

## Switch Mode Power Supplies: SPICE Simulations and Practical Designs

Christophe Basso – February 2008

Corrections of typos, mistakes and errors found by readers (or by the author himself!)

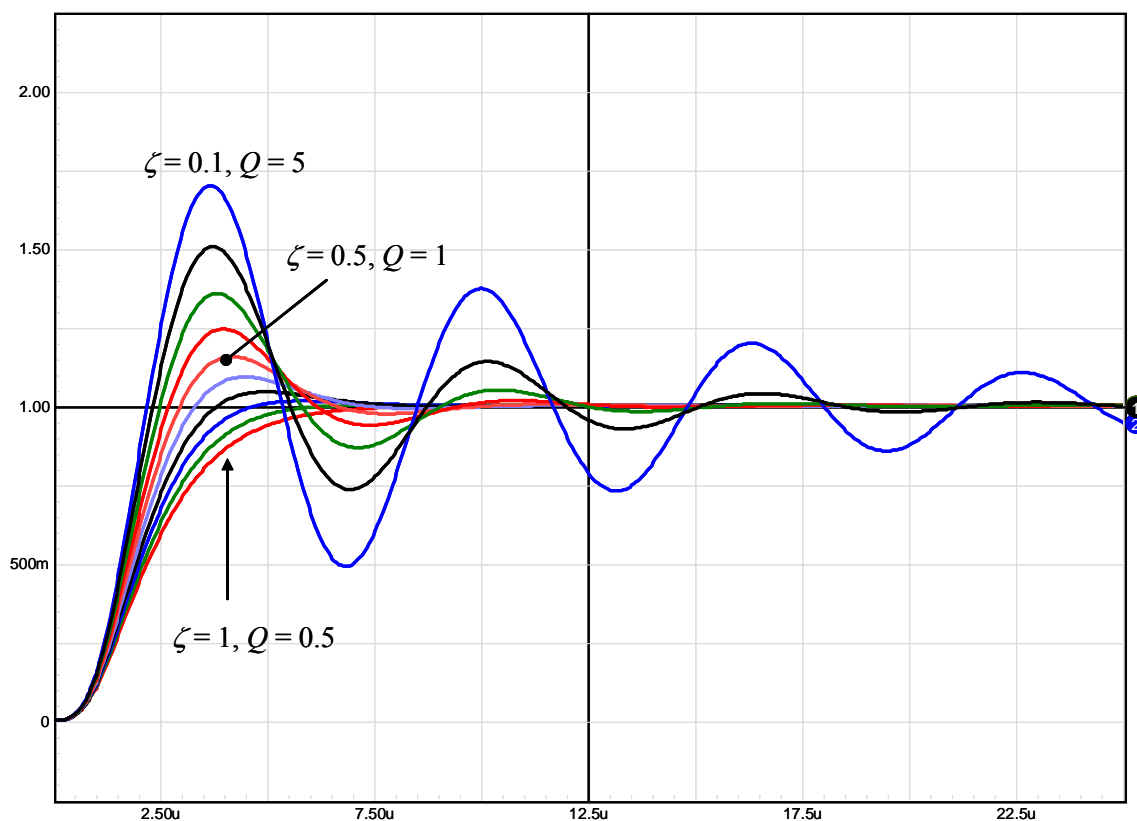
**Page xvi:** Sorry Monsieur Balocco, your name was misspelled with two “l”. One is enough: Dr. Didier Balocco from Saft Power Systems.

**Page 4:** equation (1-1) result is incorrect, it should be  $140 \Omega$  (Fig. 1-1 is ok though)

**Page 22:** below equation (1-32): “for a buck,  $V_1 = V_{in} - V_{out}$  and not  $V_{out} - V_{in}$ .”  
Contributed by C. Denton, March 2008.

**Page 57:** to gain a comprehensive understanding of the *buck-boost* operation... The word buck is missing.  
Contributed by Kulsangcharoen Ponggorn, June 2008.

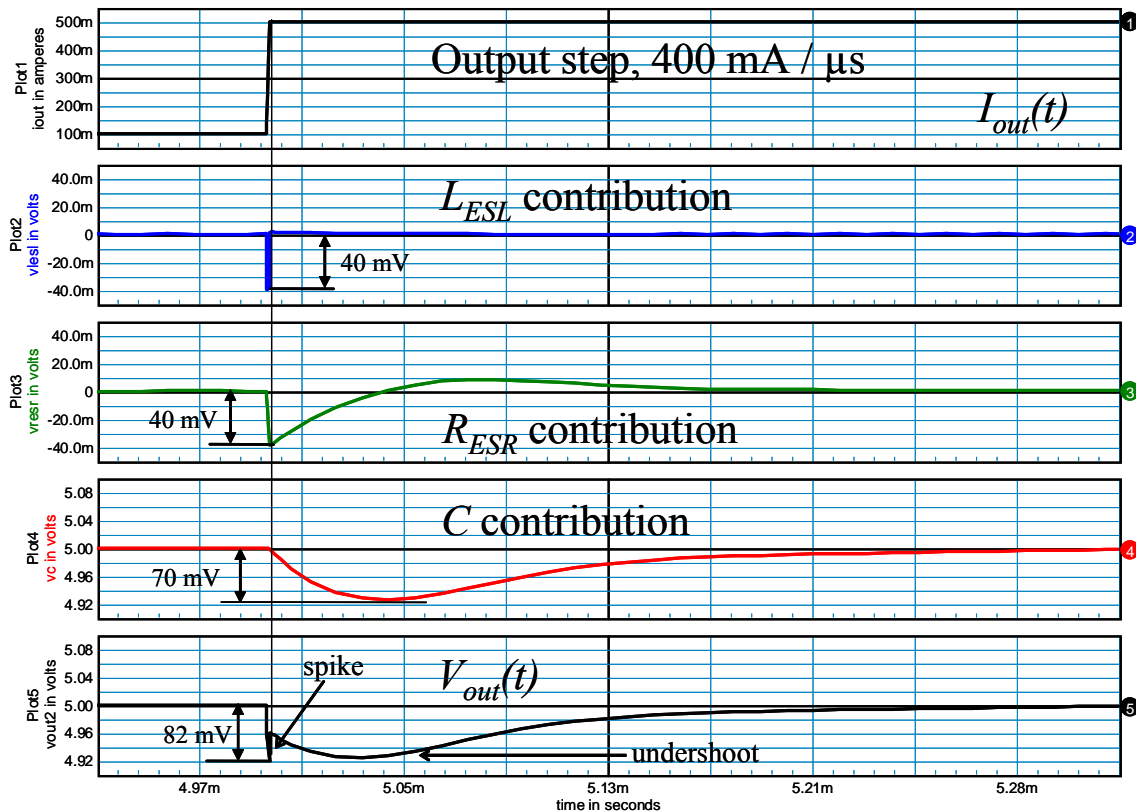
**Page 69, figure 1-50:** I don’t know what happened to the captions on the graph, but those on the picture are certainly not at the right place. Here is the corrected graph:



**Figure 1-50**

**Page 92, figure 1B-15:** the upper curve caption should be “output step,  $400 \text{ mA}/\mu\text{s}$ ” and not “stemp,  $400 \text{ mA}/\text{ms}$ ”!

**Page 92, figure 1B-15:** the amplitude caption in the figure is wrong, the  $2 \text{ mV}$  does not make sense. The real capacitor contribution alone is  $70 \text{ mV}$  as corrected in the below figure.



**Figure 1-B5:** ...step,  $S_1 = 400 \text{ mA}/\mu\text{s}$  (not 450 mA)

**Page 167, CCM PWM switch CM listing**

A capacitor has been purposely added between terminals C and P to create the sub harmonic effects at half of the switching frequency. To obtain exactly the same curve as with Ridley models, the capacitor must be connected after the voltage source VM, between nodes cx and p accounting for the presence of this capacitor in the measured current. It was previously connected between c and p, leading to a slight high-frequency deviation. The correction has been included before print, the book listing is thus good.

Contributed by Ekrem Cengelci on May 2007.

**Page 236:** Eq. (2B-6) should be:  $T(t) = 1 - 2e^{-t} + e^{-2t}$

Contributed by Jason Neudorf, May 2008.

**Page 268:** Fig. 3-22, page 268: in the picture,  $R_{load}$  should be  $2.5 \Omega$  and not  $2.5 \text{ W}$ .

Contributed by C. Denton, March 2008.

**Page 269:** Fig. 3-23a, page 268: in the picture,  $f_c$  should be  $5 \text{ kHz}$  and not  $5 \text{ Hz}$ .

Contributed by C. Denton, March 2008

**Page 276:** Fig. 3-28, page 276: in the schematic parameters list,  $f_{p2}$  should be  $50\text{k}$  and not  $50$ .

Contributed by C. Denton, March 2008.

**Page 288:** The table describing the TL431 and TLV431 features an obvious typo. The breakdown voltage of the TLV431 is not 1 V but 18 V!

Reference	Vref	Ibias,min	Precision	Max voltage	Max current
TL431I	2.495 V	1 mA	± 2% @ 25 °C	36 V	100 mA
TL431A	2.495 V	1 mA	± 1% @ 25 °C	36 V	100 mA
TL431B	2.495 V	1 mA	± 0.4% @ 25 °C	36 V	100 mA
TLV431A	1.24 V	100 µA	± 1% @ 25 °C	18 V	20 mA
TLV431B	1.24 V	100 µA	± 0.5% @ 25 °C	18 V	20 mA

Contributed by Chalermkiat, June 2008.

**Page 293:** Fig. 3-39, page 293: in the schematic parameters list, it should be fc = 1k and not just “1” and below should be pm = 100 and not kpm = 100.

Contributed by C. Denton, March 2008.

**Page 322:** Reference 3. → “Note from the author: it’s too old, can’t find place...”. Obviously, this sentence was left over during the editing process!

**Page 411:** “Numerical application gives a cutoff frequency of 54 kHz” and not 45 kHz.

Contributed by Kulsangcharoen Ponggorn, July 2008.

### Page 418, equation 5-17:

*This equation defines the diode conduction losses by:*

$$P_{cond,diode} = V_f I_{d,avg} + R_d I_{d,rms}^2 \quad (5-17)$$

*In the above expression,  $V_f$  should be replaced by  $V_{T0}$  where  $V_{T0}$  represents the threshold voltage of the junction. If you look at figure 1 (see the appendix at the end), the diode model appears on the right side. It combines a constant voltage source,  $V_{T0}$ , in series with a dynamic resistor  $R_d$ . The total voltage drop  $V_f$  measured at a given current  $I_{d0}$ , combines  $V_{T0}$  and the dynamic resistor drop. If you use  $V_f$  as in Eq. (5-17), the term  $R_d$  is counted twice. Therefore, the total average power dissipated by the diode is correctly expressed by:*

$$P_{cond} = V_{T0} I_{d,avg} + R_d I_{d,rms}^2 \approx V_f I_{d,avg}$$

$V_{T0}$  depends on the diode technology. It is measured when the diode starts conducting (a few hundred of µA). The drop is roughly 0.4 V for a Schottky and 0.6 V for a PN diode.

### The correction is as follows:

... The conduction losses for a diode are given by

$$P_{cond} = V_{T0} I_{d,avg} + R_d I_{d,rms}^2 \approx V_f I_{d,avg} \quad (5-17)$$

where  $I_{d,avg}$  = average current in the diode

$V_f$  = forward voltage at the considered diode current

$V_{T0}$  = forward voltage at which the diode starts to conduct (≈0.4 V for a Schottky, ≈0.6 V for a PN diode)

$$R_d = \dots$$

**Page 469: figure 5-14a:**

The caption should say ...The CCM *buck-boost* converter...

**Page 562: equation 6-166**

It should be  $R_1$  not  $R_3$ :

$$R_1 = \frac{275 \times \sqrt{2} - 3}{250 \mu} = 1.6 \text{ M}\Omega$$

**Page 583: FIGURE 7-3a**

The PWL definition in the figure should be: V2 4 0 Pulse 0 5 0 10n 10n 5u 10u  
Contributed by R. MacIlvain, July 2008.

**Page 586: FIGURE 7-4a**

The PWL definition in the figure should be: V2 4 0 Pulse 0 5 0 10n 10n 5u 10u  
Contributed by R. MacIlvain, July 2008.

**Page 633: voltage-mode control table**

The dc gain,  $V_{out}/V_{error}$ , should be:

$$\frac{NV_{in}}{(1-D)^2 V_{peak}} \quad \text{The } N \text{ is missing}$$

**Page 652:** ...below 15 V, then there is no arm to let the driver... → there is no harm!  
Contributed by C. Denton, April 2008.

**Page 679, equation 7-166:**

$$P_d = V_{T0} I_{d,avg} + R_d I_{d,rms}^2 + DI_R \text{PIV} \approx V_f I_{d,avg} \quad (7-166)$$

**Page 693, equation 7-204:**

$$P_d = V_{T0} I_{d,avg} + R_d I_{d,rms}^2 + DI_R \text{PIV} \approx V_f I_{d,avg} \quad (7-204)$$

**Page 825, table 8-2:**

In the “where” section, the definition for  $S_n$  has to be changed:

$$S_n = \frac{NV_{in} - V_{out}}{L} NR_{sense} \quad \text{this is the on-time secondary slope reflected to the primary.}$$

The equation given in the page,  $S_n = \frac{V_{in}}{L_p} R_{sense}$ , corresponds to the magnetizing current slope. It can, by the way, be considered as a free external ramp.

**Page 834:** small typo on the current  $I_{valley}$  (or  $I_{peak}$ ) should be  $I_{p,valley}$  or  $I_{p,peak}$  :

$$P_{SW,on} = \frac{I_{p,valley} V_{bulk} \Delta t}{6} F_{sw} \quad \text{eq. 8-125a}$$

$$P_{SW,on} = \frac{I_{p,valley} V_{bulk,max} \Delta t}{6} F_{sw} = \frac{1.56 \times 400 \times 45n}{6} \times 100k \approx 470 \text{ mW} \quad \text{eq. 8-125c}$$

$$P_{SW,off} = \frac{I_{p,peak} V_{bulk} \Delta t}{2} F_{sw} \quad \text{eq. 8-125d}$$

$$P_{SW,off} = \frac{I_{p,peak} V_{bulk,max} \Delta t}{2} F_{sw} = \frac{1.84 \times 400 \times 45n}{2} \times 100k = 1.65 \text{ W} \quad \text{eq. 8-125e}$$

Contributed by T. Sutto, May 2008.

**Page 856:** equation 8B-12

The equation should be:  $C_{eq} = C_{L2} \left( \frac{N_3}{N_2} \right)^2 \parallel C_{L1}$ , the  $C_{L2}$  sub term is missing.

For equations 8B-13c and 8B-13d,  $F_{sw}$  should be replaced by  $f$ , where  $f$  is a sinusoidal signal of course.

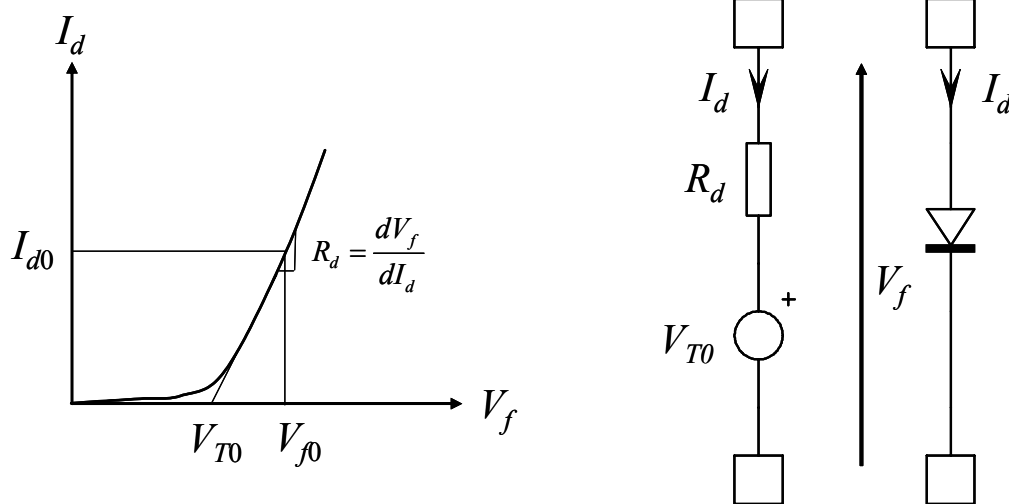
**Page 860:** equation 8C-2

In the numerical application, the  $10^4$  is gone, but the result is correct:

$$W_a A_c = \frac{P_{out}}{K_c K_t B_{max} F_{sw} J} 10^4 = \frac{250 \times 10000}{507 \times 0.0005 \times 0.11 \times 100000 \times 400} = 2.24 \text{ cm}^4 \quad \text{eq. 8C-2}$$

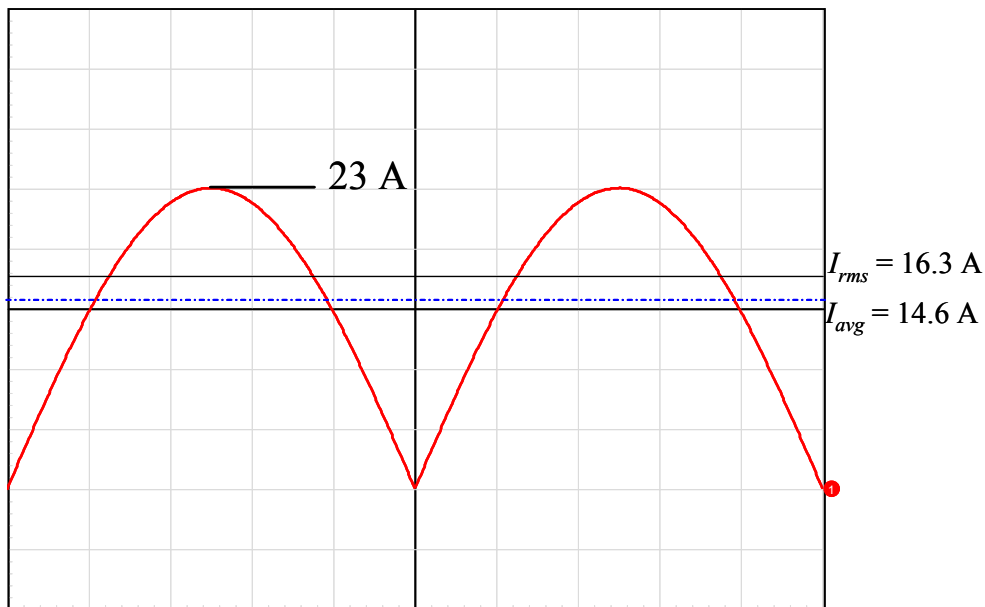
Contributed by T. Sutto, May 2008.

## Appendix 5X – conduction diode loss calculations



**Figure 1:** the equivalent diode representation.

In most of the examples, the conduction losses are simply calculated by  $P_{cond} = V_f I_{d,avg}$  which is ok since the total drop given by the data-sheets at a certain average current combines the contribution of the dc source  $V_{T0}$  and the ohmic drop. However, what is the error if we do not account for the ac ripple? Suppose we have a diode crossed by a full-wave signal like below:



**Figure 2:** an example of a rectified current flowing in a diode.

The rms current is expressed by:  $I_{d,rms} = \frac{I_{d,peak}}{\sqrt{2}}$

The average current is:  $I_{d,avg} = \frac{2I_{d,peak}}{\pi}$

In Eq. (5-17), we would assume the following losses:

$$P_{d,avg} = V_{T0}I_{d,avg} + R_d I_{d,rms}^2 \quad (5-17)$$

Replacing by the rms and average definitions, we obtain:

$$P_{d,avg} = \frac{2V_{T0}I_{d,peak}}{\pi} + \frac{1}{2}R_d I_{d,peak}^2 \quad (5-17b)$$

If we now neglect the rms current effect on the dynamic resistor, we have:

$$P_{d,avg} = V_f I_{d,avg} = (V_{T0} + R_d I_{d,avg}) I_{d,avg} \quad (5-17c)$$

Again, replacing by the definition, we have:

$$P_{d,avg} = \left( V_{T0} + R_d \frac{2I_{d,peak}}{\pi} \right) \frac{2I_{d,peak}}{\pi} = \frac{2V_{T0}I_{d,peak}}{\pi} + \frac{4}{\pi^2} R_d I_{d,peak}^2 \quad (5-17d)$$

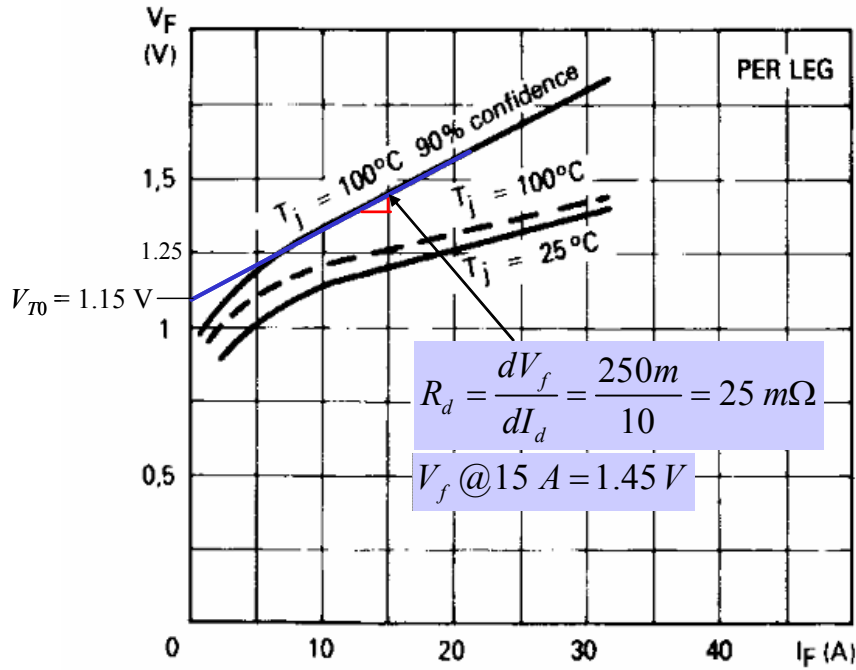
If we compare equations 5-17b and 5-17d, the resistive factor is respectively weighted by 0.5 and  $\frac{4}{\pi^2}$ , 0.405.

Suppose the peak current of figure 2 is 23 A, leading to:

$$I_{d,rms} = \frac{I_{d,peak}}{\sqrt{2}} = \frac{23}{1.414} = 16.3 \text{ A} \quad (5-17e)$$

$$I_{d,avg} = \frac{2I_{d,peak}}{\pi} = \frac{46}{3.14} = 14.6 \text{ A} \quad (5-17f)$$

We have selected a power diode whose characteristic appears on figure 3:



**Figure 3:** forward voltage versus direct current.

From the curve, we have extracted  $V_{T0}$  (1.15 V), the dynamic resistor (the slope of the blue curve, 25 mΩ) and the total forward drop at a 15 A current (1.45 V). Let's apply our previous formulas with these numbers:

$$P_{cond} = V_{T0} I_{d,avg} + R_d I_{d,rms}^2 = 1.15 \times 14.6 + 25m \times 16.3^2 = 23.4 W \quad (5-17g)$$

$$P_{cond} = V_f I_{d,avg} = 1.45 \times 14.6 = 21.2 W \quad (5-17h)$$

The second formula differs from the first by 9.4%.

Some manufacturers also give power curves in relationship to the peak to average current coefficient  $K_f$  (figure 4). When this factor equals 1, this is a dc current (no ac ripple). Otherwise, with a signal as in figure 2, we would have:

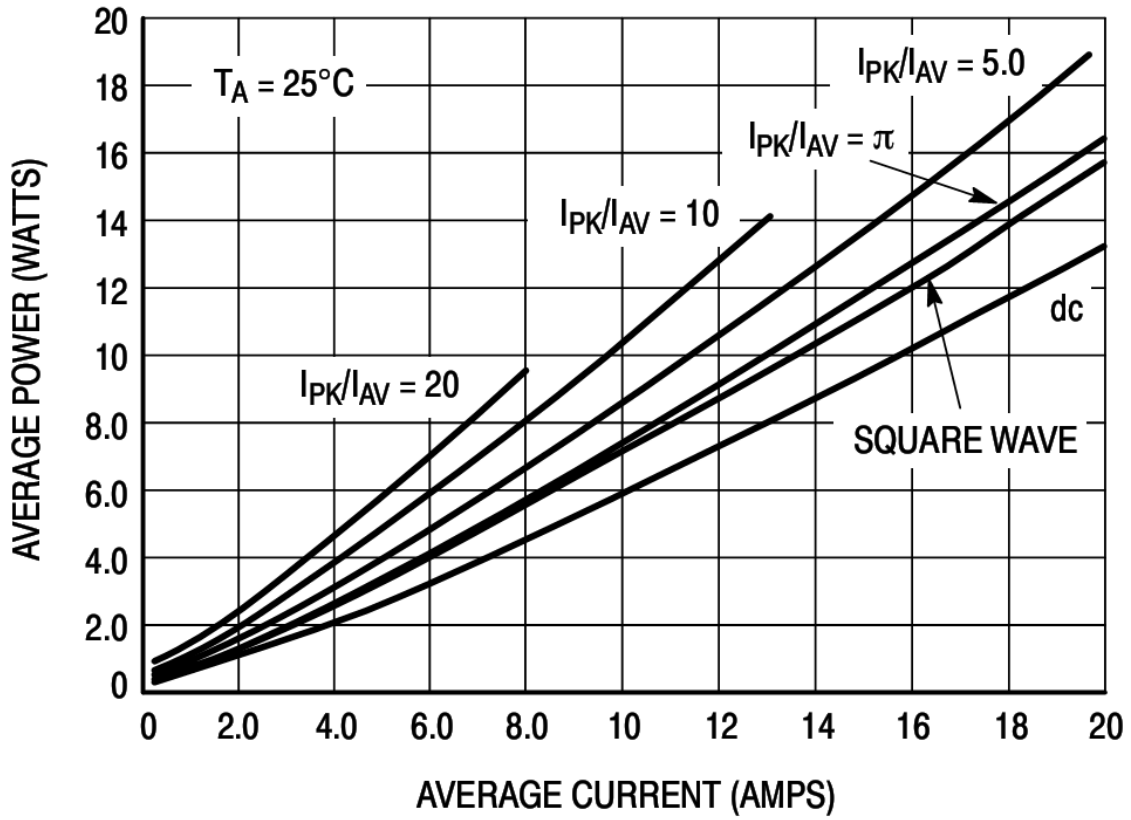
$$K_f = \frac{I_{d,peak}}{I_{d,avg}} = \frac{\pi I_{d,peak}}{2 I_{d,peak}} = \frac{\pi}{2} \approx 1.6 \quad (5-17i)$$

For single wave rectification, this factor equals  $\pi$ .

For a square wave signal with a duty cycle  $D$ , the peak to average current factor is:

$$K_f = \frac{I_{d,peak}}{I_{d,avg}} = \frac{I_{d,peak}}{D I_{d,peak}} = \frac{1}{D} \quad (5-17j)$$

Figure 4 square-wave curve seems to imply a duty-cycle of 50% ( $K_f = 2$ ).



**Figure 4:** some manufacturers give power dissipation curves depending on the ac ripple amplitude.