SGS-THOMSON
MICROELECTRONICS

APPLICATION NOTE

TURBOSWITCH ™ IN A PFC BOOST CONVERTER

B. Rivet

1. INTRODUCTION

SGS-THOMSON offers two families of 600V ultrafast diodes (TURBOSWITCH”A” and ”B”) having different compromises between the forward characteristics and the reverse recovery characteristics.

This paper explains why TURBOSWITCH”B” is a suitable family for PFC boost converters working in discontinuous mode, and why the TURBOSWITCH”A” should be used for PFC’s working in continuous mode.

In this kind of application, the main concern for the designer is to evaluate the power losses. For that, SGS-THOMSON proposes a very powerful tool. A program has been developed in order to calculate the losses in the diode and in the transistor in a PFC working in continuous mode at a constant frequency. This application note describes how the calculations are performed. This software determines clearly that there is an optimum MOSFET turn on di/dt to increase the efficiency of the design and reduce EMI.

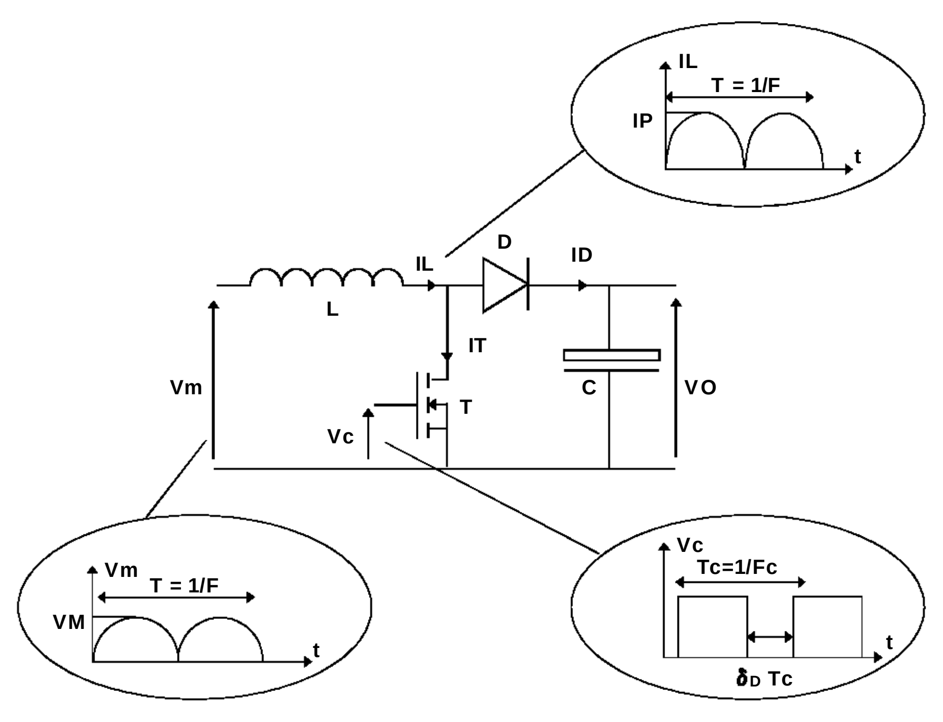
2. PARAMETERS DEFINITION

The basic circuit of the fig.1 shows the current, voltage and frequencies notations used in this paper.

List of the parameters :

Vm : mains voltage
V_M : peak value of the mains voltage
I_L : current in the coil
I_D : current in the diode
I_T : current in the transistor
I_P : peak current in the coil
δ_D : duty cycle of the diode
Fc : switching frequency
Vo : output voltage
F : mains frequency

Fig.1 : Boost PFC converter notations



3. TURBOSWITCH IN A PFC BOOST CONVERTER WORKING IN DISCONTINUOUS MODE

The discontinuous mode is used for power below 200-300W. In this mode, the current in the diode before reaching zero A decreases very slowly (less than 1A/µs). The slope is fixed by the coil and is equal to (Vm - Vo)/L. The low value of this slope generates low values of reverse recovery current (I_{RM}) and therefore low switch-off losses. For this reason the forward voltage (V_F) of the diode becomes the most important parameter. The best choice is to use a TURBOSWITCH"B" 1-2A/600V.

The major part of the losses is the conduction losses (Pcond). They can be calculated with a good approximation by :

$$\text{Pcond} = V_F\,(I_{F(AV)}) \times I_{F(AV)}$$

The average current in the diode is equal to the output power (POUT) divided by the output voltage Vo :

$$I_{F(AV)} = P_{OUT} / Vo$$

4.TURBOSWITCH IN PFC BOOST CONVERTER WORKING IN CONTINUOUS MODE

In continuous mode (output power higher than 200-300W) the current in the diode decreases very quickly. The $(di_F/dt)_{OFF}$ of the diode is fixed by the MOS transistor control and is equal to a few hundred A/µs ($(di_F/dt)_{OFF}$ of the diode is equal to the $(di_F/dt)_{ON}$ of the transistor).

The reverse recovery current of the diode when the transistor switches on flows in the transistor and generates high turn-on losses in the transistor. For this reason the most important parameter of the diode is the I_{RM}.

The TURBOSWITCH"A" family represents the optimum in term of V_F/I_{RM} compromise for this type of application and is recommended.

The calculations of the average current, RMS current and power losses in the diode and in the transistor are very complex. This is why SGS-THOMSON has developed a software which performs calculations and proposes the best TURBOSWITCH for the application. The boost converter is assumed to work in a continuous mode and at a constant frequency. This development tool, the PFC diskette, is available in a 5 1/4 inches format.The following paragraph explains how the calculations are performed.

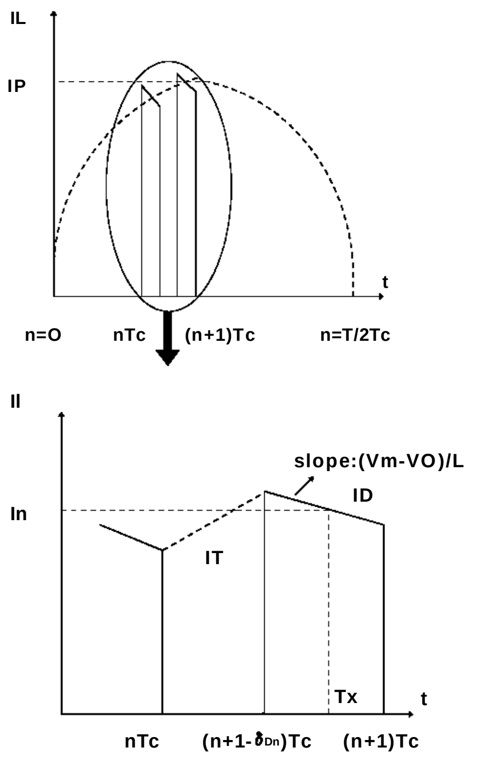
4.1. Results concerning the diode

4.1.1. Conduction losses

The current waveform in the diode is a succession of trapezoids. The duty cycle δ_{Dn} and the amplitude of the latter are varying as a function of the input mains voltage.

The fig.2 shows the current in the diode between the time nTc and (n+1)Tc.

Fig.2 : Current in the diode between nTc and (n+1)Tc



$$\delta_{Dn} = \frac{Vmn}{Vo}$$

$$Vmn = V_M \sin\left(\frac{2\,\Pi\,(n+1)Tc}{T}\right)$$

$$I_L = In = Ip \sin\left(\frac{2\,\Pi\,(n+1)Tc}{T}\right)$$

$$Tx = \left(n+1-\frac{\delta_{Dn}}{2}\right)Tc$$

Average current and RMS current in the diode

The program calculates the average and RMS current in the diode with the iterative formulae :

$$I_{D(AV)} = \frac{2}{T}\sum_{n=o}^{N-1}\left[\frac{A}{2}Tc^2\,\delta_{Dn}\,(2n+2-\delta_n)+BTc\delta_{Dn}\right]$$

$$I_{D(RMS)} = \left[\frac{2}{T}\sum_{n=o}^{N-1}(Cn+Dn)\right]^{1/2}$$

with :

$$A = \frac{Vmn - Vo}{L}$$

$$N = \frac{T}{2Tc}$$

$$B = In - A\,(\,n + 1 - \frac{\delta_{Dn}}{2}\,)\;Tc$$

$$Cn = \frac{A^2}{3} Tc^3 \delta_{Dn} [3(n(n+2-\delta_{Dn})+1-\delta_{Dn})+\delta_{Dn}{}^2]$$

$$Dn = ABTc^2\,\delta_{Dn}\,(2n + 2 - \delta_{Dn}\,) + B^2\,Tc\,\delta_{Dn}$$

Conduction losses in the diode

The conduction losses in the diode are calculated with the maximum value of V_{TO} and Rd (respectively the threshold voltage and the dynamic resistance of the forward characteristic). It must be pointed out that these power losses correspond to a worst case situation.

$$Pcond = V_{TO}\,I_{D(AV)} + Rd\,I_{D(RMS)}{}^2$$

4.1.2.Turn-on losses in the diode

These losses are estimated with the formula

$$P_{ON} = 0.4\,(V_{FP}-V_F)I_F\,.\,t_{FR}\,.\,F$$

V_{FP} : Peak forward voltage

t_{FR} : forward recovery time

This formula provides only an estimate, which is sufficient because turn ON losses are low with regard to conduction losses. The program interpolates data of the curve V_{FP} and t_{FR} versus $(di_F/dt)_{ON}$ of the diode(Fig3). These data have been stored on the disk for each part number.

Fig.3 : V_{FP} versus di_F/dt.
(STTA806D)

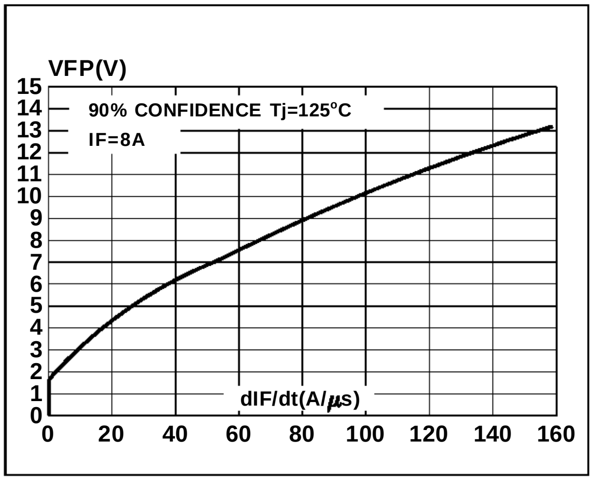
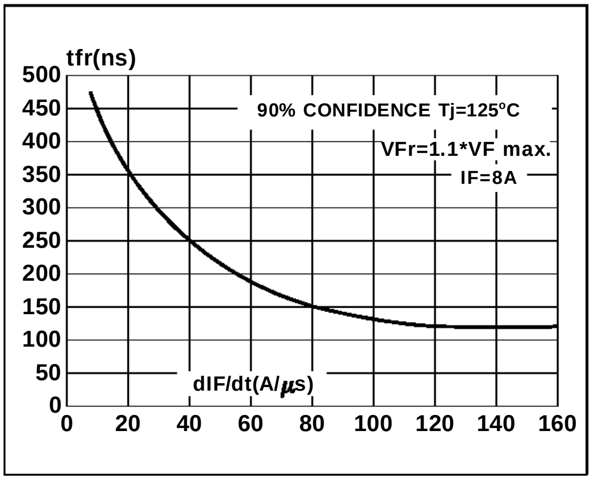


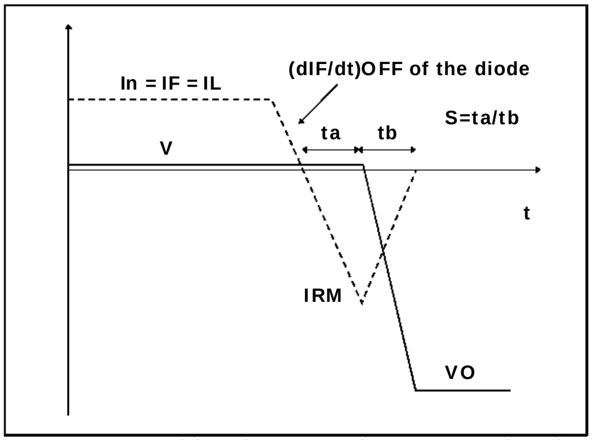
Fig.3 Bis : t_{FR} versus di_F/dt.
(STTA806D)



4.1.3.Turn-off losses in the diode

The fig.4 shows the theorical waveform of the current and the voltage when the diode switches off.

Fig.4 : Current and voltage waveform during diodes switch OFF



In a PFC working in a continuous mode, the $(di_F/dt)_{OFF}$ of the diode is fixed. But current (I_F = I_L) acts as a function of the time,as do the softness factors and the current IRM (Fig.5).

These data were also stored for each individual part number.

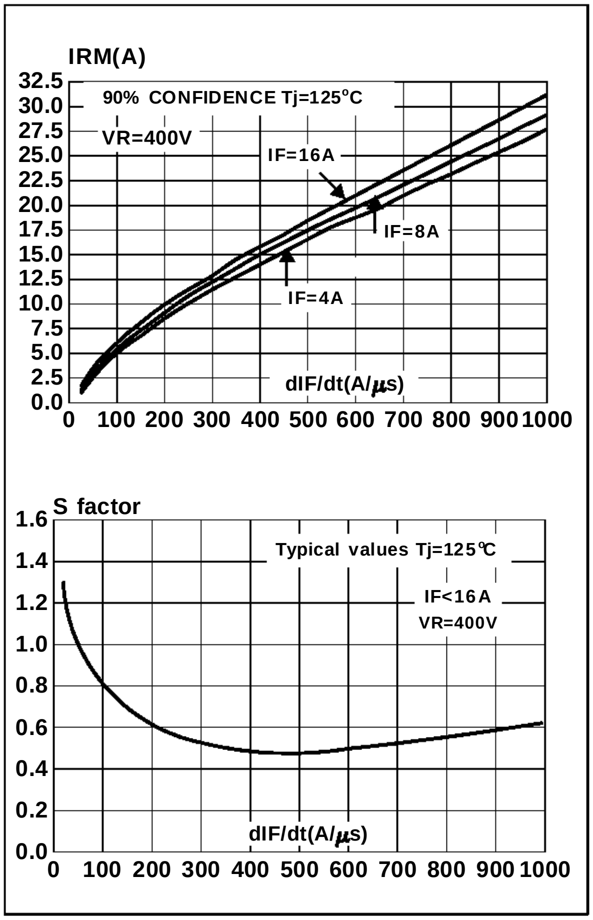
$$P_{OFF} = \frac{1}{T}\sum_{n=o}^{N-1} \frac{Vo\,I_{RMn}{}^2\,Sn}{3\,(\,di_F/dt\,)_{\,OFF}}$$

I_{RM}n and Sn are respectively the reverse current and softness factor corresponding to the $(di_F/dt)_{OFF}$ of the application and at the time nTC when

$$IF = In = Ip\ \left(\sin \frac{2\,\Pi\,(n+1)\ Tc}{T} \right)$$

These losses are calculated with data (S, I_{RM}) at 90% confidence.

Fig.5 : I_{RM} and S versus di_F/dt.
(STTA806D)



4.1.4.Turn-on losses in the transistor due to the diode

When the transistor turns on the reverse recovery current flows in the transistor (Fig.6)

Turn-on losses in the transistor due to the diode are calculated with the same data as the turn-off losses in the diode.
The formula used is :

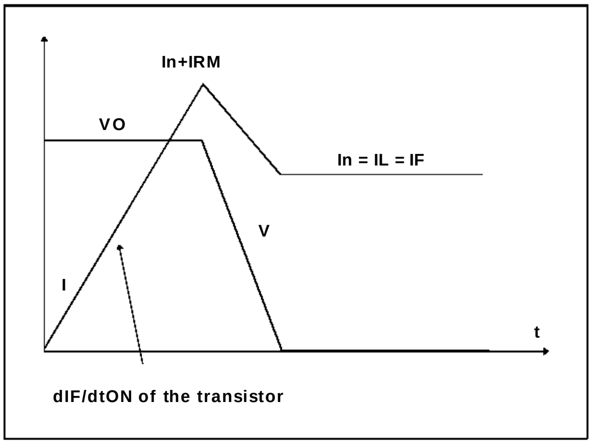
$$P_{ON} = 2\,\frac{Vo}{T} \sum_{n=o}^{N-1} (\,Mn + Gn\,)$$

with :

$$Mn = \frac{I_{RMn}{}^{2}\,(\,3 + 2\,Sn\,)}{6\,(\,di_F/dt\,)_{OFF}}$$

$$Gn = \frac{In\ \ I_{RMn}(\,2 + Sn\,)}{2\,(\,di_F/dt\,)_{OFF}}$$

Fig.6 : Current and voltage waveform during transistor turn-on.

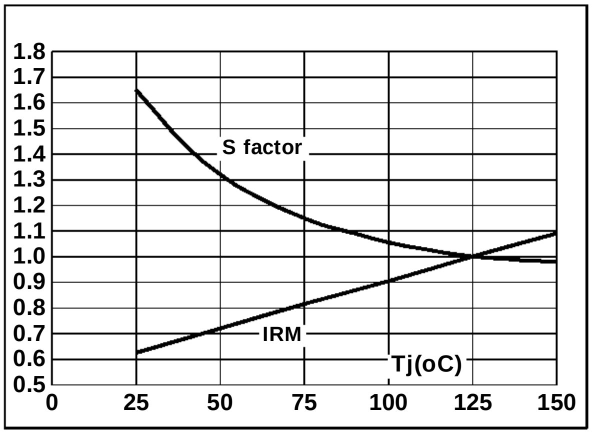


4.1.5. Junction temperature of the diode

S factor and IRM depend on the temperature (Fig.7). This program takes into account these variations to calculate the junction temperature. Two options are available :

Enter Tcase (case temperature) or, Enter Tamb (ambient temperature) and Rth (c-a) (case ambient thermal resistance).

Fig 7 : Relative variation of dynamic parameters versus junction temperature
(STTA806D)

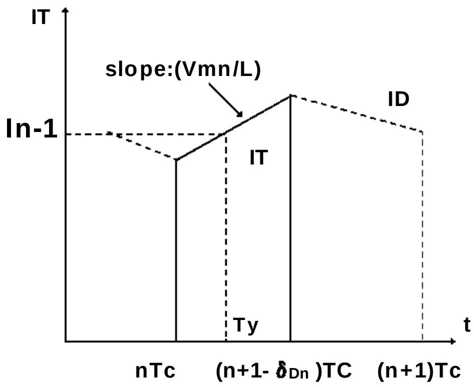


4.2.Results concerning the transistor

4.2.1.Conduction losses

The current waveform in the transistor is also a succession of N trapezoids and the duty cycle of the transistor, and the amplitude of which varies as a function of the input main voltage. Fig.8 shows the current in the transistor between the time nTc and (n+1)Tc.

Fig.8 : Current in the transistor betweenTc and (n+1)Tc



$$\delta_{Dn} = \frac{Vmn}{Vo}$$

$$Vmn = V_M \sin\left(\frac{2\,\Pi\,(n+1)Tc}{T}\right)$$

$$I_{n-1} = Ip \sin\left(\frac{2\,\Pi\,nTc}{T}\right)$$

$$Ty = \frac{(2n+1-\delta_{Dn})Tc}{2}$$

The program calculates the average and RMS current in the transistor with the formulae.

$$I_{T(AV)} = \frac{2}{T}\sum_{n=o}^{N-1}\left[\frac{A((n+1-\delta_{Dn})^2-n^2)Tc^2}{2}+Ln\right]$$

$$I_{T(RMS)} = \left[\frac{2}{T}\sum_{n=o}^{N-1}[In+Jn]\right]^{1/2}$$

with :

$$A = \frac{Vmn}{L}$$

$$B = I_{n-1} - A\left(\frac{2n+1-\delta_{Dn}}{2}\right)Tc$$

$$Ln = BTc(1-\delta_{Dn})$$

$$In = \frac{A^2}{3}Tc^3((n+1-\delta_{Dn})^3-n^3)$$

$$Jn = ABTc^2((n+1-\delta_{Dn})^2-n^2)+B^2Tc(1-\delta_{Dn})$$

Conduction losses

We have :

$$Pcond = rds_{ON}\, I_{T(RMS)}^2$$

rds_{ON} : rds_{ON} of the transistor

4.2.2.Total turn-on losses in the transistor

The principle of the calculation is the same as the calculation of turn-off losses in the diode.

The formula used is :

$$P_{ON}(T_R) = \frac{2Vo}{T}\sum_{n=o}^{N-1}[Kn/(dI_F/dt)_{OFF}]$$

with :

$$Kn = \frac{(In+I_{RMn})^2}{2}+Sn\frac{I_{RMn}^{\;2}}{3}+Sn\frac{I_{RMn}\,I_n}{2}$$

5. EXAMPLE OF SIMULATION

Data entered in the software :

Diode : STTA2006P

$(di_F/dt)_{OFF}$ of the diode= 500A/µs
$(di/dt)_{ON}$ of the diode = 500A/µs
F = 50Hz
F_C = 50 000HZ
V_M = 300V
V_O = 400V
L = 100µH
Ip = 20A
Rds_{ON} = 0.1Ω
Tcase = 60°C

Results

Diode results

$I_{D(AV)}$ = 7.5A
$I_{D(RMS)}$ = 11.8A
P_{ON} = 0.5W
P_{OFF} = 1W
Pcond = 11W
Tj = 76°C
$P_{ON}\ T_{R(D)}$ = 18.6W

Transistor results

$I_{T(AV)}$ = 5.2A
$I_{T(RMS)}$ = 9.1A
$P_{ON}(T_R)$ = 22.6W
$Pcond(T_R)$ = 8.3W

6. OPTIMUM MOSFET TURN ON di/dt

P_{OFF} in the diode and $P_{ON}(T_R)$ are the only losses depending on the $(di/dt)_{ON}$ of the transistor ((di/dt) of the diode)).

The software allows you to draw the curve $P_{ON}(T_R)$ + $P_{OFF}(D)$ versus the $(di/dt)_{ON}$ of the the transistor ($(di/dt)_{OFF}$ of the diode).

Example :

The curve fig.9 shows the variation of $P_{OFF}(D)$ + $P_{ON}(TR)$ versus the $(diF/dt)_{OFF}$ of the diodes. We enter in the program the following data :

Diode : STTA2006P

F = 50Hz
F_C = 50kHz
V_M = 300V
V_O = 400V
L = 100µH
T_C = 80°C
Ip = 12A

This curve shows that in order to optimize the efficiency, the designer has to fix the $(di_F/dt)_{ON}$ of the transistor at 500A/µs. When the switching time decreases in the area of di/dt < 500A/µs, P_{OFF} + $P_{ON}(T_R)$ decreases. But for di_F/dt > 500A/µs, the increasing of I_{RM} takes over the influence of the switching time and P_{OFF} + $P_{ON}(T_R)$ increases.

The reverse recovery of the diode produces EMI that increases with the di_F/dt. In this application the best compromise to reduce the noise and have the best efficiency is to fix $di_F/dt \approx 350$A/µs ($P_{OFF}(D)$ + $P_{ON}(T_R)$) at 350A/µs $\approx$ ($P_{OFF}(D)$ + $P_{ON}(T_R)$) at 500A/µs.

Another way to reduce EMI produced by the diode is to overdimension the diode. Indeed the noise generated by the diode decreases as a function of the junction temperature.

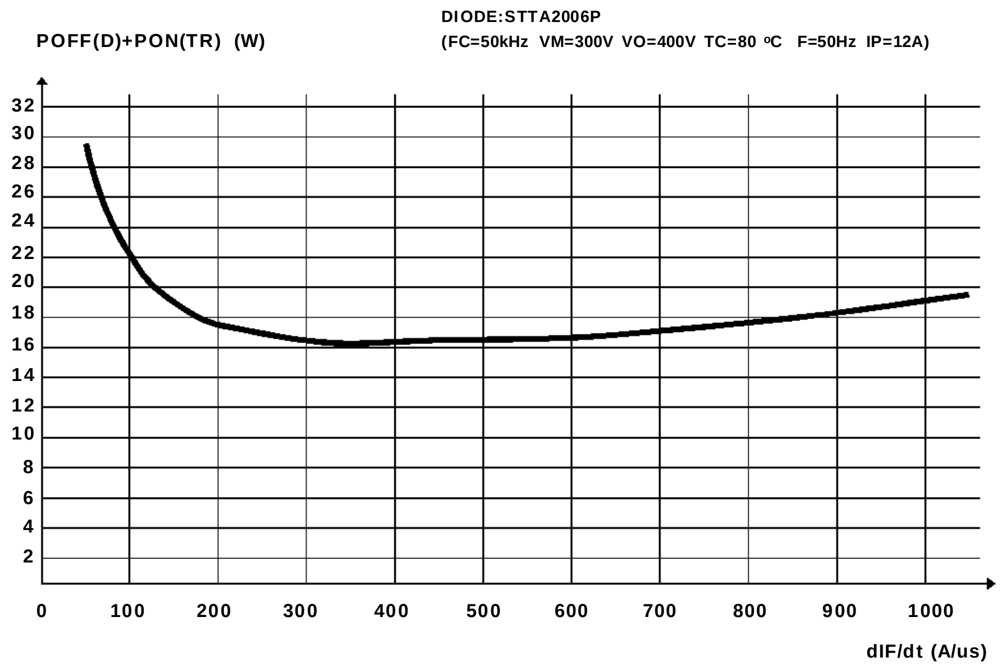
7. CONCLUSION

This paper explains why TURBOSWITCH"A" and TURBOSWITCH"B" are the right choices of diodes respectively for PFC working in continuous and discontinuous mode.

The software described in the application note is now available. It can help the designer to evaluate the influence of the different parameters (switching frequency, coil, (diF/dt)ON of the transistor ...) on the power losses in the diode and in the transistor.

This program is especially interesting to determine the optimum (di/dt)ON of the transistor. This will increase the efficiency of the converter and decrease noise.

Fig.8 : OFF losses (D) + ON losses (TR) versus (di_F/dt)ON of the transistor .



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