

**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.

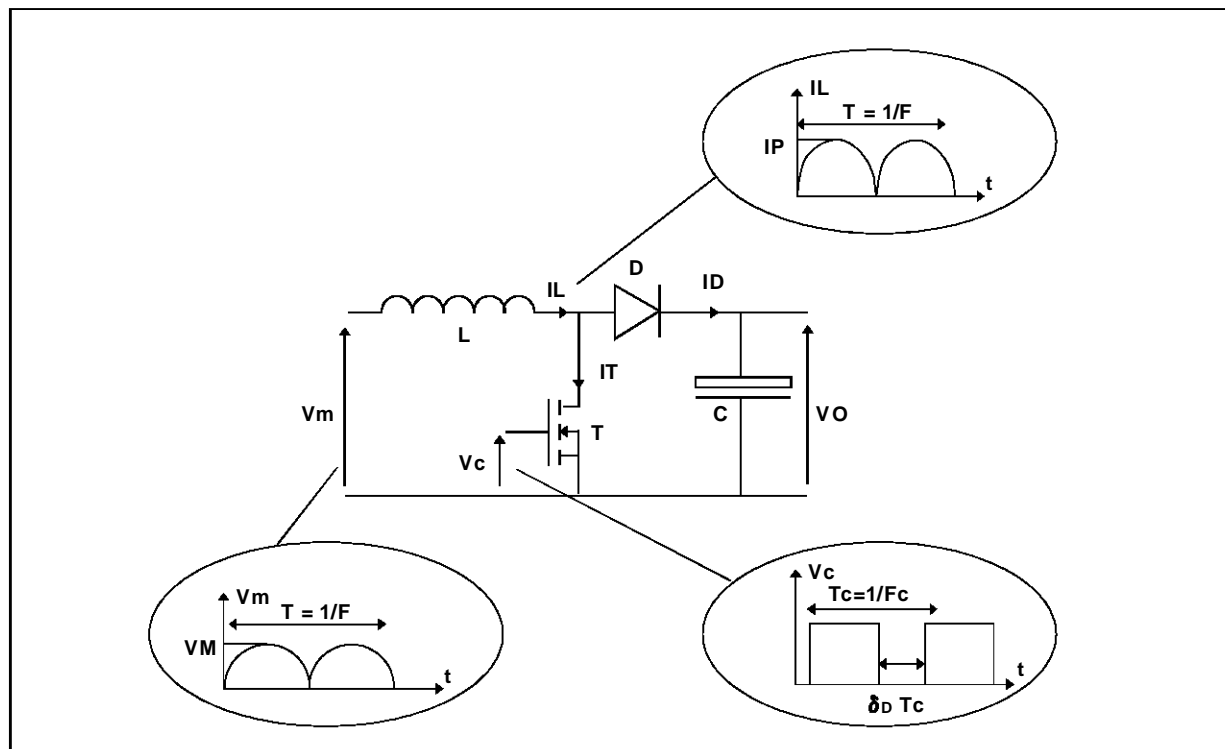
**2.PARAMETERS DEFINITION**

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

List of the parameters :

- $V_m$  : 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
- $\delta_D$  : duty cycle of the diode
- $F_c$  : switching frequency
- $V_o$  : output voltage
- $F$  : mains frequency

**Fig.1** : Boost PFC converter notations





with :

$$A = \frac{V_{mn} - V_o}{L}$$

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

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

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

$$Dn = AB T_c^2 \delta_{Dn} (2n + 2 - \delta_{Dn}) + B^2 T_c \delta_{Dn}$$

**Conduction losses in the diode**

The conduction losses in the diode are calculated with the maximum value of  $V_{TO}$  and  $R_d$  (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.

$$P_{cond} = V_{TO} I_{D(AV)} + R_d I_{D(RMS)}^2$$

**4.1.2. Turn-on losses in the diode**

These losses are estimated with the formula

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

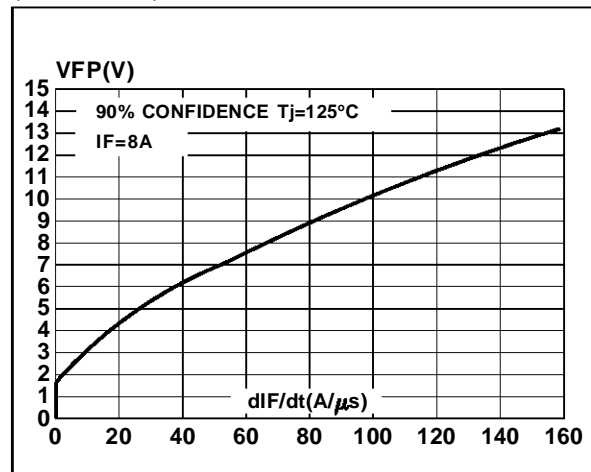
$V_{FP}$  : Peak forward voltage

$t_{FR}$  : 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 (Fig.3). These data have been stored on the disk for each part number.

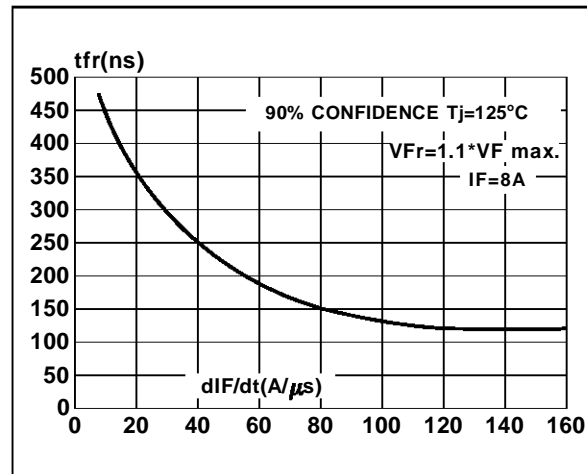
**Fig.3 :**  $V_{FP}$  versus  $di_F/dt$ .

(STTA806D)



**Fig.3 Bis :**  $t_{FR}$  versus  $di_F/dt$ .

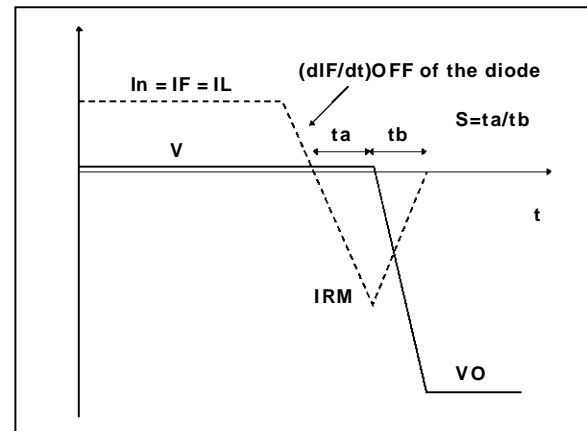
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**4.1.3. Turn-off losses in the diode**

The fig.4 shows the theoretical 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  $I_{RM}$  (Fig.5).

These data were also stored for each individual part number.

$$P_{OFF} = \frac{1}{T} \sum_{n=0}^{N-1} \frac{V_o I_{RMn}^2 S_n}{3 (di_F/dt)_{OFF}}$$

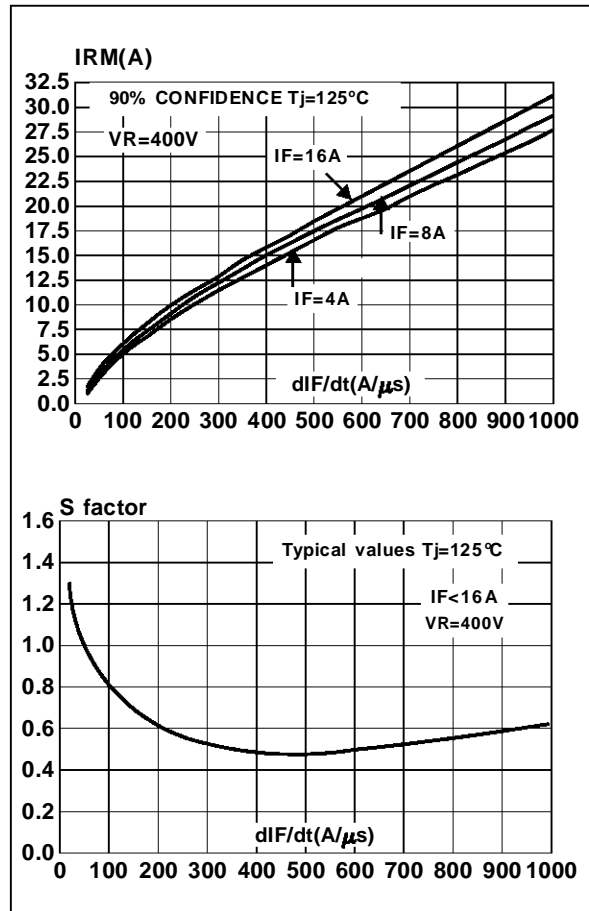
$I_{RMn}$  and  $S_n$  are respectively the reverse current and softness factor corresponding to the  $(di_F/dt)_{OFF}$  of the application and at the time  $nT$  when

## APPLICATION NOTE

$$IF = I_n = I_p \left( \sin \frac{2\pi(n+1)T_c}{T} \right)$$

These losses are calculated with data (S, I<sub>RM</sub>) at 90% confidence.

**Fig.5:** I<sub>RM</sub> and S versus di<sub>F</sub>/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 :

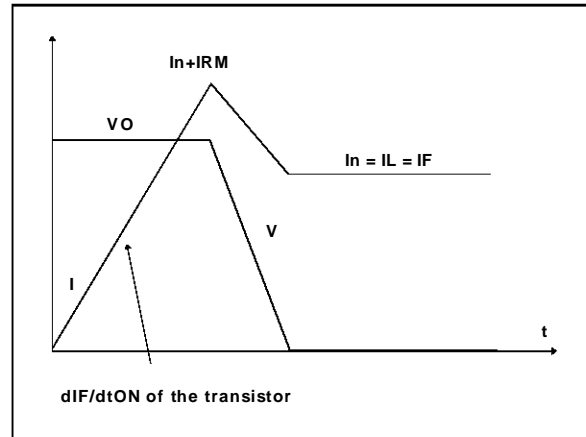
$$P_{ON} = 2 \frac{V_O}{T} \sum_{n=0}^{N-1} (M_n + G_n)$$

with :

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

$$G_n = \frac{I_n I_{RMn} (2 + S_n)}{2 (di_F/dt)_{OFF}}$$

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

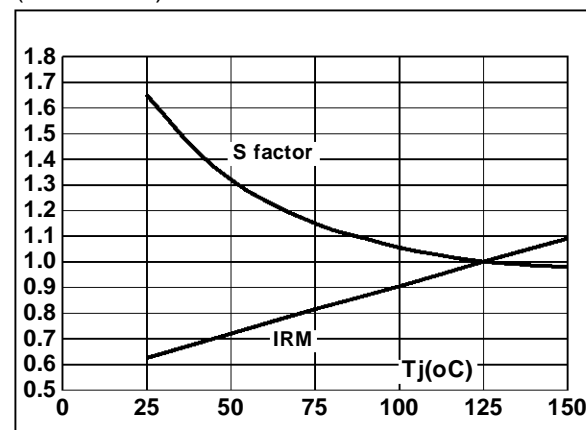


### 4.1.5. Junction temperature of the diode

S factor and I<sub>RM</sub> depend on the temperature (Fig.7). This program takes into account these variations to calculate the junction temperature. Two options are available :

Enter T<sub>case</sub> (case temperature) or, Enter T<sub>amb</sub> (ambient temperature) and R<sub>th</sub> (c-a) (case ambient thermal resistance).

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

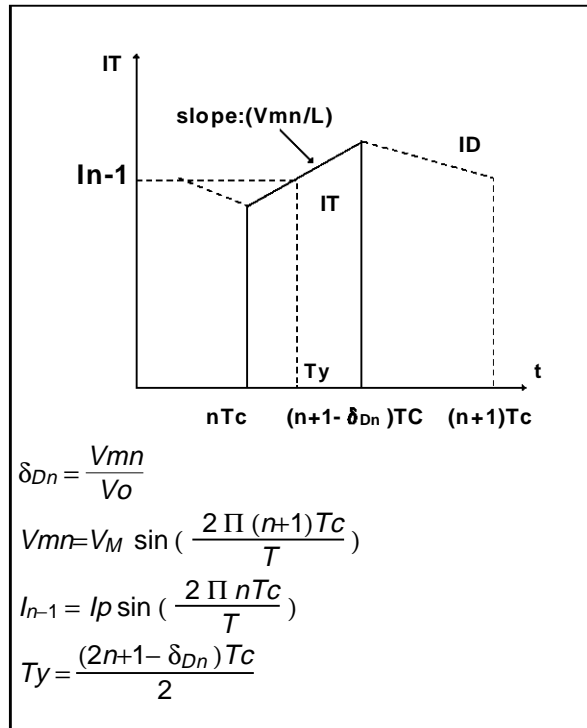


## 4.2. Results concerning the transistor

### 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 nT<sub>c</sub> and (n+1)T<sub>c</sub>.

**Fig.8 :** Current in the transistor between  $T_c$  and  $(n+1)T_c$



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

$$I_{T(AV)} = \frac{2}{T} \sum_{n=0}^{N-1} \left[ \frac{A((n+1-\delta_{Dn})^2 - n^2)T_c^2}{2} + Ln \right]$$

$$I_{T(RMS)} = \left[ \frac{2}{T} \sum_{n=0}^{N-1} [I_n + J_n] \right]^{1/2}$$

with :

$$A = \frac{V_{mn}}{L}$$

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

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

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

$$J_n = AB T_c^2 ((n+1-\delta_{Dn})^2 - n^2) + B^2 T_c (1 - \delta_{Dn})$$

Conduction losses

We have :

$$P_{cond} = r_{dSON} I_{T(RMS)}^2$$

$r_{dSON}$  :  $r_{dSON}$  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 :

$$P_{ON}(T_R) = \frac{2V_o}{T} \sum_{n=0}^{N-1} [K_n / (di_F/dt)_{OFF}]$$

with :

$$K_n = \frac{(I_n + I_{RMn})^2}{2} + S_n \frac{I_{RMn}^2}{3} + S_n \frac{I_{RMn} I_n}{2}$$

**5. EXAMPLE OF SIMULATION**

Data entered in the software :

Diode : STTA2006P

$(di_F/dt)_{OFF}$  of the diode = 500A/ $\mu$ s

$(di/dt)_{ON}$  of the diode = 500A/ $\mu$ s

- F = 50Hz
- F<sub>C</sub> = 50 000HZ
- V<sub>M</sub> = 300V
- V<sub>O</sub> = 400V
- L = 100 $\mu$ H
- I<sub>p</sub> = 20A
- R<sub>dSON</sub> = 0.1 $\Omega$
- T<sub>case</sub> = 60°C

Results

Diode results

- I<sub>D(AV)</sub> = 7.5A
- I<sub>D(RMS)</sub> = 11.8A
- P<sub>ON</sub> = 0.5W
- P<sub>OFF</sub> = 1W
- P<sub>cond</sub> = 11W
- T<sub>j</sub> = 76°C
- P<sub>ON</sub> T<sub>R(D)</sub> = 18.6W

Transistor results

- I<sub>T(AV)</sub> = 5.2A
- I<sub>T(RMS)</sub> = 9.1A
- P<sub>ON</sub>(T<sub>R</sub>) = 22.6W
- P<sub>cond</sub>(T<sub>R</sub>) = 8.3W

## APPLICATION NOTE

### 6. OPTIMUM MOSFET TURN ON di/dt

$P_{OFF}$  in the diode and  $P_{ON}(TR)$  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  $P_{ON}(TR) + P_{OFF}(D)$  versus the  $(di/dt)_{ON}$  of 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  $(di/dt)_{OFF}$  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	=	100 $\mu$ H
$T_C$	=	80°C
$I_p$	=	12A

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

The reverse recovery of the diode produces EMI that increases with the  $di/dt$ . In this application the

best compromise to reduce the noise and have the best efficiency is to fix  $di/dt \approx 350A/\mu s$  ( $P_{OFF}(D) + P_{ON}(TR)$ ) at 350A/ $\mu s \approx (P_{OFF}(D) + P_{ON}(TR))$  at 500A/ $\mu s$ .

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.

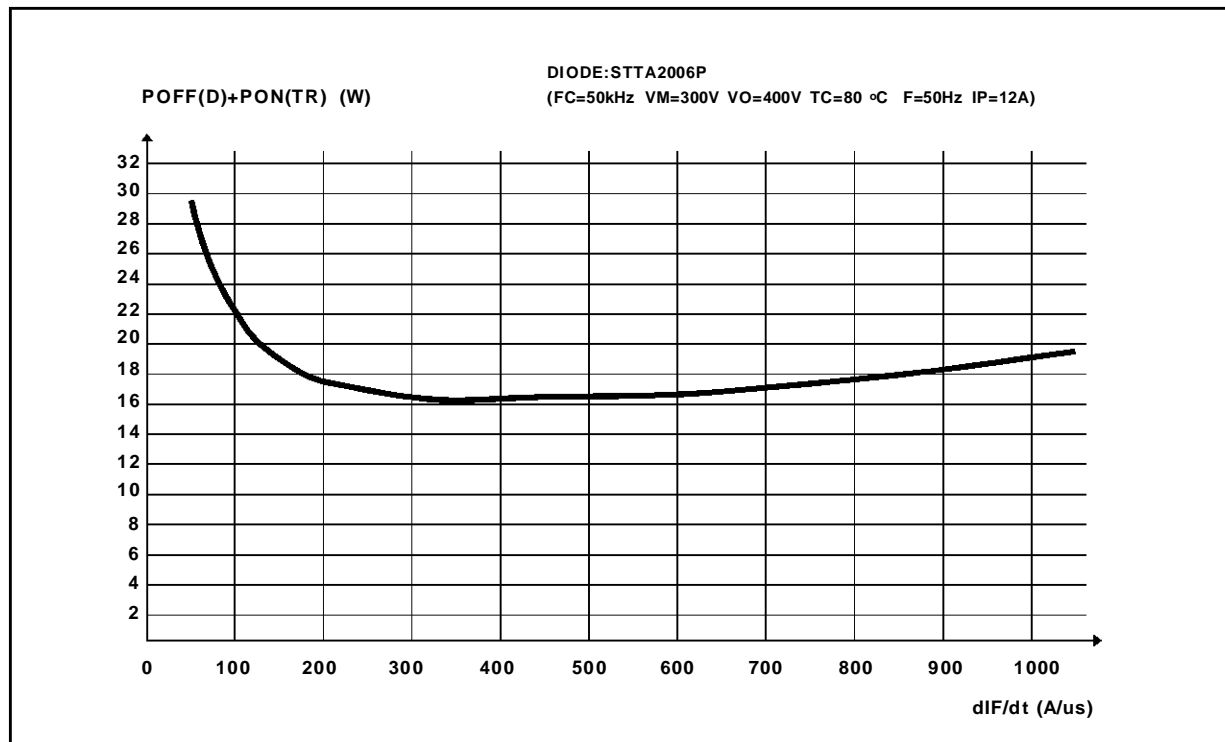
### 7. CONCLUSION

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,  $(di/dt)_{ON}$  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  $(di/dt)_{ON}$  of the transistor .



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