SERIES OPERATION OF FAST RECTIFIERS

B. Rivet

The use of several rectifiers connected in series is necessary to obtain voltage ratings beyond the capabilities of single diodes and also when some special requirement, such as very low switching losses, oblige to implement several low voltage ultra fast diodes.

Rectifiers connected in series tend to share unequally the voltage across the string in blocking conditions because of the variations in reverse characteristics : leakage currents and turn off switching parameters.

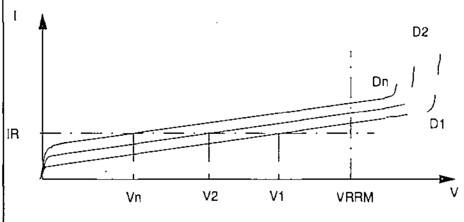
To ensure that each diode operates within its voltage rating it is generally necessary to add a voltage sharing network.

This paper gives the rules of calculation of this auxiliary network and shows how this circuit could be optimized : reduction of power dissipation and cost.

I - STEADY STATE VOLTAGE SHARING :

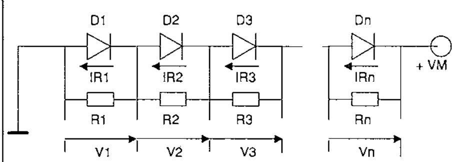
The difference in blocking characteristics results in unequal steady state voltage (fig.1).

Figure 1 : Dispersion of diodes reverse characteristics. The reverse current through the string D1, D2, ...Dn is I_R and the voltages across the diodes are respectively V1, V2; ...Vn.



In order to equlize the voltage, a resistor is connected across each diode (Fig.2).

Figure 2 : Use of shunt resistors for steady state voltage sharing.



1) Calculation of sharing resistors :

The calculation of these resistances is based on the worst case situation.

The maximum unbalance in blocking voltage when n diodes are connected in series occurs when (n-1) diodes have the maximum leakage current and one diode D1 has the lowest possible leakage current.

In this case D1 will support the highest voltage V1 and this tendency is aggravated by the assumption that the corresponding resistor R1 is at the upper limit of its tolerance (a), while all the others are at the lowest limit so,

$$R1 = R(1+a)$$

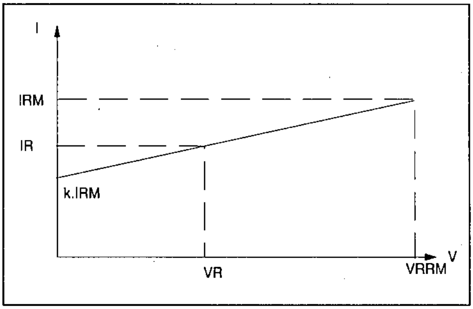
$$R2 = R3 = ...Rn = R$$

In order to calculate the current in the string we approximate the reverse characteristic with a straight line. We define the slope by the coefficient k according to fig.3.

Figure 3 : Reverse characteristic modelisation of a fast rectifier.

$$I_R = I_{RM}(T_j).[k+\frac{V_R(1-k)}{V_{RRM}}]$$

With k = 0.8



So the leakage current I_{RM} of diodes D2 ... Dn under the blocking voltage V2 ... Vn is :

$$I_{R2} = I_{R3} = ...I_{Rn} = I_{RM}\,[k+\frac{V_n\,(1-k)}{V_{RRM}}]$$

where IRM is the maximum leakage current at VRRM (maximum voltage specified for this diode), and at the operating junction temperature. For D1 the maximum reverse current at V_{RRM} is :

$$I_{RM}-\Delta I_R$$

In these conditions the leakage current of diode D1 is :

$$I_{R1} = (I_{RM}-\Delta I_R)\,(k+\frac{V_1(1-k)}{V_{RRM}})$$

Taking into account all these parameters, the voltage V1 across the diode D1 is given by the relation :

$$V_1=\frac{V_M(1+a)(V_{RRM}+(1-k)I_{RM}R)+k(n-1)(1+a)\Delta I_R\,R\,V_{RRM}}{R\,I_{RM}\,n(1-k)(1+a)+V_{RRM}(n+a)-R\Delta I_R(1-k)(1+a)(n-1)} \quad (1)$$

The resistance R must be choosen to limit the voltage V1 under the maximum value V_{RRM} specified for this rectifier. Thus :

$$R<\frac{V_{RRM}(V_{RRM}(n+a)-V_M(1+a))}{\Delta I_R\,V_{RRM}(1+a)(n-1)-I_{RM}(1-k)(1+a)(nV_{RRM}-V_M)} \quad (2)$$

For the to-day fast rectifiers we can use k=0.8

2) I_{RM} evaluation

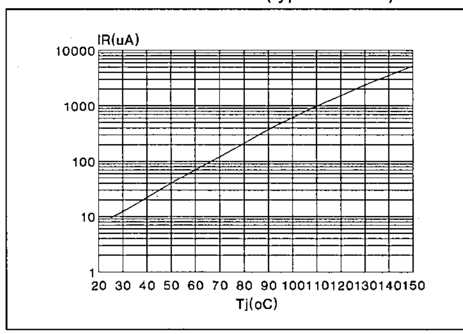
I_{RM} is the maximum leakage current at the maximum reverse voltage V_{RRM}. This current depends on the junction temperature (Fig.4).

Generally in the data sheet the manufacturer specifies a maximum value I_{RM} at V_{RRM} at Tj=100°C.

When we know the operating junction temperature (Tj) it is possible to calculate I_{RM} by using the following relation :

$$I_{RM}(T_j) = I_{RM}(100°C)\exp[-0.054(100-T_j)]$$

Figure 4 : Reverse leakage current versus junction temperature.
Example :
BYT 261-1000 (typical value)



3) Δ I_R estimation

In fact ΔI_R is the sum ΔI_{R1} and ΔI_{R2}

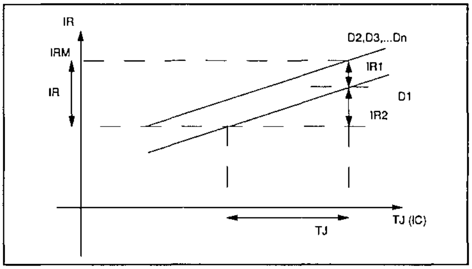
- ΔI_{R1} is due to the leakage current dispersion of the rectifiers in the same conditions of voltage and temperature.
For the fast rectifiers to day available on the market the dispersion of the reverse current at $V_R = V_{RRM}$ and Tj = 100°C is about :

$$\Delta I_{R1} = 0.6\,I_{RM}$$

This dispersion varies from one batch to another.

- ΔI_{R2} is due to the difference between the junction temperatures of each devie (ΔTj).

Figure 5 : The variation ΔI_R is the dispersion of I_R at max operation junction temperature (ΔI_{R1}) plus the variation due to Tj (ΔI_{R2})



The junction temperature is given by the thermal resistance junction to ambient Rth (j-a) and the power dissipation due to the conduction losses (PC) and the switching losses (PS).

PC is linked to the forward voltage (V_F) and PS is linked to the reverse recovery charge (Q_{RR}). So the variation of the junction temperature is :

$$\Delta Tj = \Delta Rth\,(PC+PS) + Rth\,(\frac{\Delta V_F}{V_F}PC + \frac{\Delta Q_{RR}}{Q_{RR}}PS)$$

Where ΔV_F is the dispersion of the forward voltage and Q_{RR} the dispersion of the reverse recovery charge.

For series operation, it is recommended to use pieces coming from the same lot, so the dispersion on the parameters V_F, Q_{RR} and Rth is minimized;

In most cases the evaluation of ΔTj is difficult but, from experience, it is generally lower than 10°C.

We propose to take a safety margin and to use :

$$\Delta I_R = 0.85\ I_{RM}$$

4) Simplified formula

The relation (2) is often used by using the following approximations

k = 1 : supposing the reverse current I_{RM} constant, whatever the blocking voltage across the diode.

a = 0 : Neglecting the effect of the tolerance of resistors. thus :

$$R < \frac{n\,V_{RRM} - V_M}{(n-1)\Delta\,I_R}$$

As for the ΔI_R the worst case is taken into account.

$\Delta I_R = I_R$ with $I_R = I_R$ max at Tj max specified (100°C)

$$R < \frac{n\,V_{RRM} - V_M}{(n-1)\,I_R}$$

This formula is "pessimistic" and induces a low resistance and then a high power dissipation.

5) Example

- Given
Maximum blocking voltage : V_M = 2500V
Part number used : BYT12-PI1000
Power dissipation per diode : P = 7W
Case temperature : Tcase = 52°C

- Rectifier specification :
V_{RRM} = 1000V
I_R (Max at Tj=100°C) = 2.5mA
Rth j-c = 4°C/W

- Problem :

Calculation of sharing resistors for 3 diodes in series.

- Solutions :

a) Simplified method :

$$R < \frac{n\,V_{RRM} - V_M}{(n-1)\,I_R}$$

With n = 3
V_{RRM} = 1000V
V_M = 2500V
I_R = 2.5mA

Thus Rmin = 100 kOhms

Power dissipation per resistor : 3.45 W ! (with duty cycle δ = .5)

b) Calculation with relation (2) :

$$R < \frac{V_{RRM}\,(V_{RRM}\,(n+a) - V_M\,(1+a))}{\Delta I_R\,V_{RRM}\,(1+a)(n-1) - I_{RM}\,(1-k)(1+a)(nV_{RRM} - V_M)}$$

General data for fast rectifiers :

$$\Delta I_R = 0.85\ I_{RM}$$
$$k = 0.8$$

Intermediate calculations :

Tj = P.Rth j-c + Tcase = 80°C

I_{RM} = I_{RM}(80°C)
= I_{RM}(100°C) exp[-0.0054(100-80)]
=0.85mA

ΔI_{RM} = 0.72mA

Assuming we use resistors with 5% of tolerance, then a = .10
Let : Rmin = 220 kOhms

Power dissipation per resistor=1.58W(with δ=.5)

6) Question : is it possible to remove the sharing resistors ?

With the relation (1) we can find the value of V1 when the value of R tends to infinite. Then we calculate the condition to have

$$V1 < V_{RRM}$$

Solving we find

$$\frac{\Delta I_R}{I_{RM}} < \frac{(1-k)\,(n\,V_{RRM} - V_M)}{V_{RRM}\,(n-1)}$$

In the previous example this condition should be

$$\frac{\Delta I_R}{I_{RM}} = 5\%$$

If is obvious that this condition is generally very difficult to meet without hard selection.

II - TRANSIENT VOLTAGE SHARING

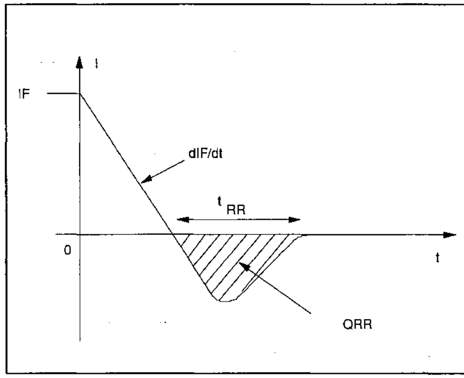
1) The problem

When a diode is switched from the forward conduction to the reverse blocking state, a reverse current flows through the device during the reverse recovery time trr.

After this delay all the charges (minority carriers) stored in the junction are eliminated and the diode turns off. The time integral of the reverse recovery current is called reverse recovery charge (Q_{RR}).

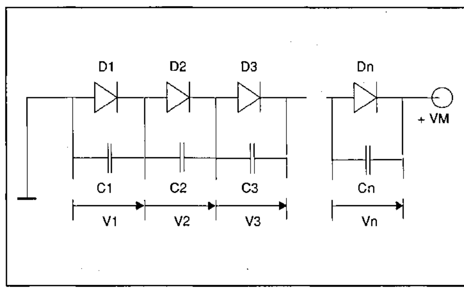
Fig.6 defines the reverse recovery parameters. When a string of n diodes in series switches off, the diode which has the lowest recovery charge turns off the first and supports an important proportion of the total voltage VM and its maximum reverse voltage V_{RRM} could be reached or exceeded.

Figure 6 : Reverse recovery current waveform.



Voltage sharing during the reverse recovery phase is achieved by using a shunt capacitors string connected across the diodes (Fig.7).

Figure 7 : Use of shunt capacitors for transient voltage sharing.



2) Calculation of sharing capacitors

The calculation of capacitance C is also based on the worst case situation.

We assume that (n-1) diodes D2, D3 ... Dn with a reverse recovery charge $Q_{RR} + \Delta Q_{RR}$, and one diode D1 with lowest value Q_{RR}.

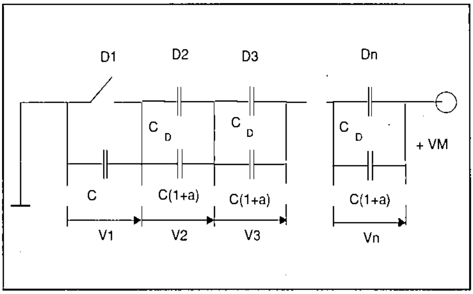
We suppose also that the corresponding capacitor C1 is at the lowest limit of tolerance (a) while the others are at the upper limit
so : C1 = C
C2 = C3 = ... = Cn = C(1+a)
When all the stored charges of diode D1 have been evacuated, the charge remaining in the other diodes is ΔQ_{RR}.
At this time the voltage across D1 is V1 and the voltage across the other diodes of the string is :

$$V_2 = V_3 = \ldots V_n = \frac{V_M - V_1}{(n-1)}$$

So these diodes can be assimilated to a capacitor

$$C_D = \frac{\Delta Q_{RR}}{V_n} = \frac{\Delta Q_{RR}\,(n-1)}{V_M - V_1}$$

Figure 8 : Equivalent diagram when D1 swtches off. Diodes D2, D3, ...Dn are equivalent to a capacitor CD = ΔQRR(n-1) / (VM-V1)



In these conditions the voltage across D1 is :

$$V_1 = \frac{\Delta Q_{RR}\,(n-1) + C\,V_M\,(1+a)}{C\,(n+a)}$$

In order to limit the voltage across D1 under the specified value V_{RRM} we calculate C by solving thus : $V1 < V_{RRM}$

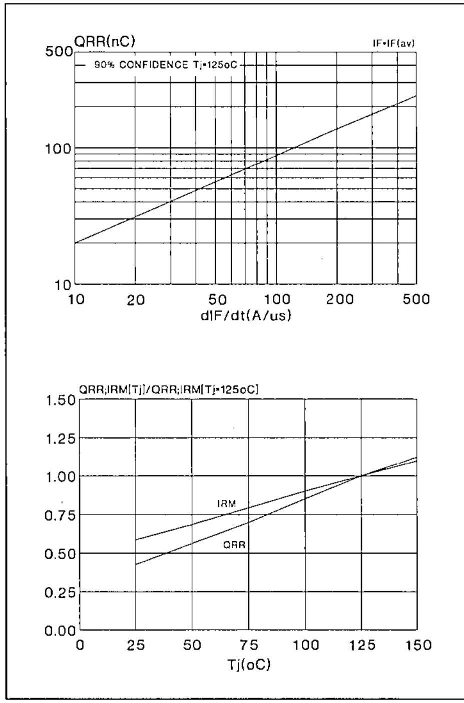
$$C > \frac{(n-1)\Delta Q_{RR}}{(n+a)V_{RRM} - V_M\,(1+a)}$$

<u>3) Q_{RR} and ΔQ_{RR} consideration</u>

For a given diode the reverse recovery charge QRR is function of the circuit commutation conditions such as the magnitude of forward current (I_F), the rate of decay of this current (dIF/dt) and the junction temperature.

Typical values of QRR are given in the data sheet of each part number (Fig.9).

Figure 9 : Example of reverse recovery charge specification. (case of BYW 51)



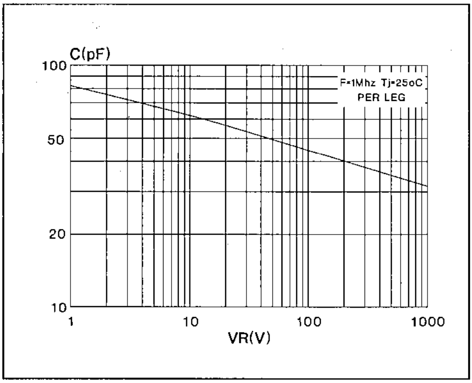
For fast rectifiers coming from the same lot the dispersion of this parameter is low and we can use, with a good safety margin :

$$\Delta Q_{RR} = .30\ Q_{RR}$$

<u>4) Is it possible to remove the equalizing capacitor ?</u>

In blocking state diodes have a junction capacitance. For a given diode this capacitance decreases with an increase in the applied reverse voltage according to Fig.10.

Figure 10 : Junction capacitance versus reverse voltage
(example : BYT 261-1000)



When D1 has evacuated all its stored charge it is equivalent to a capacitor CJ1 and the other diodes D2, D3 ... Dn are equivalent to a capacitor which is the sum of the junction capacitance CJ2, CJ3 ... CJn and the capacitance

$$C_D = \frac{\Delta Q_{RR}\,(n-1)}{V_M - V_1}$$

Figure 11 : Equivalent diagram when D1 switches off in case of low QRR : The junction capacitances CJ1, CJ2; ....CJn, play the role of sharing capacitors.

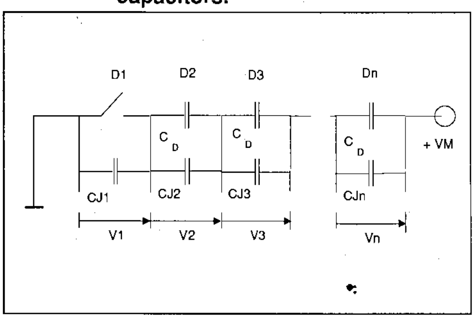


Fig.11 shows the equivalent circuit

In the worst case CJ1 is the junction capacitor of D1 at the maximum voltage V_{RRM}
Putting

$$CJ1 = CJ \text{ at } V_{RRM}$$

$$C_{J2} = C_{J3} \ldots C_{Jn} = C_J \;\; at \;\; \frac{V_M - V_{RRM}}{n-1}$$

We have

$$V_1 = \frac{\Delta Q_{RR}\,(n-1) + V_M\, C_{Jn}}{C_{J1}\,(n+1) + C_{Jn}}$$

Auxiliary capacitors are not necessary if

$$V1 < V_{RRM}$$

$$\text{or} \quad \Delta Q_{RR} < \frac{V_{RRM}\,[C_{J1}\,(n-1) + C_{Jn}] - V_M\, C_{Jn}}{n-1}$$

Generally, the value of the junction capacitance at the operating voltage is very close to the value at V_{RRM} (CJ1) so we can write

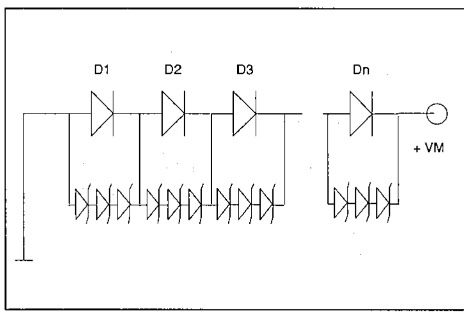
$$\Delta Q_{RR} < \frac{C_{J1}\,(n\,V_{RRM} - V_M)}{n-1}$$

This condition can be met by using very fast rectifiers in applications where the dIF/dt is low (like in some resonant converters or flyback converters) and consequently low Q_{RR}.

III - EQUALIZATION BY TRANSIL DIODES

TRANSIL are avalanche diodes designed for operation in breakdown characteristic and they are used as clamping device in a wide field of applications. To limit the voltage across the rectifiers of a string below the maximum value, TRANSIL diodes can be used according to diagram Fig.12.

Figure 12 : Voltage sharing by TRANSIL diodes.



TRANSIL operates as a voltage limiter at steady state, during the switching phase, and also in case of external voltage transients.

1) Steady state

In blocking condition the TRANSILS connected across the diode D1 (Which has the lowest reverse current) operate in the breakdown characteristic. The current through these TRANSILS is I_R and the power dissipation is :

$$V_{BR}.\Delta I_R.\delta \quad (\delta = \text{duty cycle})$$

Where V_{BR} is the maximum breakdown voltage of TRANSILS. In general this extra power dissipation is lower than in the case of sharing by resistors and TRANSILS in axial packages can be used.

2) Switching phase

When the fastest diodes of the string switches off the TRANSILS across it operate in breakdown characteristic and the reverse recovery current of the other diodes flows through these TRANSILS. The charge remaining in the string at this moment is :

$$(n\text{-}1)\ \Delta Q_{RR}$$

and we can estimate the maximum energy in the TRANSILS with

$$E < 1/2(n\text{-}1)\ .\ \Delta Q_{RR}\ .\ V_{BR}$$

This relation does not take into account the losses due to the capacitive current through the string.

3) Example

GIVEN :
Use of a 3-BYT12-PI1000 for $V_M = 2500V$
Operating conditions :
$Tj = 100°C$
$di/dt = 20A/\mu s$
$F = 25$ kHz
$\delta = .5$

RECTIFIER SPECIFICATION :
$V_{RRM} = 1000V$
I_{RM} at $V_{RRM} = 2.5mA$ at $Tj = 100°C$
$Q_{RR} = .5\mu C$ (in operating conditions)

PROBLEM :
3 TRANSILS diodes are connected in series across each rectifier. What is the suitable part number ?

DESIGN STEPS :

- V_{BR} calculation :

$$V_{BR}\min > \frac{2500}{3x3} = 277V$$

$$V_{BR}\max < \frac{1000}{3} = 333V$$

- Power dissipation in steady state :
$P1 < I_R\ .\ V_{BR}\max\ .\delta$

with $I_R = .85 \times 2.5 \approx 2mA$
$V_{BR}\max = 330V$
$P1 < 330mW$

- Power dissipation in switching phase :
$P2 = E.F < 1/2\ (n\text{-}1)\ Q_{RR}\ .\ V_{BR}\max\ .\ F$
with $\Delta Q_{RR} = .5 \times .3 = .15\mu C$
$F = 25$ kHz and $n = 3$
then $P2 < 1.2W$

- Max total power dissipation P1 + P2 1.530 W

Solution : 1.5 KE series can be used (1.5KE300CP)

CONCLUSION

When using several fast rectifiers in series it is necessary to make sure that any diode will not be subjected to continuous or transient voltages in excess of their ratings.
In most cases, this is achieved by using sharing networks across each diode. It is important to optimize this circuit in order to reduce power consumption and to save space.
Parallel resistor can be optimized by using the modelisation of the fast recovery diodes reverse characteristic proposed in this paper. Then, thanks to a good knowledge of the reverse current and its variation in the operating conditions (possibly by measurement and selection) it is possible to implement a resistor with a value as high as possible.
Parallel capacitors also have to be reduced as much as possible with the knowledge the switching characteristics of the string in the actual conditions. The reverse recovery charge (Q_{RR}) is not always accessible with the datasheet and a measurement is often necessary.
In certain applications using ultra fast diodes of the same lot, where the Q_{RR}, and therefore the ΔQ_{RR} is very low, the sharing capacitor can be reduced to zero.
In systems where there is a risk of external overvoltages or where there are transient states not well known, TRANSIL diodes are a solution to the sharing voltage problem in sofar as the total power dissipation of the TRANSIL string remains compatible with the existing packages for these devices.

References :
1. B.M. BIRD and K.G. KING :
"An introduction to Power Electronics"
2. J.M. PETER - SGS-THOMSON Microelectronics : "Analysis and optimisation of high frequency Power rectification"