AN604
Application note

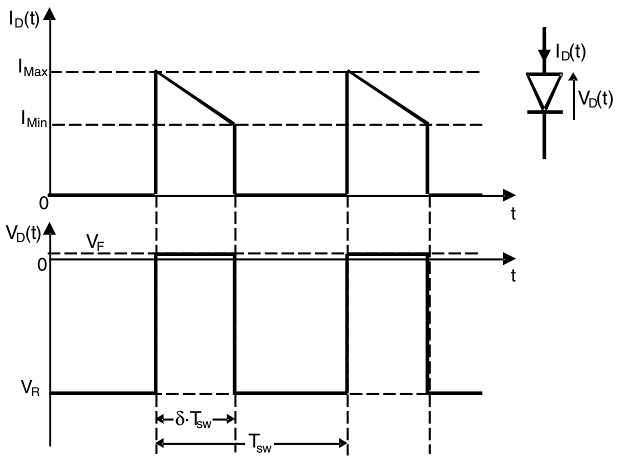
Calculation of conduction losses in a power rectifier

Introduction

This application note explains how to calculate conduction losses in a power diode by taking into account the forward voltage dependence on temperature and the current waveform.

The ideal current and voltage waveforms of an ultrafast diode in a power supply system during a switching cycle are shown in *Figure 1.*

Figure 1. Ideal current and voltage waveforms of a diode in a switch mode power supply



F_{sw}	Switching frequency
T_{sw}	Switching period
δ	Duty cycle
$\delta \cdot T_{sw}$	Duration of diode conduction
I_{max}	Maximum forward current
I_{min}	Minimum forward current
V_F	Forward voltage
V_R	Reverse voltage

The conduction losses in a diode appear when the diode is in forward conduction mode due to the on-state voltage drop (V_F). Most of the time the conduction losses are the main contributor to the total diode power losses and the junction temperature rising. This is the reason why it is important to accurately estimate them.

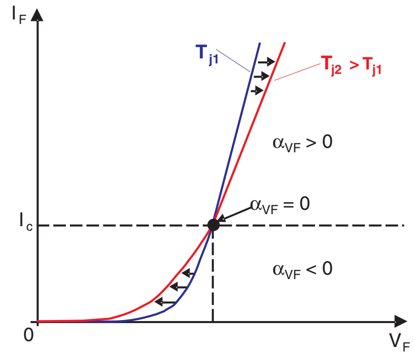
Contents

1 Diode forward characteristics

1.1 Junction temperature dependence

For two different junction temperatures, the current versus forward voltage curves cross at a current level point I_c, depending on the diode technology. When the current is lower than I_c, the temperature coefficient α_{VF} of the forward voltage is negative. When the current is higher, the temperature coefficient becomes positive. This behavior is shown in *Figure 2.* For Schottky and bipolar diodes, I_c is high and the working area corresponds to $\alpha_{VF} < 0$. For SiC and GaN technologies, I_c is low and the α_{VF} can be positive or negative. When of $\alpha_{VF} < 0$, the forward voltage and the conduction losses decrease when the junction temperature increases.

Figure 2. Forward (I_F,V_F) characteristics of a diode



1.2 Diode forward characteristics modeling: $V_{T0}(T_j)$, $R_D(T_j)$

Forward characteristics (I_F and V_F) can be modeled by a straight line defined by a threshold voltage V_{T0}, and a dynamic resistance R_D. V_{T0} and R_D are calculated for 2 forward current levels (I_{F1}, I_{F2}) for a given junction temperature as shown in *Figure 3.* Thus we can write:

Equation 1

$$V_F(I_{F_1}, T_j) = V_{T0}(T_j) + R_D(T_j) \cdot I_{F_1}$$

Equation 2

$$V_F(I_{F_2}, T_j) = V_{T0}(T_j) + R_D(T_j) \cdot I_{F_2}$$

Using Equations *1* and *2*, we obtain $V_{T0}(T_j)$ and $R_D(T_j)$ expressions:

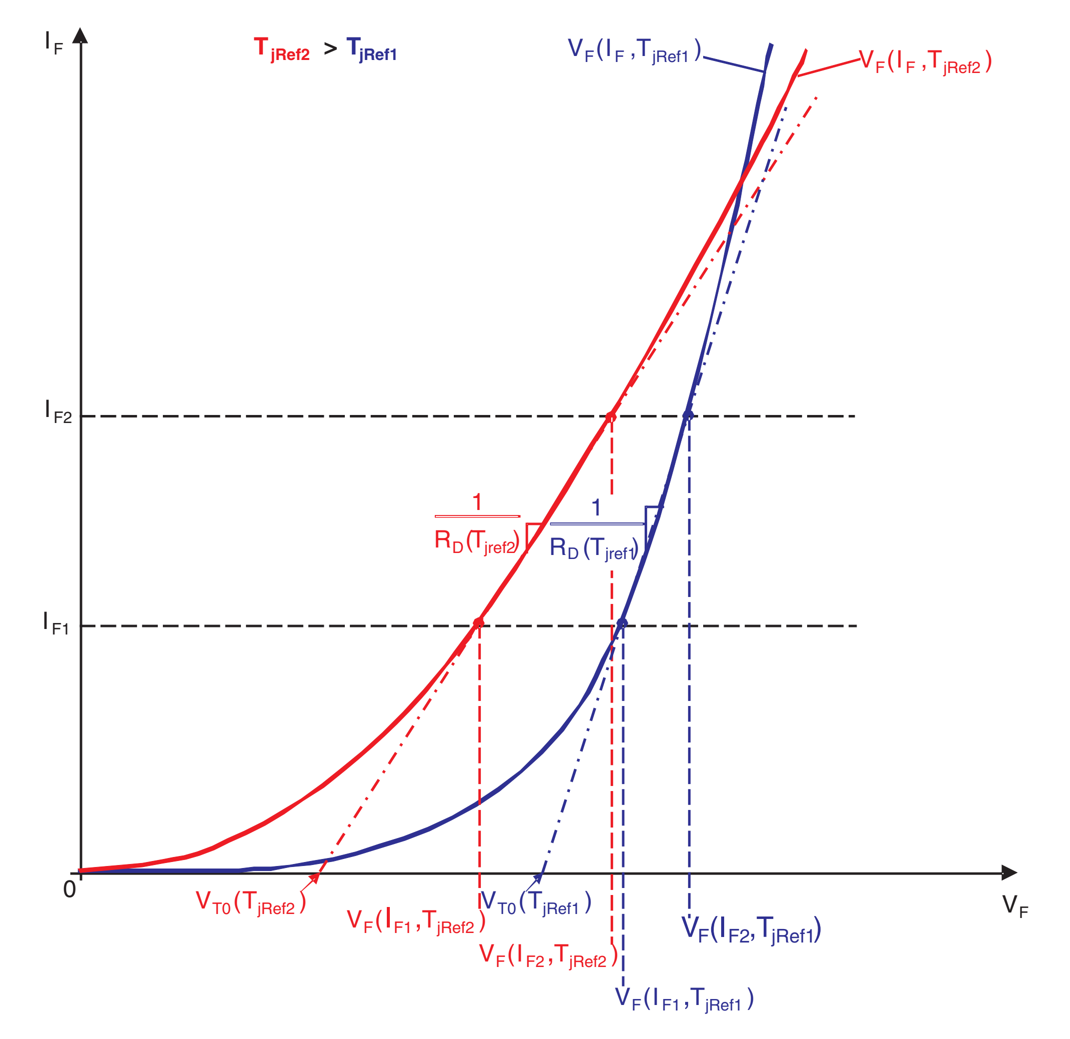
Equation 3

$$R_D(T_j) = \frac{V_F(I_{F_2}, T_j) - V_F(I_{F_1}, T_j)}{I_{F_2} - I_{F_1}}$$

Equation 4

$$V_{T0}(T_j) = \frac{V_F(I_{F_1}, T_j) \cdot I_{F_2} - V_F(I_{F_2}, T_j) \cdot I_{F_1}}{I_{F_2} - I_{F_1}}$$

Figure 3. $V_{T0}(T_j)$ and $R_D(T_j)$ parameters



V_{T0} and R_D are given in each ST diode datasheet. In most cases they are calculated at 125 °C with maximum V_F values for $I_{F1} = I_{F(AV)}$ and $I_{F2} = 2 \cdot I_{F(AV)}$, where $I_{F(AV)}$ is the average forward current rating of the diode. For a quick calculation these values can be used. For more accurate estimation, R_D and V_{T0} must be calculated using the specific application conditions. See the example in *Chapter 3*.

For any junction temperature $V_{T0}(T_j)$, $R_D(T_j)$ and the forward voltage drop $V_F(I_F,T_j)$ can be calculated as follow:

Equation 5

$$V_{T0}(T_j) = V_{T0}(T_{jRef1}) + \alpha_{V_{T0}} \cdot (T_j - T_{jRef1})$$

Equation 6

$$R_D(T_j) = R_D(T_{jRef1}) + \alpha_{R_D} \cdot (T_j - T_{jRef1})$$

Equation 7

$$V_F(I_F, T_j) = V_F(I_F, T_{jRef1}) + (T_j - T_{jRef1}) \cdot (\alpha_{V_{T0}} + \alpha_{R_D} \cdot I_F)$$

Where α_{VTO} and α_{RD} are thermal coefficients calculated from the 2 reference temperatures: T_{jref1} and T_{jref2}. A common choice of T_{jref1} and T_{jref2} is 25 °C and 125 °C. These thermal coefficients are calculated with the following equations:

Equation 8

$$\alpha_{V_{T0}} = \frac{V_{T0}(T_{jref2}) - V_{T0}(T_{jref1})}{T_{jref2} - T_{jref1}}$$

Equation 9

$$\alpha_{R_D} = \frac{R_D(T_{jref2}) - R_D(T_{jref1})}{T_{jref2} - T_{jref1}}$$

Note: $\alpha_{VT0} < 0$ and $\alpha_{RD} > 0$ whatever the diode technology.

2 Conduction losses: basic equations

Conduction losses are the average dissipated power in the diode during the forward conduction phase given in Equation 10:

Equation 10

$$P_{COND}(T_j) = \frac{1}{T_{sw}} \int_0^{T_{sw}} V_F(I_F, T_j) \cdot I_F(t) \cdot dt$$

Equation 10 can also be written as follows:

Equation 11

$$P_{COND}(T_j) = V_{T0}(T_j) \cdot I_{F(av)} + R_D(T_j) \cdot I^2_{F(rms)}$$

Where $I_{F(AV)}$ is the forward average current and $I_{F(RMS)}$ is the forward root mean square current flowing through the diode.

Note: In case of a square waveform, a short formula can be used to calculate conduction losses:

Equation 12

$$P_{COND}(T_j) = V_F(I_F, T_j) \cdot I_{F(AV)} \cdot \delta$$

2.1 Application parameters: average and rms currents

The average and rms currents are different for each application condition. They can be calculated using Equations 12 (average current) and 13 (rms current).

Equation 13

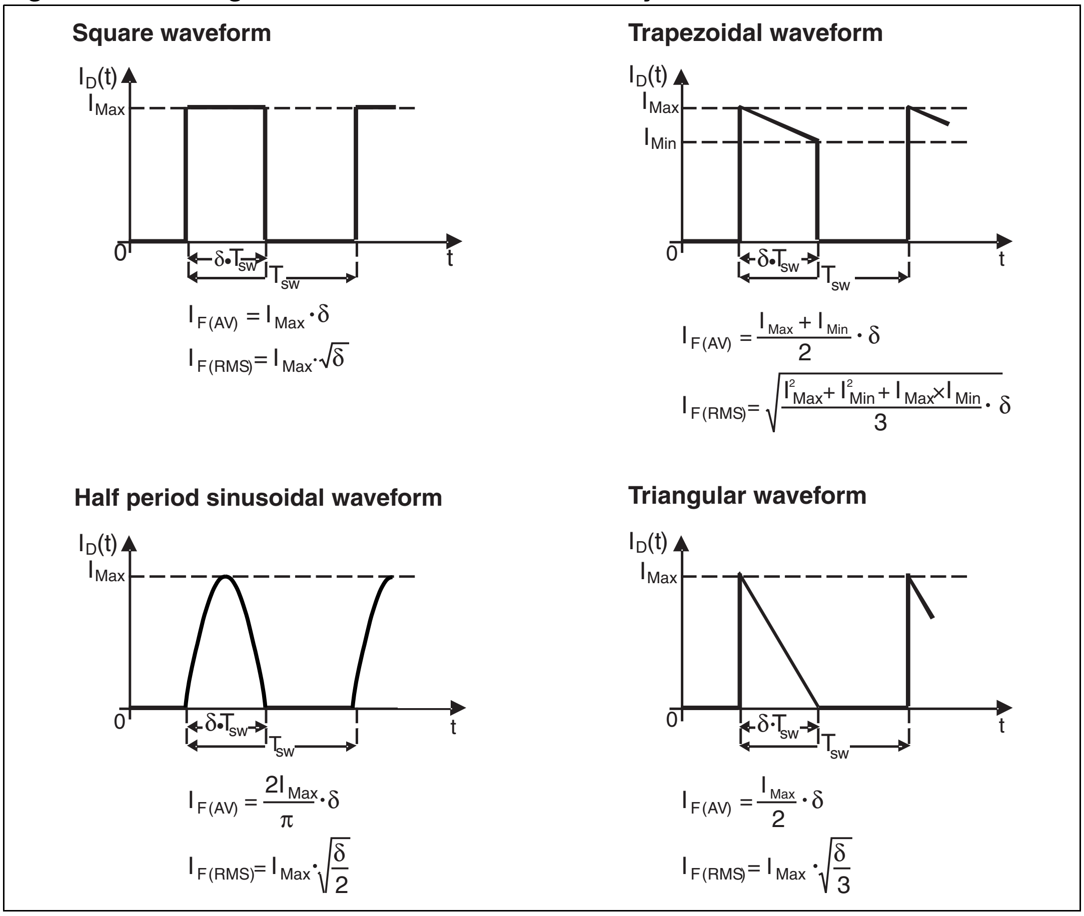
$$I_{F(AV)} = \frac{1}{T_{sw}} \int_0^{T_{sw}} I_F(t) \cdot dt$$

Equation 14

$$I_{F(RMS)} = \sqrt{\frac{1}{T_{sw}} \int_0^{T_{sw}} I_F^2(t) \cdot dt}$$

Figure 4 presents simplified expression of average and rms currents of commonly observed waveforms in a power rectifier. In most cases, these waveforms can be used for a rough estimation.

Figure 4. Average and rms currents of commonly observed waveforms



3 An application example

Let us consider the example of a 90 W notebook adapter. This is a flyback converter (*Figure 5*) working in continuous mode. The output voltage V_{out} is 19 V and the maximum output current is 4.7 A. The rectifier diode is an ST power Schottky STPS30M100S. *Figure 6* shows the ideal waveforms of the diode: I_{Min} = 4 A, I_{Max} = 11.8 A and δ = 0.6.

Let us calculate the maximum conduction losses in the diode for this application.

Figure 5. Flyback converter

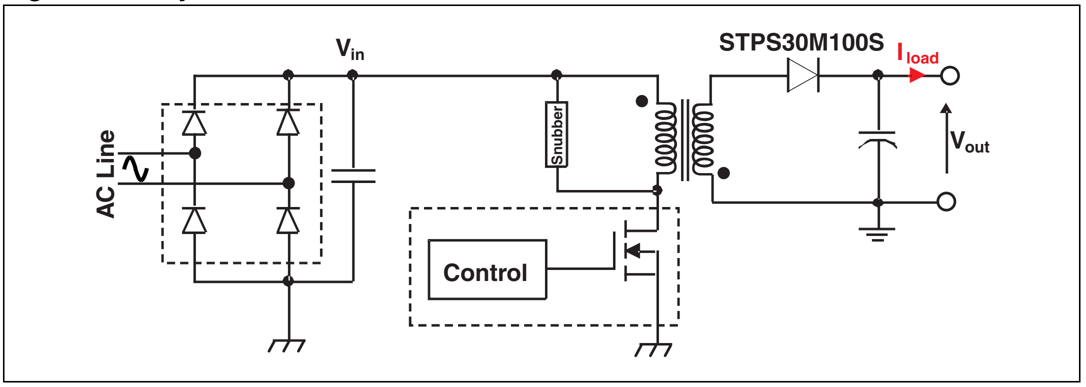
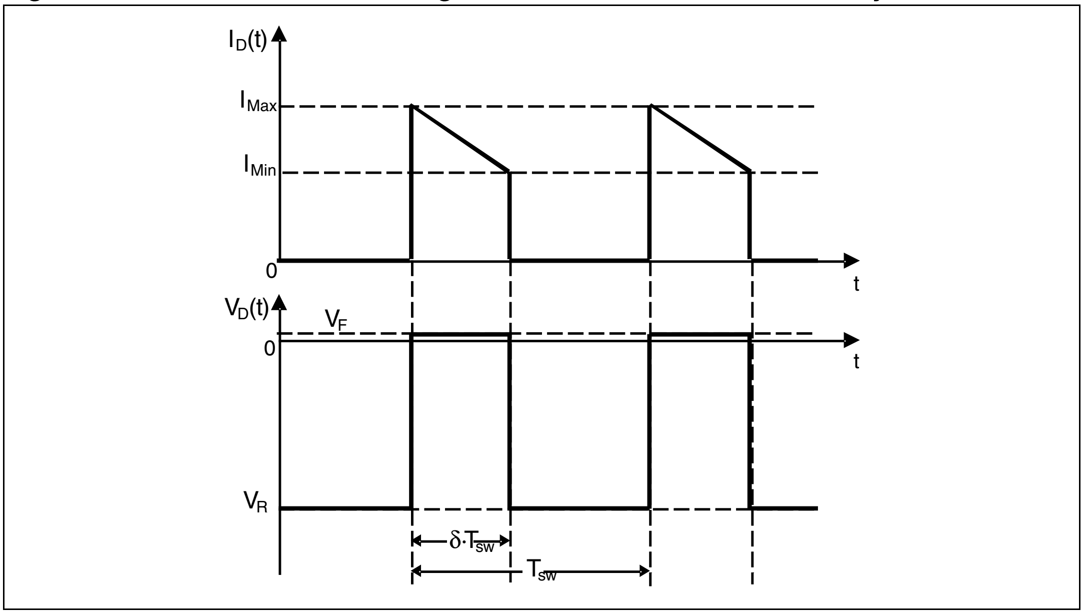


Figure 6. Ideal current and voltage waveforms of the diode in the flyback converter.



3.1 Average and rms current calculation

The first step is the calculation of the average and rms currents.

The forward average current is the output current: $I_{F(AV)} = I_{load} = 4.7$ A.

As illustrated in *Figure 6*, the forward current has a trapezoidal shape. The formula to calculate the rms current of trapezoidal waveform is given in *Figure 4.* $I_{F(RMS)}$ is then:

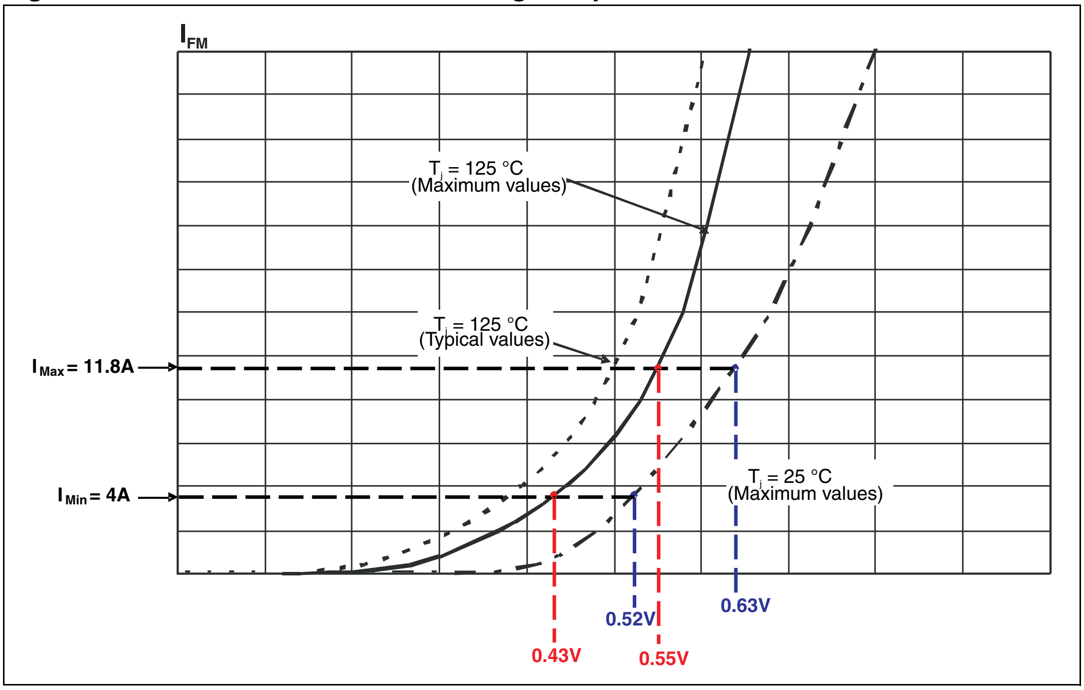
Equation 15

$$I_{F(RMS)} = \sqrt{\frac{(11.8)^2 + (4)^2 + 11.8 \cdot 4}{3} \cdot 0.6} = 6.4 \text{ A}$$

3.2 V_{T0} (T_j) and R_D (T_j) calculation

The second step is the calculation of V_{T0} (T_j) and R_D (T_j) in the application condition range.

Figure 7. STPS30M100S forward voltage drop versus forward current



T_{jref1} = 25 °C and T_{jref2} = 125 °C. To calculate maximum conduction losses, read maximum values of V_F at I_{Min} and I_{Max} in *Figure 7.* This figure is available in the STPS30M100S datasheet. These values are summarized in *Table 1.*

Table 1. $V_{F(Max)}$ values at I_{Min} and I_{Max}

I_F (A)	$V_{F(Max)}(I_F, 25\ °C)$ (V)	$V_{F(Max)}(I_F, 125\ °C)$ (V)
I_{Min} = 4	0.52	0.43
I_{Max} = 11.8	0.63	0.55

From Equations (3), (4), (8) and (9) calculate $V_{T0}(T_{jref1})$, $V_{T0}(T_{jref2})$, $R_D(T_{jref1})$, $R_D(T_{jref2})$, α_{VT0} and α_{RD}. Calculated values of these parameters are summarized in Table 2.

Table 2. V_{T0}, R_D, α_{VT0}, and α_{RD} parameters

T_{jref} (°C)	V_{T0} (V)	R_D (mΩ)	α_{VT0} (V·°C^{-1})	α_{RD} (Ω·°C^{-1})
T_{jref1} = 25	0.464	14.123	-951.358×10^{-6}	12.839×10^{-6}
T_{jref2} = 125	0.368	15.406		

From Equations 5 and 6 we can write $V_{T0}(T_j)$ and $R_D(T_j)$ as follow:

Equation 16

$$V_{T0}(T_j) = 0.487 - 951.358 \times 10^{-6} \cdot T_j$$

Equation 17

$$R_D(T_j) = 13.802 \times 10^{-3} + 12.839 \times 10^{-6} \cdot T_j$$

3.3 Conduction losses expression

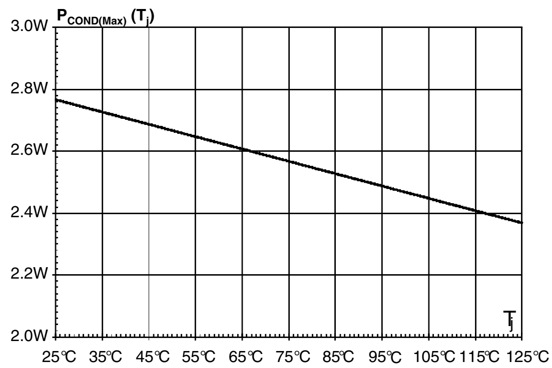
From Equations 7, 15 and 16 the expression for maximum conduction losses is then:

Equation 18

$$P_{COND(Max)}(T_j) = 2.866 + 3.987 \times 10^{-3} \cdot T_j$$

Finally, let us plot the value of conduction losses in the diode as a function of the junction temperature (Figure 8).

Figure 8. Maximum conduction losses versus junction temperature



4 Revision history

Table 3. Document revision history

Date	Revision	Changes
Aug-1993	1	Initial release
03-May-2004	2	Stylesheet update. No content change
24-Aug-2011	3	Completely revised for currently available products.