AN599
APPLICATION NOTE

PARALLEL OPERATION OF POWER RECTIFIERS

INTRODUCTION

In parallel operation of several diodes, the current is not split into equal parts because of differences between forward characteristics.

The current through the rectifier having the lowest voltage drop will be higher than the current through the other diodes.

On the other hand the temperature coefficient of the forward voltage is negative and therefore this unbalanced situation at switching ON can become worse up to a stable equilibrium state.

The designer has to be sure that at this final state the diodes operate below the maximum specified limits.

The aim of this study is to calculate the acceptable difference between forward voltage drops of diodes to be paralleled in a given application.

QUALITATIVE ANALYSIS AND LIMITATIONS

Let's assume that we have two diodes D1 and D2 connected in parallel.

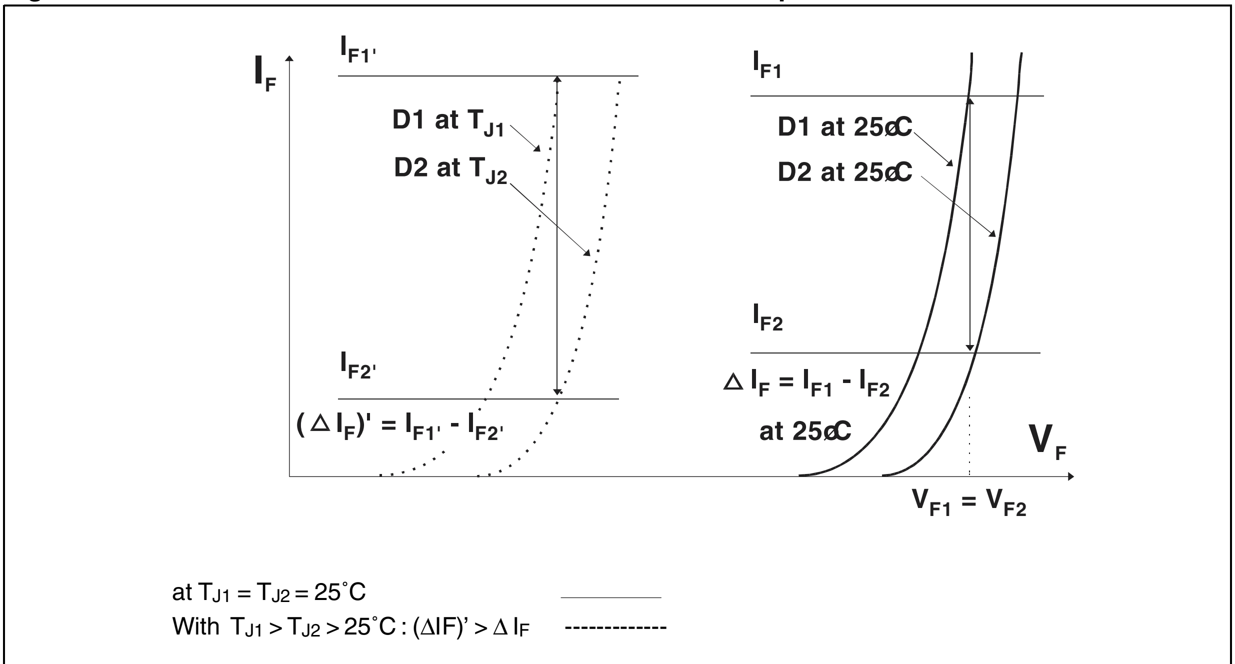
The forward characteristics of the two diodes at $T_{J1} = T_{J2} = 25°C$ are shown in Figure 1.

The total current $I_T = I_{F1} + I_{F2}$ is not split into equal parts.

The thermal dissipation makes the difference $\Delta I_F = I_{F1} - I_{F2}$ increase.

Indeed, the current through D1 is higher than through D_2 so $T_{J1} > T_{J2}$, and because the forward voltage has a negative temperature coefficient, the difference ΔI_F increases.

Figure 1. Forward characteristics of two diodes D1 and D2 in parallel



For a safe and reliable operation it is absolutely necessary to remain within the maximum ratings of the devices :

1) T_{J1} lower than the maximum junction temperature

2) Current through D1 compatible with the specified maximum RMS current.

SIMPLIFIED FORWARD CHARACTERISTIC MODEL

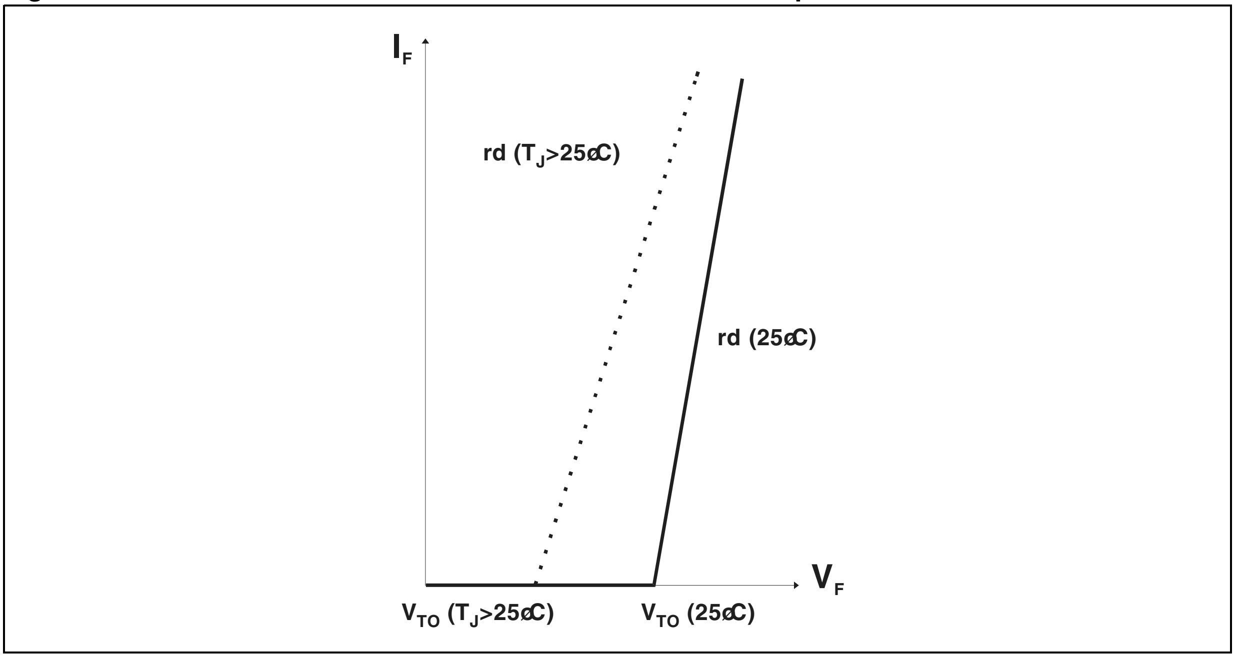
The forward characteristic of a diode may be assimilated to a straight line whose equation is:

$$V_F = V_{TO} + rd \times I_F \quad \text{(Figure 2)}$$

V_{TO} and rd act as a function of the temperature.

V_{TO} has a negative temperature coefficient (α_{TO}) and rd has a positive temperature coefficient (α rd).

Figure 2. Forward characteristics model of rectifier versus temperature

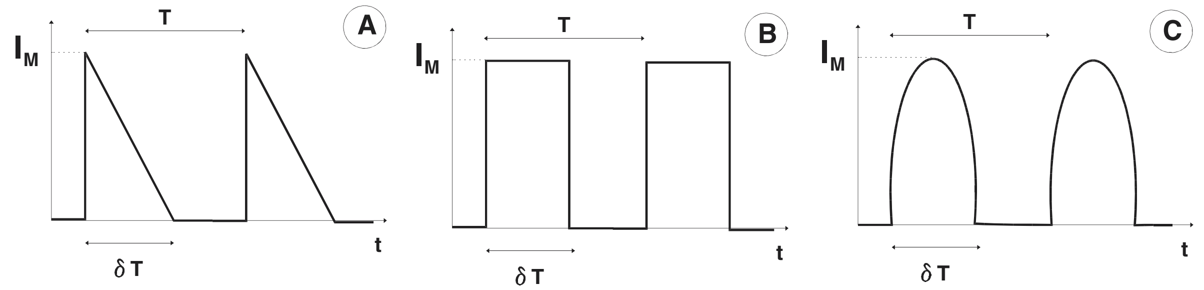


This model allows to easily calculate the operating point (V_F, I_F) of each diode and to evaluate the power losses due to the conduction.

$$P_{cond} = V_{TO} \times I_{F\,(AV)} + rd \times I_F{}^2{}_{(RMS)} \quad (1)$$

In practice the waveforms of current can be assimilated to simple forms (rectangular, triangular, sinusoidal), so $I_{F(AV)}$ and $I_{F(RMS)}$ can be expressed with the peak current (I_M) and the duty cycle (δ) (Figure 3)

Figure 3. Average and RMS values for different currents wave forms.



$$I_{F(AV)} = \frac{I_M \times \delta}{2} \qquad I_F^{\,2}{}_{(RMS)} = \frac{I_M^{\,2} \times \delta}{3}$$

$$I_{F(AV)} = \delta \times I_M \qquad I_F^{\,2}{}_{(RMS)} = \delta \times I_M^{\,2}$$

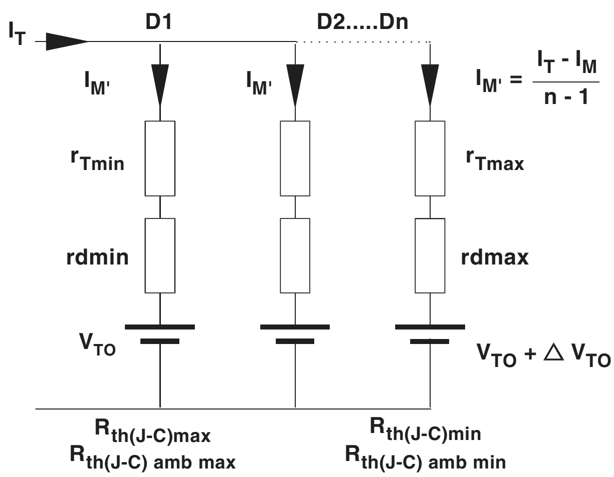
$$I_{F(AV)} = \frac{2 \times I_M \times \delta}{\pi} \qquad I_F^{\,2}{}_{(RMS)} = \frac{I_M^{\,2} \times \delta}{2}$$

OPERATING WITH SEVERAL DIODES IN PARALLEL

Taking into consideration the dispersion of both the diodes parameters as well as the circuit parameters, we can calculate the maximum difference between V_F (measured at 25°C and at the nominal current specified for the device $I_F = I_{F(AV)}$) in order to be sure than no diode will operate out of its specification.

The calculation is based on the worst case situation (Figure 4): we suppose that D1 has the lowest V_{TO} and rd and the highest $R_{th(j-c)}$ and T_{CASE}. This diode supports the highest current I_M and operates at the highest junction temperature.

Figure 4. Worst configuration of several diodes in parallel



As a first step, we have to determine the maximum acceptable peak current (I_M) through D1 in these conditions.

Thermal limitation: I_{M1}

The maximum total power dissipation in the diode is given by:

$$P_T = \frac{T_{Jmax} - T_{CASE(max)}}{R_{th(j-c)max} + R_{th(c)}^{(1)}}$$

Note: 1. Case of double diodes. $R_{th(c)}$: Coupling thermal resistance

The total power dissipation is

$$P_T = P_{COND} + P_{COM}$$

P_{COND}: conduction losses $P_{COND} = \rho P_T$

P_{COM}: commutation losses $P_{COM} = (1-\rho) P_T$

For SCHOTTKY diodes, the commutation losses are negligible ($\rho = 1$)

We can write P_{COND} versus I_M for rectangular waveform:

(For the other waveforms see the annex).

$$P_{COND} = V_{TO}\,(100°C)\,\delta .I_M + rd\,(100°C)\,\delta .I_M^{\,2}$$

So

$$I_{M1} = \frac{-V_{TO}\delta + [(V_{TO}\delta)^2 + 4 \cdot P_{COND} \cdot rd \cdot \delta]^{\frac{1}{2}}}{2 \cdot rd \cdot \delta} \quad (2)$$

RMS current limitation: I_{M2}

If $I_{F(RMS)}$ is the maximum RMS current specified in the data sheet, the limit in the case of a rectangular waveform will be:

$$I_{M2} = \frac{I_{F(RMS)}}{\sqrt{\delta}}$$

It is obvious that we will take the minimum value of I_{M1} and I_{M2}

Calculation of ΔV_F

Table 1. The Diodes Parameters are:

$\propto_{TO}$	Temperature coefficient of V_{TO}
$\propto rd$	Temperature coefficient of rd
V_{TO}	Threshold voltage at $T_J = 25°C$
rd	Dynamical resistance at $T_J = 25°C$ and its dispersion (rd min, rd max)
$R_{th(j-c)}$	Junction to case thermal resistance and its dispersion $R_{th(j-c)min}$, $R_{th(j-c)max)}$
T_{Jmax}	max operating junction temperature

Table 2. The "Application" Parameters are:

I_T	Peak current through the diodes and its waveform
δ	Duty cycle
n	Number of diodes
T_C	Case temperature and the dispersion T_C min (coldest case) and T_C max (hotest case)
$r_{t\,max}$ $r_{t\,min}$	Min and max values of the resistances of wires and various connections.

By solving electrical and thermal equations corresponding to the circuit of the Figure 5 in the case of rectangular waveform, we find:

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

With

$$\Delta V_{F1} = (r_{T\,min} + rd\,min)\, I_M - (r_{T\,max} + rd\,max)\, I_M'$$

$$\Delta V_{F2} = R_{th(j-c)\,max}\,(\alpha_{TO} + \alpha\ rd\ .\ I_M)\ .\ P1$$

$$\Delta V_{F3} = (\alpha_{TO} + \alpha\ rd\ .\ I_M)\ .\ (T_{C\,max} - T_{C\,min})$$

$$\Delta V_{F4} = R_{th\,(j-c)\,min}\ .\ (\alpha_{TO} + \alpha\ rd\ .\ I_M')\ .\ P2$$

$$\Delta = 1 + R_{th\,(j-c)\,min}\,[\alpha_{TO} + rd\ .\ I_M'\,]\ \delta\ .\ I_M'$$

$$P_1 = \frac{V_{TO}\delta I_M + rdmin\,\delta I_M'^2}{\rho}$$

$$P_2 = \frac{V_{TO} \cdot I_M' + rdmax \cdot I_M'^2}{\rho}$$

$$I_M' = \frac{I_T - I_M}{n - 1}$$

Information about of diodes parameters

α_{TO} and α_{rd} are given for some part numbers in the following table:

Table 3.

	BYV255 -xxx	BYT60P -xxx	BYW51 -xxx
$\alpha_{TO}\left(\frac{V}{°C}\right)$	$-1.6\ 10^{-3}$	$-1.6\ 10^{-3}$	$-1.6\ 10^{-3}$
$\alpha_{rd}\left(\frac{\Omega}{°C}\right)$	$+2\ 10^{-6}$	$+3\ 10^{-6}$	$+16\ 10^{-6}$

* Datasheet gives V_{TO} max (100°C) and rd max (100°C)
with these values we can determine V_{TO} (25°C) and rd max (25°C):

V_{TO} (25°C) = V_{TO} max (100°C) – α_{TO} x 75

rd max (25°C) = rd max (100°C) – α_{rd} x 75

* rd min and $R_{th\ (j\text{-}c)min}$ can be calculated by:

rd min = k · rd max with k = 0.75

$R_{th(j\text{-}c)min}$ = k · $R_{tj(j\text{-}c)max}$ with k = 0.75

* We recommande to take T_{Jmax} = 110°C to increase the safety margin for parallel operation.

EXAMPLES OF APPLICATION

Example of rectifiers in discrete package

In this example we look for the maximum peak current I_T versus V_F that can flow in three BYV255 (n = 6) connected in parallel.

The current is rectangular and we consider 3 different duty cycles (δ = 0.3, δ = 0.5, δ = 0.7).

As a good estimation, the conduction losses can be considered to be 95% of the total losses (δ = 0.95)

Application data is

$T_{C\ max}$ = 80°C

$T_{C\ min}$ = 78°C

ρ = 0.95

rt max = 0.5mΩ

rt min = 0.4mΩ

Diodes data is

From data sheet of BYV255 we get:

$R_{th(j\text{-}c)max}$ = 0.4°C/W

$R_{th(c)}$ = 0.1°C/W

$V_{TO\ max}$ = 0.7V (at 100°C)

rd max = 1.35mΩ (at 100°C)

$I_{F(RMS)}$ = 150A

From the recommendations of § 3.4 we can calculate:

$R_{th(j\text{-}c)\ min}$ = 0.3°C/W

V_{TO} at 25°C = 0.82V

rd max at 25°C= 1.20mΩ

rd min at 25°C = 0.9mΩ

Calculations:

a) I_{M1}

In this example we have to take into account Rth(c) because there are two diodes in the package.

Thus:

$$P_{COND} = \frac{\rho(T_{Jmax} - T_{Cmax})}{R_{th(j-c)} + R_{th(c)}}$$

$P_{COND} = 57\ W$

The following table gives I_{M1} value for δ = 0.3 – 0.5 – 0.7 (according to the relation (2) of page 3)

Table 4.

δ	I_{M1} [A]
0.3	196
0.5	130
0.7	97

b) I_{M2}

$$I_{M2} = \frac{I_{F(RMS)}}{\sqrt{\delta}}$$

The following table gives the I_{M2} limits for δ = 0.3 – 0.5 – 0.7

Table 5.

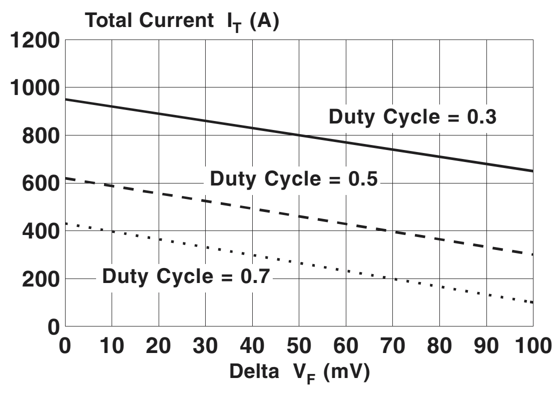
δ	I_{M2} [A]
0.3	274
0.5	212
0.7	179

c) Results

These two tables show that the I_M current is imposed by thermal considerations ($I_{M1} < I_{M2}$).

Using formulas (5) - (6) - (7) - (8) we can draw the curve as in Figure 5, I_T versus ΔV_F for different duty cycles.

Figure 5. Peak current I_T versus Δ V_F for different duty cycles with 3 BY255 in parallel



IV.2 Example of double rectifiers

In this example we consider a BYW51. The two diodes in the same package are connected in parallel. The current is rectangular with δ = 0.5. The commutation losses are negligible (ρ = 1)

Application data is:

$\rho = 1$

$r_{T\,min} = 0.5m\Omega$

$r_{T\,max} = 0.5m\Omega$

Diode data:

From data sheet of BYW51 we get

$R_{th(j-c)} = 2.5°C/W$

$R_{th(c)} = 0.1°C/W$

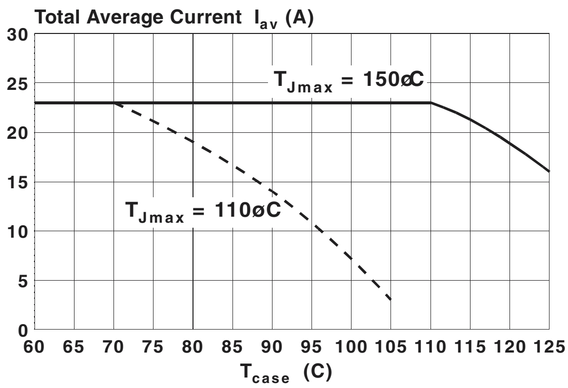
$V_{TO\,max} = 0.66V$(at 100C)

rd max = 14mΩ (at 100C)

Figure 6 shows the total average current versus T_C.

The flat part of the curves corresponds to the $I_{F(RMS)}$ limitation and the other part corresponds to the thermal limitation. The calculation is done with $\Delta V_F = 30mV$.

Figure 6. I_{AV} versus Tc for BYW51 double rectifier in parallel operation ($\delta = 0.5$)

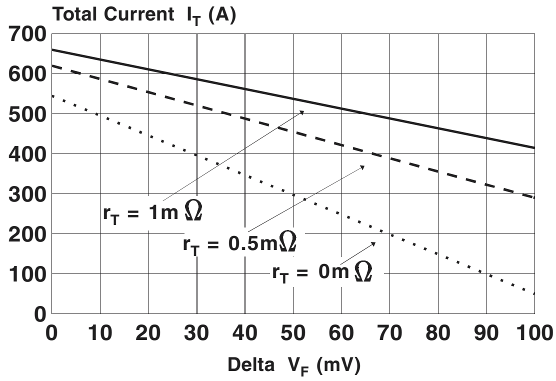


V - INFLUENCE OF THE WIRING RESISTANCE: r_T

When all diodes are connected through the same wiring resistance, the total current is better split into the circuitry.

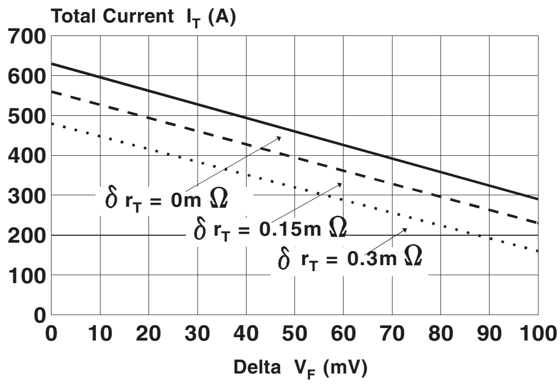
Figure 7 shows the good influence of the wiring resistance when all diodes are connected through the same r_T (Same conditions as BYV255 example, with $\delta = 0.5$)

Figure 7. It versus Δ V_F for different resistances of connections. (Case of 3 BYV255 with δ = 0.5)



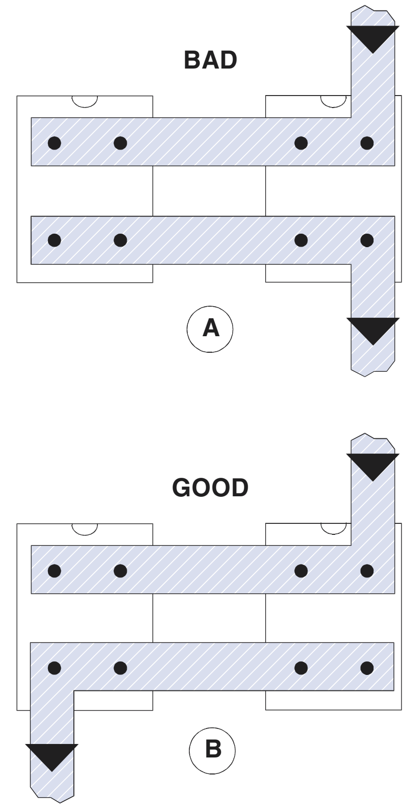
If diodes are connected through very different wiring resistance, the current imbalance can be important. Figure 8 shows r_T influence for different values of r_T tolerance.

Figure 8. It versus Δ V_F for different wiring resistance dispersion. (Case of 3 BYV255 with δ = 0.5)



Particular care must be taken to connect several diodes in parallel. The assembly must be as symmetrical as possible in order to reduce variation of r_T from one rectifier to another (see Figure 9). In the same way it is necessary to mount the packages on a single and efficient heat sink in order to reduce the variation of the case temperatures.

Figure 9. Assembly of 2 ISOTOP packages: (B) configuration provides a better balance of stray resistances



VI - COMMENTS ABOUT DVF IN MANUFACTURING

VI.1 Double rectifiers (Note 1) (2 diodes in the same package): These devices house 2 silicon dice coming from the same wafer and the dispersion is low: 90% of the production offers a ΔV_F lower than 30mV.

VI.2 Rectifiers in separate packages: (or discrete). In this case the dispersion is more important and when a ΔV_F lower than 100mV is needed in the application, a screening is necessary.

Note: 1. BYT261 - BYV255 - BYW51, ... etc

CONCLUSION

Ultra fast rectifiers and power schottky diodes can be easily connected in parallel to provide a reliable high current device if a few simple rules are applied.

This paper shows how we can calculate, for a given application, the maximum value of the forward voltage drop variation (ΔV_F) which guarantees that each diode will operate always below its maximum ratings.

This calculation takes into account the dispersion of the diode parameters (given by the manufacturer) and the electrical and thermal characteristics of the circuit.

Thus, it is possible to know if a special selection in term of V_F is needed or if the number of diodes connected in parallel is large enough to allow the use of standard parts without risk of overcurrent for one of the rectifiers.

ANNEX

A - TRIANGULAR WAVEFORM

So

$$I_{M1} = \frac{-V_{TO}\left(\frac{\delta}{3}\right) + \left[\left(V_{TO}\frac{\delta}{2}\right)^2 + 4 \cdot P_{COND} \cdot rd \cdot \frac{\delta}{3}\right]^{\frac{1}{2}}}{(2/3) \cdot rd \cdot \delta}$$

$$I_{M2} = \frac{I_{F(RMS)}\sqrt{3}}{\delta}$$

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

With

$\Delta V_{F1} = (r_T\ min + rd\ min) \cdot I_M - (r_T\ max + rd\ max) \cdot I_M'$

$\Delta V_{F2} = R_{th(j-c)\ max}\ (\alpha_{TO} + \alpha\ rd \cdot I_M) \cdot P1$

$\Delta V_{F3} = (\alpha_{TO} + \alpha\ rd \cdot I_M) \cdot (T_{C\ max} - T_{C\ min})$

$\Delta V_{F4} = R_{th\ (j-c)\ min} \cdot (\alpha_{TO} + \alpha\ rd \cdot I_M') \cdot P2$

$\Delta = 1 + R_{th\ (j-c)\ min}\ [\alpha_{TO} + rd \cdot I_M'\ ]\ (\delta/2) \cdot I_M'$

$$P_1 = \frac{V_{TO}(\delta/2) I_M + r_{dmin}(\delta/3) I_M^2}{\rho}$$

$$P_2 = \frac{V_{TO}(\delta/2) \cdot I_M' + r_{dmax}(\delta/3) I_M^{2}{}'}{\rho}$$

$$I_M' = \frac{I_T - I_M}{n - 1}$$

B - SINUSOIDAL WAVEFORM

$$I_{M1} = \frac{-2V_{TO}\left(\frac{\delta}{\pi}\right) + \left[\left(2V_{TO}\frac{\delta}{\pi}\right)^2 + 2 \cdot P_{COND} \cdot rd \cdot \delta\right]^{\frac{1}{2}}}{rd \cdot \delta}$$

$$I_{M2} = \frac{I_{F(RMS)}\sqrt{2}}{\delta}$$

$$\Delta V_F < \frac{\Delta V_{F1} + \Delta V_{F2} + \Delta V_{F3} - \Delta V_{F4}}{\Delta}$$

With

$\Delta V_{F1} = (r_T\ min + rd\ min) \cdot I_M - (r_T\ max + rd\ max) \cdot I_M'$

$\Delta V_{F2} = R_{th(j-c)\ max}\ (\alpha_{TO} + \alpha\ rd \cdot I_M) \cdot P1$

$\Delta V_{F3} = (\alpha_{TO} + \alpha\ rd \cdot I_M) \cdot (T_{C\ max} - T_{C\ min})$

$\Delta V_{F4} = R_{th\ (j-c)\ min} \cdot (\alpha_{TO} + \alpha\ rd \cdot I_M') \cdot P2$

$\Delta = 1 + R_{th\ (j-c)\ min}\ [\alpha_{TO} + rd \cdot I_M'\ ]\ (\delta/\pi) \cdot I_M'$

$$P_1 = \frac{2V_{TO}(\delta/\pi)I_M + r_{dmin}(\delta/3)I_M^2}{\rho}$$

$$P_2 = \frac{V_{TO}(\delta/\pi) \cdot I_M' + r_{dmax}(\delta/3)I_M^{2}{}'}{\rho}$$

$$I_M' = \frac{I_T - I_M}{n - 1}$$

REVISION HISTORY

Table 6. Revision History

Date	Revision	Description of Changes
January-1993	1	First Issue
7-Jun-2004	2	Stylesheet update. No content change.