AN1542
APPLICATION NOTE

THE THERMAL RUNAWAY LAW IN SCHOTTKY USED IN OR-ing APPLICATION

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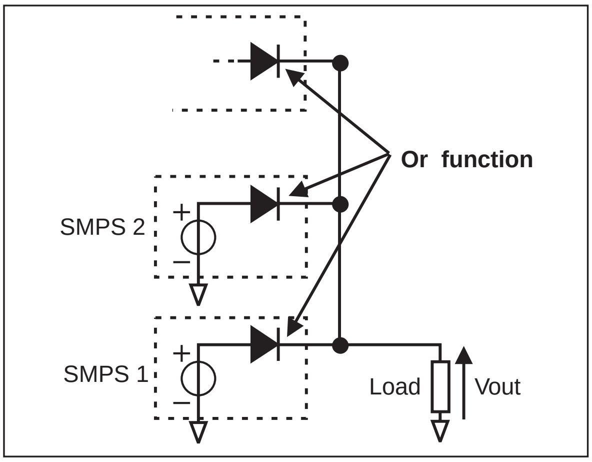
INTRODUCTION

Nowadays, some critical applications require very high available power supplies. Typically, these applications are servers or telecommunication base stations.

In such systems, the power supplies are built with several power supplies connected in parallel in order to be fault tolerant. Thanks to redundancy, the total failure rate stays very low and the availability can exceed 99.99%.

The connection of several power supplies needs the OR function, commonly built with diodes, to tolerate faults in the SMPS.

Fig. 1: Supplies connected in parallel



1. OR-ing FUNCTION PRESENTATION

The OR-ing function is commonly built with diodes.

The diode has to let the current pass through when the associated SMPS is working in normal operation. When a SMPS fails in short circuit, the diode has to block reverse voltage in order to maintain output voltage on the load.

The purpose of the OR function is to prevent fault propagation between supplies connected in parallel.

2. TYPICAL PREFERRED DEVICE

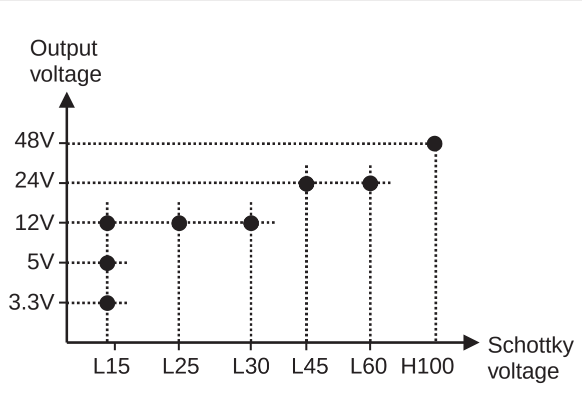
In normal operation the diode is conducting in forward mode. So, the first requirement of the component, irrespective of the maximum repetitive reverse voltage (V_{RRM}) and the current rating ($I_{F(AV)}$), is the forward voltage drop (V_F).

The lower the forward voltage drop, the lower the forward losses in the diode, and the better the SMPS efficiency.

For this reason, Power Schottky diodes are commonly used in OR-ing application. The L series (for example STPS60L30CW) are optimized to provide very low forward voltage drop: $V_{F\ typ} = 0.33V$ (30A @125°C per diode).

The following graph presents the typical Schottky used in OR-ing application on common voltage outputs:

Fig. 2: Typical Schottky used as OR-ing function on common voltage outputs



Using Schottky diodes provides very low forward losses. But the main important technology trade off for Schottky is between forward voltage drop and leakage current:

The optimization of forward voltage drop is inevitably made to the detriment of leakage current.

High leakage current gives rise to the thermal runaway problem.

3. THERMAL RUNAWAY RISK

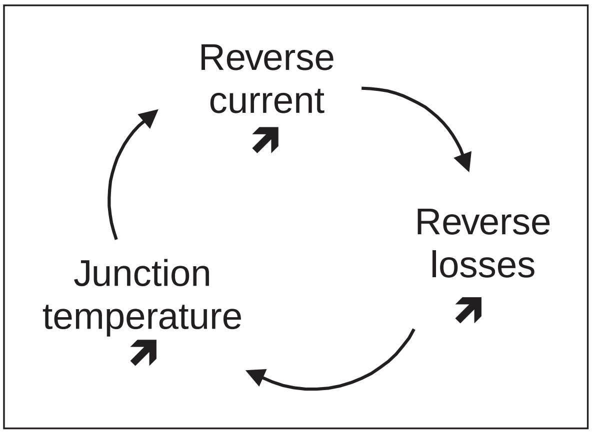
The risk of thermal runaway comes from the fact that leakage current increases quickly with the junction temperature.

3.1. Problems

Using a Schottky as OR-ing function provides a very low forward voltage drop. But when the diode is blocking because its associated supply has a fault in short circuit mode, the diode has to operate in reverse mode with high junction temperature (due to preceding forward losses) and so with relatively high reverse current.

This high reverse current can generate high reverse losses, and so increase junction temperature, and so reverse current as well… This is the thermal runaway phenomenon.

Fig. 3: Thermal runaway diagram



The problem is to quantify the risk of thermal runaway in order to prevent it.

3.2. Result in classical cases

In the classical simple case where both the following assumptions are made:

- Constant thermal resistance system
- OR-ing diode on its own heatsink

The reverse losses in the Schottky diode, due to associated SMPS short circuit failure, is a monotonous function of the time. Consequently the thermal runaway diagram of fig. 3 is covered in only one rotation- sense.

To determine if the Power Schottky will goes into thermal runaway mode consists of finding the elements that will determine the rotation sense of fig. 3.

During the forward mode, the forward current (I_F) defines the junction temperature (T_j) (linked to forward voltage (V_F), device thermal resistance $R_{th(j-a)}$) and ambient temperature (T_{amb}):

$$T_j = T_{amb} + R_{th(j-a)}(I_F x V_{F@ I_{fwd}})$$

During the fast mode change of the diode (from the forward mode to the reverse one, the change is fast in comparison to device thermal constant), the junction temperature due to the preceding forward mode stay continuous (c.f. fig. 5) and will determine the leakage current (I_{rev}) (linked to the reverse voltage V_{rev}):

$$I_{rev}\left(T_j;V_{rev}\right) = I_{rev}\left(100°C;V_{rev}\right) \times e^{c\left(T_j - 100°C\right)}$$

$c \approx 0.055°C^{-1}$ (thermal constant)

This reverse current will determine the new junction temperature trend (linked to reverse voltage and device thermal resistance). This variation trend between the initial junction temperature (due to forward mode) and the new one (due to reverse mode) gives the T_j variation and the rotation-sense in fig. 3.

In a constant thermal resistance system, the thermal stability can be determined by comparing forward losses (P_{fwd}) in the power Schottky just before the SMPS failure (t_0-δt) and the reverse losses (P_{rev}) occurring just after (t_0+δt) the eventual SMPS short-circuited fault.

The stability can be guaranteed if $P_{fwd} > P_{rev}$ @t_0

Fig. 4: Typical loss variation in the OR-ing before and after the SMPS failure

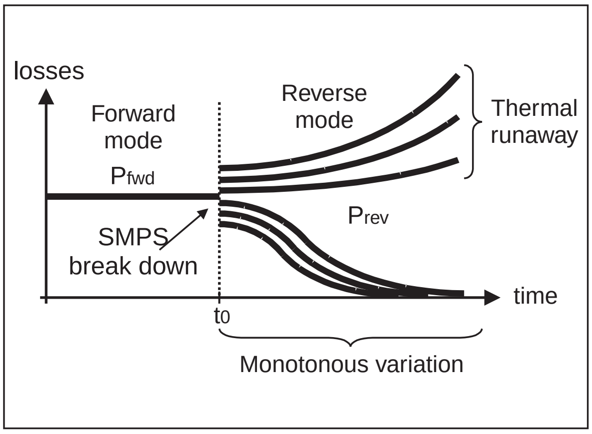
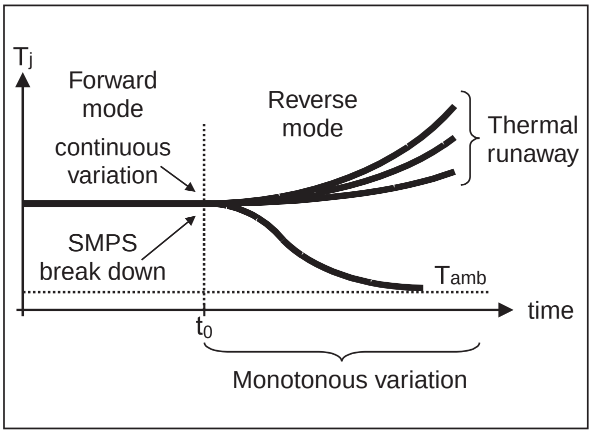


Fig. 5: Typical junction temperature variation in the OR-ing before and after the SMPS failure

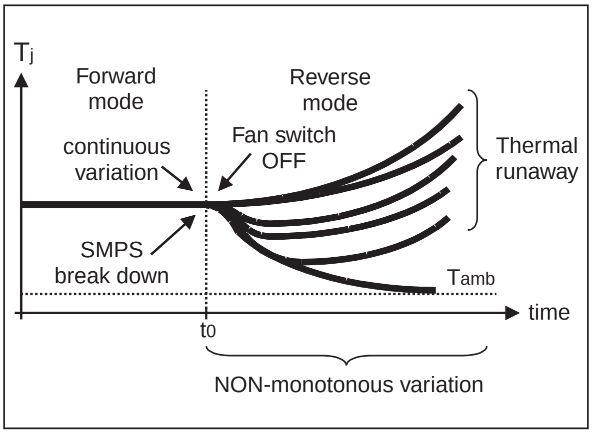


3.3. Results in more complicated cases

More complicated cases, where the assumptions of §3.2 do not exist, can be considered.
For example:

- OR-ing diode not on its own heatsink.
  The OR-ing diode can be mounted on common heatsink with other dissipative devices. In this case, the junction temperature of the OR-ing diode can be influenced by the other devices, thanks to coupling thermal resistance.
- Non constant thermal resistance system:
  The convection can be forced by a fan connected to the Anode side of the OR-ing diode. In case of SMPS failure, the fan will stop and the $R_{th(j-a)}$ will increase. In this case, the junction temperature variation will not be monotonous.

Fig. 6: Example of junction temperature variation in non-constant thermal resistance system

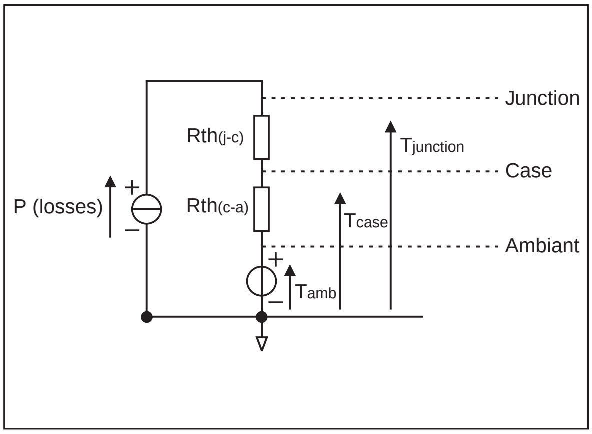


In these more complicated cases, device thermal behavior can be simulated with tools like PSPICE.

The following analogies have to be used:

Thermal:	**Electrical:**
Temperature	Voltage
Power	Current
Resistance	Resistance

Fig. 7: Thermal / electric analogy for simulation



This analogy can be use to analyze any complex thermal problem.

4. FROM THERMAL RUNAWAY TO PRODUCT OPTIMIZATION

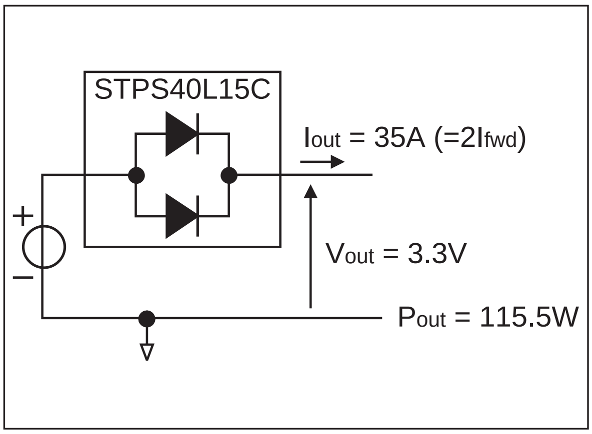
STMicroelectronics has developed a Schottky family dedicated to the OR-ing function. This “L” family demonstrates very low forward voltage in order to reduce conduction losses. Consequently, the leakage current is relatively high.

For example, the “L15" family (V_{RRM}=15V) is optimized for 3.3V, 5V and eventually 12V output as OR-ing diode.

Due to the specific thermal runaway law of the Schottky in OR-ing application, we can optimize the device choice in order to improve the SMPS efficiency, while keeping the risk of thermal runaway under control.

For example, let’s take a 3.3V 35A output, with a STPS40L15C as OR-ing diode. The two diodes have to be considered like connected in parallel:

Fig. 8: SMPS output synopsis



In the forward mode, the forward losses can be calculated as:

$$\begin{aligned} P_{fwd} &= 2\times\left(V_{T0}\cdot I_{fwd} + R_d\cdot I_{fwd}^2\right) \\ &= 2\times\left(0.18 I_{fwd} + 8.010^{-3} I_{fwd}^2\right) \quad (datasheet) \\ &= 112W \end{aligned}$$

Theses losses decrease the global SMPS efficiency about 9.7%.

The risk of thermal runaway can be evaluated by calculating the maximum junction temperature that **must not be reached** in forward mode to avoid reverse losses being higher than forward losses, thus avoiding thermal runaway.

$$\begin{aligned} P_{rev} &= 2\times V_{out}\cdot I_{rev}\left(T_j;3.3V\right) \;(2\ diodes\ in\ parallel) \\ &= 2\times V_{out}\cdot I_{rev}\left(100^\circ C\ ;\ 3.3V\right)\times e^{c\left(Tj-100^\circ C\right)} \end{aligned}$$

$$c \approx 0.055^\circ C^{-1} \quad \left(thermal\ constant\right)$$

$$I_{rev}\left(100^\circ C\ ;\ 3.3V\right) \;(per\ diode,\ datasheet)$$

Note that it is very important to use maximum reverse current values to evaluate reverse losses. Actually, the worst case must be considered to evaluate junction temperature in order to be sure to avoid thermal runaway.

The limit of the thermal runaway criteria being defined by $P_{fwd} = P_{rev}$, the maximal junction temperature $T_{j\ max}$ corresponds to $P_{rev\ max} = P_{fwd}$:

$$P_{rev\ \max} = 2\times V_{out}\cdot I_{rev}\left(100^\circ C\ ;\ 3.3V\right)\times e^{c\left(T_{j\ \max}-100^\circ C\right)}$$

$$\begin{aligned} T_{j\ \max} &= 100^\circ C + \frac{1}{c} ln\left(\frac{P_{fwd}}{2\times V_{out}\cdot I_{rev}\left(100^\circ C\ ;\ 3.3V\right)}\right) \\ &= 137^\circ C \end{aligned}$$

The maximum junction temperature reachable in forward mode before the risk of thermal runaway occurs is so high, that we can consider a well adapted device. This one will have a lower forward voltage so a highest reverse current.

The same process can be applied to different devices

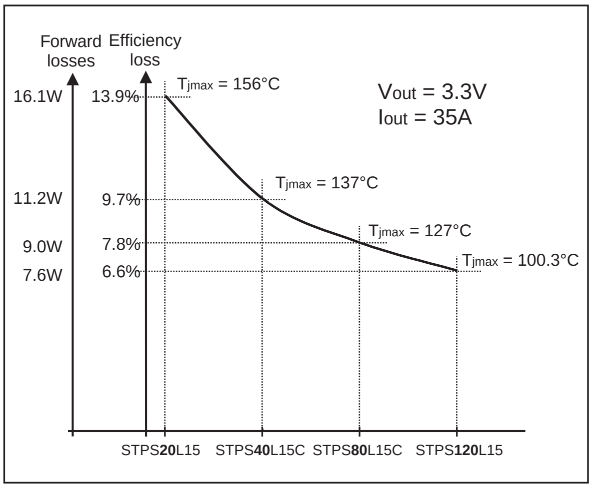
STPS80L15C
Forward losses P_{fwd} = 9.0W
The efficiency loss about 7.8%.
Maximal junction temperature before thermal runaway: T_{jmax} = 127°C

STPS120L15
Forward losses: P_{fwd} = 7.6W
The efficiency loss is about 6.6%
Maximal junction temperature before thermal runaway: T_{jmax} = 100.3°C

STPS20L15 (the 20A average current specified is only indicative value)
Forward losses: P_{fwd} = 16.1W
The efficiency loss is about 13.9%
Maximal junction temperature before thermal runaway: T_{jmax} = 155.9°C

The comparison between the 4 parts considered on the 3.3V 35A output can be summarized on the following graph:

Fig. 9: Comparison between 4 parts, forward losses, efficiency loss and T_{jmax}.



Using the specific thermal runaway law, the SMPS designer can optimize the OR-ing diode choice in order to improve the global efficiency.

The risk of thermal runaway is controlled by limiting the junction temperature during the forward mode below the maximum value evaluated.

CONCLUSION

STMicroelectronics is developing “L” family diodes dedicated to the OR-ing application. This family shows very low forward voltage in order to reduce conduction losses and to improve efficiency: STPSXXL15, STPSXXL25, STPSXXL30, STPSXXL45, and STPSXXL60.

With the very simple law presented, it becomes straightforward to optimize devices choice by evaluating the risk of thermal runway in Schottky used in OR-ing function in SMPS.

This reliable and accurate law allows the optimization of the devices used in order to improve converter efficiency while controlling the risk of thermal runaway risk.

ANNEXE: EVALUATION OF MAXIMUM REVERSE CURRENT FROM DATASHEET

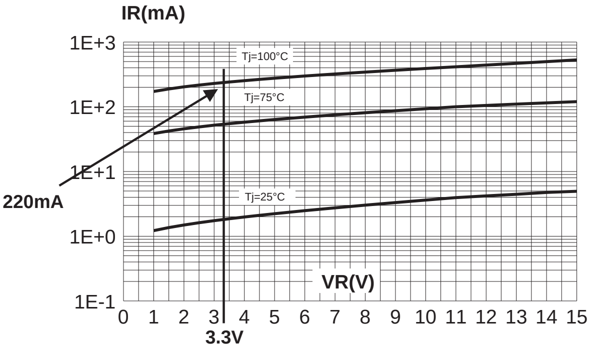
To evaluate the limit before thermal runaway, the maximum value of the reverse current has to be considered. Actually, this parameter is critical for thermal runaway and the worst case must be considered.

To evaluate the maximum reverse current of a power Schottky, take the typical value given in figure. Apply the ratio between typical and maximal value given in the table (in the adapted V_R and T_j field). Finally, use the adapted formula to get the expected junction temperature.

Example: STPS80L15C (twin diode in parallel) under 3.3V @125°C

Figure 5 of the STPS80L15C datasheet gives the typical value of the reverse current @100°C for 3.3V (per diode):

Fig. 5: Reverse leakage current versus reverse voltage applied (typical values, per diode).



$I_{rev\ typ}$ (100°C ; 3.3V) = 220mA

The static electrical characteristics table gives the ratio between typical and maximum values (per diode):

STATIC ELECTRICAL CHARACTERISTICS (per diode).

Symbol	Parameter	Tests conditions		Min.	Typ.	Max.	Unit
I_R *	Reverse leakage current	Tj = 25°C	V_R = 5V			4	mA
		Tj = 100°C			280	400	
		Tj = 25°C	V_R = 12V			11	
		Tj = 100°C			0.44	1.1	A
		Tj = 25°C	V_R = 15V			16	mA
		Tj = 100°C			0.53	1.3	A

Pulse test :* tp = 380 µs, δ < 2%

$$I_{rev\ \max}\left(100^{\circ}C\ ;\ 3.3V\right) = 220 \times \frac{400}{280} = 314mA$$

The following formula allows the calculation of the reverse current in a power Schottky for every junction temperature from a reference value:

$$I_{rev}\left(T_j\ ;\ 3.3V\right) = I_{rev}\left(100^{\circ}C\ ;\ 3.3V\right) \times e^{c\left(Tj-100^{\circ}C\right)}$$
$$\left(c \approx 0.055^{\circ}C^{-1}\ thermal\ cons\tan t\right)$$

$$I_{rev}\left(125^{\circ}C\ ;\ 3.3V\right) = I_{rev}\left(100^{\circ}C\ ;\ 3.3V\right) \times e^{c\left(125-100\right)} = 12A$$

So, the global maximum reverse current value for the two diodes of the STPS80L15C connected in parallel under 3.3V @125°C is:

$$I_{rev\ \max}\left(125^{\circ}C\ ;\ 3.3V\right) = 2 \times 12A \approx 2.4A$$

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