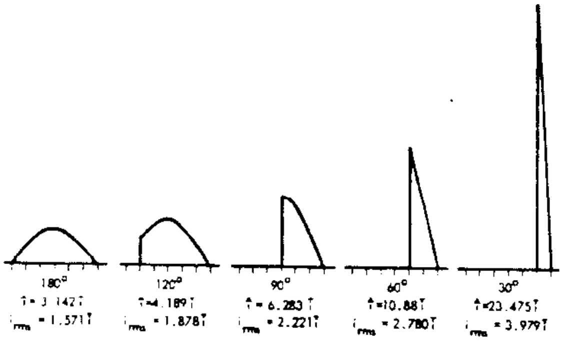

Figure 1 – Sinusoidal Current Waveforms of Equal Average Value but Different Conduction Angles

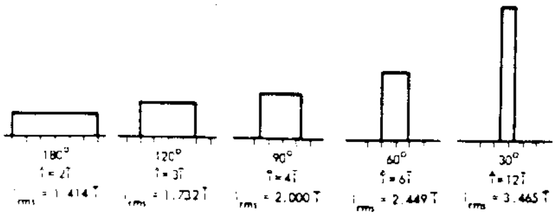

Figure 2 – Rectangular Current Waveforms of Equal Average Value but Different Conduction Periods

WHERE RECTANGULAR CURRENTS ARE ENCOUNTERED

The current waveshapes observed in single phase full wave (bi-phase) and polyphase rectifier units usually are more rectangular than sinusoidal. Load inductance tends to prevent rapid variations in load current, making the current waves flat topped. On the other hand, inductance in the ac supply (including rectifier transformer reactance) prevents instantaneous transfer (commutation) of current from one rectifying element to the next, resulting in overlapping current flow through the circuit elements that are commutating. The resulting current waveforms are illustrated in Figure 3. When phase retard is used in such rectifier equipment to control the average output voltage, the angle of current flow remains essentially fixed; the initiation of the current wave is simply delayed by the angle of phase retard, α, as can be seen from Figure 4. It is interesting to note that as α is increased, for a given value of load current, commutation takes less time so that the current waveform becomes more rectangular.

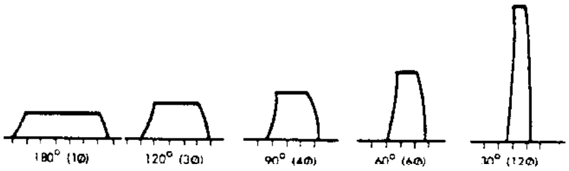

Figure 3 – Anode Current Waveforms of Rectifier Unit Having Inductance in AC Supply and Load

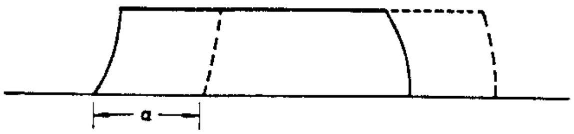

Figure 4 – Effect of Phase Retard, Angle α, on Anode Current Waveform in Rectifier Circuit

The duration of current flow (the conduction period) is determined by the rectifier circuit and not by the angle of phase retard. Conduction periods for common rectifier circuits are given in Table 1.

TABLE 1

Conduction Periods of Common Rectifier Circuits, Inductive and Resistive Loads

Circuit	Conduction Period
Single Phase Center Tap (bi-phase, single-way)	180°
Single Phase Bridge (double-way)	180°
Three Phase Wye (single-way)	120°
Three Phase, Double Wye with IPT (single-way)	120°
Three Phase Bridge (double-way)	120°
Six Phase Star (single-way)	60°
Twelve Phase Quadruple Zig-Zag (single-way)	30°

The current flow through thyristors in many inverter circuits also tends to be rectangular. The current flows through an inductance from a source having a fixed direct voltage and the thyristors serve to switch the current from one transformer winding to another; thus, essentially rectangular current waves result.

CALCULATION PROCEDURE

The calculation of thyristor current rating for rectangular waveform currents is not difficult. Basically, all the device data that are required is the on-state voltage (forward voltage drop) curve at maximum rated junction temperature, the transient thermal impedance curve for times between 1 and 10 milliseconds, and the rated thermal resistance of the device, junction-to-case. If a curve of instantaneous on-state power loss vs. instantaneous anode current is available this will simplify the procedure because it will not be necessary to calculate the instantaneous on-state power loss from the on-state voltage curve.

Junction temperature rise above case temperature can be calculated by the formula:

$$\Delta T_{J(JC)} = \frac{t_p}{\tau}\hat{P}_T R_{\theta JC} + \left(\hat{P}_T - \frac{t_p}{\tau}\hat{P}_T\right) Z_{\theta(t_p)}$$

$$= \hat{P}_T \left[\frac{t_p R_{\theta JC}}{\tau} + \left(1 - \frac{t_p}{\tau}\right) Z_{\theta(t_p)}\right] \qquad (1)$$

Where:

$T_{J(JC)}$ = Junction temperature rise above case temperature.

$\hat{P}_T$ = Peak on-state (triggered) power loss at a given peak anode current.

t_p = Duration of one rectangular wave of current (conduction period).

τ = Time interval between the start of one current pulse and the start of the next (the period, i.e., the reciprocal of the supply frequency).

$R_{\theta JC}$ = Thermal resistance of the thyristor, junction-to-case.

$Z_{\theta(t_p)}$ = Transient thermal impedance of the thyristor for the time duration of one current pulse.

In the above equation, the average junction temperature rise is calculated by the expression $t_p/\tau \cdot P_T \cdot R_{\theta JC}$ (average power dissipated times thermal resistance). To this is added a term which represents the temperature response of the junction in the final pulse of load current. This increment is calculated by multiplying the increment of power dissipated during the pulse which is greater than the average power dissipated, $(1 - t_p/\tau)\ P_T$, by the transient thermal impedance for the time of one current pulse, $Z_{\theta(t_p)}$. More complex expressions have been published for this temperature rise, but the above expression gives a conservative answer that is within a few degrees of the more precise value, and is far easier to calculate.

A further refinement is to allow for the heating effect of the losses during the reverse blocking and forward off-state periods. In power thyristors these losses generally are only a few watts, and so cause only a small additional temperature rise of 1 to 2 degrees Celsius (Centigrade).

Temperature Rise Above Cooling Fluid Temperatures

The equipment designer must know junction temperature rise above cooling fluid temperature (temperature of incoming air, water, oil, etc.), not simply junction temperature rise above device case temperature. The additional rise of the case above the cooling fluid is calculated by multiplying the total average on-state, off-state and reverse blocking losses by the thermal resistance from case to cooling fluid.

There are usually several thermal drops in series in the path of heat flow from case to cooling fluid, such as:

1. Thermal resistance from case to heat exchanger (often referred to as case to heat sink).

2. Thermal resistance from heat exchanger to cooling fluid.

Thermal resistance from case to heat exchanger is a function of the size of the thyristor base and presence or absence of silicone grease on the mating surfaces. Representative values are given in Table 2.

TABLE 2

Thermal Resistance, Case to Heat Exchanger

Size of Thyristor Case			Thermal Resistance to Heat Exchanger	
Hex Base	Threaded Stud	JEDEC No.	Dry	With Silicone Grease DC 100 or Equal
7/16"	10-32	TO-64	0.75°C/W	0.50°C/W
9/16"	1/4-28	TO-48	0.50°C/W	0.35°C/W
11/16"	1/4-28	TO-65	0.35°C/W	0.25°C/W
1-1/16"	1/2-20	TO-49, 83, 94	0.15°C/W	0.10°C/W
1-1/4"	3/4-16	TO-93	0.10°C/W	0.08°C/W
1-11/16"	3/4-16	–	0.05°C/W	0.04°C/W

Thermal resistance from heat exchanger to cooling fluid must be determined from the configuration and size of the heat exchanger used, the velocity of the cooling fluid, the surface finish of the heat exchanger, etc. The thermal resistance, device-mounting-surface-to-coolant, of the heat exchanger can be obtained from the heat exchanger manufacturer or from tests.

An expression for calculating junction temperature rise above cooling fluid temperature can now be written, taking into account the factors just discussed:

$$\Delta T_{J(JA)} = \left(\frac{t_p}{\tau}\hat{P}_T + \bar{P}_B\right)\left(R_{\theta JC} + R_{\theta CH} + R_{\theta HA}\right) + \hat{P}_T\left(1 - \frac{t_p}{\tau} Z_{\theta(t_p)}\right) \qquad (2)$$

Where:

$T_{J(JA)}$ = Junction temperature rise above ambient cooling fluid temperature.

$R_{\theta CH}$ = Thermal resistance, case-to-heat exchanger.

$R_{\theta HA}$ = Thermal resistance, heat-exchanger-to ambient.

$\bar{P}_B$ = Average power losses during reverse blocking and forward off-state periods.

(The other terms are the same as those for formula (1).)

The RMS value of the current rating calculated by the above procedures should not exceed the rms current rating of the thyristor being considered.

EXAMPLE

To illustrate the principles discussed above, consider a 70 Ampere (average), 110 Ampere (rms) thyristor operating in a three phase bridge rectifier circuit with inductive load. The on-state voltage and the transient thermal impedance curves for this device are given in Figures 5 and 6 respectively. Maximum thermal resistance, junction to case, is 0.30°C/Watt, and maximum rated junction operating temperature is 125°C. The device is mounted on an air cooled

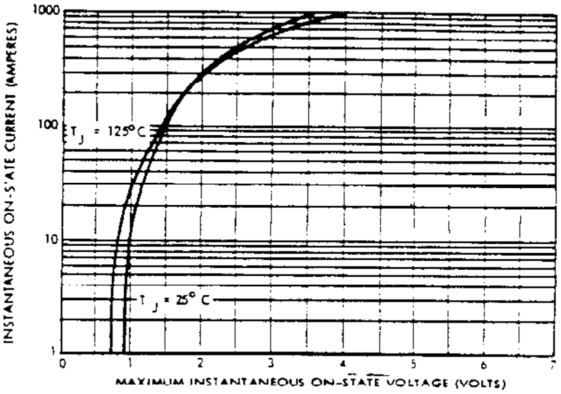

Figure 5 – Maximum Instantaneous On-State Voltage Vs. Instantaneous On-State Current

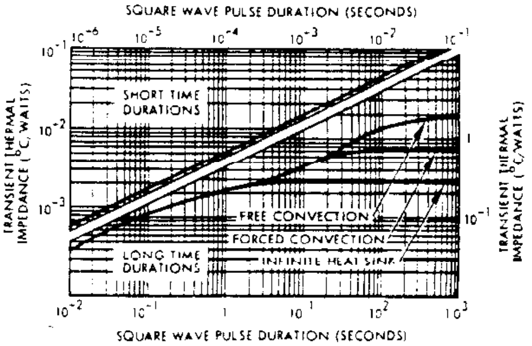

Figure 6 – Maximum Transient Thermal Impedance Vs. Square Wave Pulse Duration. Thyristor Mounted on 7 x 7 x .160" Copper Fin.

heat exchanger having a thermal resistance to ambient air of 0.30°C/Watt at a cooling air velocity of 1000 lf/min. The maximum ambient air temperature in which the device is to operate is 45°C. The supply frequency is 60 Hz and therefore the supply period, τ, is 1/60 = 0.0167 seconds. From Table 1 the conduction period is seen to be 120 deg., or 0.0167 x 120/360 = 5.6 x 10^{-3} seconds, and from Figure 6 the transient thermal impedance for a square wave pulse of this duration is found to be 3.6 x 10^{-2} °C/Watt.

From Table 2 the thermal resistance from case to heat exchanger is seen to be 0.10°C/Watt (lubricated). The average power loss during the reverse blocking and forward off-state periods can be calculated from the maximum leakage current for the thyristor, which in this case is 5 mA. A value of 3 Watts is a conservative, worst-case estimate.

The above data may be used in equation (2) to solve for the peak power loss required to raise the peak junction temperature to 125°C:

$$\left(\frac{1}{3}\hat{P}_T + 3\right)\ (0.30 + 0.10 + 0.30)$$

$$+ \hat{P}_T\left(1 - \frac{1}{3}\right) 0.036 = 125 - 45$$

$$.257\,\hat{P}_T = 77.9$$

$$\hat{P}_T = 303\ \text{W}$$

From the on-state voltage curve for 125°C junction temperature the peak current producing this amount of power loss can be found (by successive approximations) to be: 303/1.68 = 180 Amperes. The maximum permissible average current is then 180/3 = 60.0 Amperes.

Referring to Figure 2, the RMS value of this current is 180/1.732 = 104A, which is within the 110A RMS rating of the thyristor in this example.

Simplifications

The manufacturer will usually publish a curve of on-state power loss vs. direct current, such as the dc curves shown in Figures 7 and 8. Such curves permit reading the value of permissible peak amperes directly without the need for calculating them from the on-state voltage curve.

If the manufacturer has provided curves of average on-state power loss for square wave operation, such as shown in Figure 8, the average current may be read directly by converting the peak power to average power. In the case of the example, the average power is 101 Watts, which is one third the peak power, since the conduction period is one third of a cycle (120 degrees). From the 120 degree curve in Figure 8 the average current is found to be 59 Amperes.

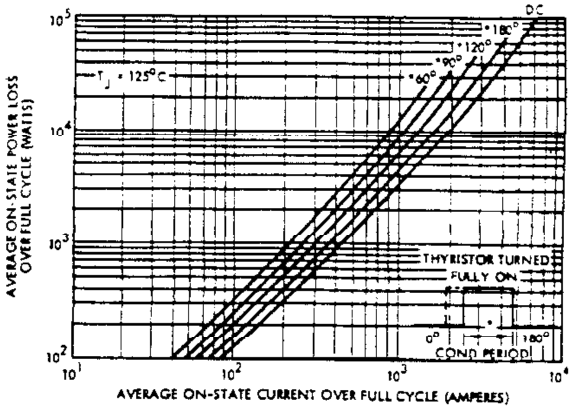

Figure 7 — Average On-State Power Loss Vs. Average On-State Current. Rectangular Waveform Current, High Current Levels.

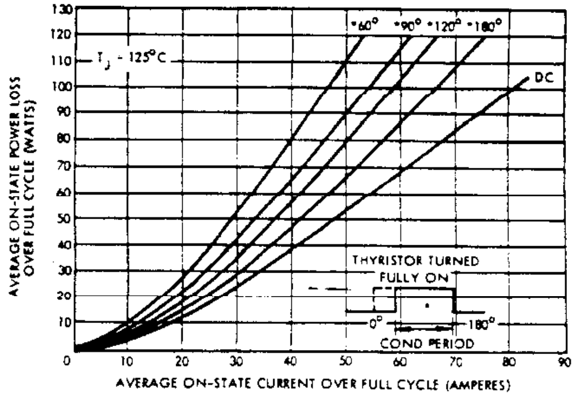

Figure 8 — Average On-State Power Loss Vs. Average On-State Current. Rectangular Waveform Current, Low Current Levels.

Using Rectangular Current Waveform Rating Curve

When the manufacturer provides curves of average on-state current vs. maximum allowable case temperature for rectangular current waves, such as the curves in Figure 9, calculations can be simplified even more. In this case the main step in determining the current rating is to calculate the temperature rise of the case above ambient due to the on-state losses, which is the product of these losses and the thermal resistance from case to ambient. Taking the previous example, this thermal resistance is 0.40°C/Watt. The average off-state and reverse blocking power losses are 3 Watts, and the temperature rise from case to ambient caused by these losses is 1.2 degrees. In effect, this raises the maximum allowable ambient temperature to 46.2°C. A current must now be found for which the maximum allowable thyristor case temperature, as read from Figure 9, will be just high enough to permit the average power generated in the thyristor to be dissipated to the cooling medium by the heat exchanger. This value of on-state current must be found by successive approximations. Since the answer in this case, 59 Amperes, has previously been calculated, the procedure can be illustrated by a single calculation:

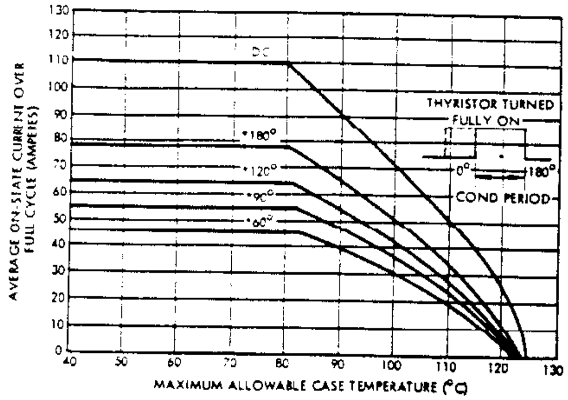

Figure 9 — Average On-State Currents Vs. Maximum Allowable Case Temperature. Rectangular Waveform Current.

Maximum case temperature permitted at
59 Amperes: 86.0°C (from Fig. 9).

Maximum temperature rise permitted between
ambient and case at 59 Amperes:

$$86.0 - 45 + (3 \times 0.40) = 86.0 - 46.2 = 39.8^{\circ}C$$

Maximum average on-state power loss permitted:

$$\frac{39.8}{0.40} = 99.5 \text{ Watts}$$

Maximum average on-state current permitted:
58.5 Amperes (from Fig. 8).

This is essentially the same as the 59 Amperes used at the start of the calculation.

OVERLOADS

The manufacturer's data sheet provides a non-recurrent surge current rating, which may be imposed on the thyristor when it is operating at maximum rated current, voltage, and temperature conditions in a half-wave circuit. Following rated non-recurrent overload the thyristor is not expected to exhibit off-state blocking capability until its junction has cooled down to the maximum rated operating temperature. A fault sufficiently severe to cause an overload of this nature is not expected to be a normal operating condition, and a thyristor is not expected to be subjected to more than approximately 100 such faults during its useful life.

On the other hand, more moderate overloads are often encountered very frequently in rectifier equipments. These are known as recurrent overloads, and since they are of indeterminate number, they must not cause the thyristor junction temperature to be raised above the maximum rated operating temperature, if long thyristor life is to be assured. Consequently, a reduction in the continuous loading on the thyristor is required, to provide an additional temperature rise which can take place during the overload.

The required amount of this temperature rise margin depends upon the severity of the overloads and their durations.

Of the many possible overload schedules, one of the most common is that of a short overload following continuous loading. The following simplified formula, which is an extension of equation (2) may be used to calculate the junction temperature rise at the end of the overload:

$$\begin{aligned}\Delta T_{J(JA)} = {} & \left(\frac{t_p}{\tau}\hat{P}_{T(SS)} + \bar{P}_B\right)\left(R_{\theta JC} + R_{\theta CH}\right. \\ & \left. + R_{\theta HA}\right) + \hat{P}_{T(SS)}\left(1 - \frac{t_p}{\tau}\right) Z_{\theta(t_p)} \\ & + \frac{t_p}{\tau}\left(\hat{P}_{T(OL)} - \hat{P}_{T(SS)}\right) Z_{\theta(OL)} \\ & + \left(\hat{P}_{T(OL)} - \hat{P}_{T(SS)}\right)\left(1 - \frac{t_p}{\tau}\right)\overline{Z}_{\theta(t_p)} \qquad (3)\end{aligned}$$

Where:

$\hat{P}_{T(SS)}$ = peak steady state on-state power loss (prior to overload).

$\hat{P}_{T(OL)}$ = peak on-state power loss during overload.

$Z_{\theta(OL)}$ = transient thermal impedance of thyristor for overload period.

(The other terms are the same as those given for (1) and (2).)

Care should be taken in determining the transient thermal impedance for the overload period. A transient thermal impedance curve for the thyristor mounted on infinite heat sink may be used only over the range where the transient thermal impedance is no more than ninety percent of the maximum value given on the curve. For longer overloads a transient thermal impedance curve for the device mounted on the heat exchanger actually being used is required. Two such curves are given in Figure 6 for the thyristor used in the example.

If a temperature rise margin, $\Delta T_{J(OL)}$, is provided for overloads when determining the steady state current loading of the thyristor, the recurrent overload which can be imposed can be found by solving the equation below for $\hat{P}_{T(OL)}$, the peak on-state power loss during the overload period:

$$\Delta T_{J(OL)} = (\hat{P}_{T(OL)} - \hat{P}_{T(SS)}) \left[\frac{t_p}{\tau} Z_{\theta(OL)} + 1 - \frac{t_p}{\tau} Z_{\theta(t_p)} \right] \quad (4)$$

Having found the maximum peak on-state power loss permitted during the overload period, the average current which can be carried during the overload period may be calculated as before.

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INTERNATIONAL RECTIFIER IOR

Semiconductor Division, 233 Kansas St., El Segundo, Calif. 90245 • Telex 67-4666 • Phone (213) 678-6281

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