# AN2649
# Application note

## A power factor corrector with MDmesh$^{TM}$ II and SiC diode

### Introduction

The electrical and thermal performances of switching converters are strongly influenced by the behavior of the switching devices. Modern power devices design requires a trade-off in terms of forward voltage drop, breakdown voltage and switching speed. In AC-DC converters such as PFC circuits, efficiency is strongly related to the switch performances and the diode recovery behavior (please refer to *1* in *Bibliography on page 18*). In the past the benefits of the improved MOSFET performances have been generally spoiled by the diode current recovery behavior. In recent years the introduction of the Silicon Carbide (SiC) Schottky diode has led to an effective advantage in the switching transient losses reduction, thanks to the very low reverse recovery current with respect to the traditional fast diode. The impact on the converter of the improved characteristics of both devices leads to an increase in efficiency.

In this application note the new generation of super-junction MOSFET (MDmesh$^{TM}$ II) and SiC diodes has been used to design a 200 W continuous PFC converter. The dynamic characteristics of both super-junction MOSFET and SiC diodes, are investigated in the actual application and compared with the traditional components in order to carry out the qualitative and quantitative improvements in terms of switching performances and converter efficiency. The presented experimental results allow analysis of information for the converter designers focusing on the determination of benefits and effectiveness of the devices utilized in the considered application.

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# 1 Design consideration

The following PFC design example is referred to as an experimental board, used for demonstration purposes as described in AN628 (please refer to *2* in *Bibliography on page 18*). The design target specifications are:

- UNIVERSAL AC input supply voltage $Vin_{rms}$ = 88 V to 264 V
- DC output regulated voltage VO = 400 V
- Rated output power PO = 200 W
- Full-load output ripple ΔVout-ripple = ± 8 V
- Maximum overvoltage value ΔVout = 50 V
- Switching frequency $f_{SW}$ = 100 kHz
- Maximum Inductor current ripple ΔIL = 35% of ILrms
- Worst-condition efficiency (at minimum input voltage) η= 90%

The guidelines for controller design (L4981A) and power component selection can be found in AN628 (please refer to *2* in *Bibliography on page 18*). In the next section instead we will discuss the choice of the power MOSFET and boost diode.

# 2 Power MOSFET

Since the MOSFET device has to sustain a minimum blocking voltage value of 500 V ($V_{DSS}$ = $V_{out}$ + VOUT - ripple + $V_{out}$), then the most important parameter for the selection is the $R_{DS(on)}$ for its relation with the power dissipation.

The device STP12NM50N with its 500 V $BV_{DSS}$ and the $R_{DS(on)}$ ($R_{DS(on)max}$ = 0.38 at T= 25 °C), is the best choice for the application. The losses at turn-on depend on the selected boost diode and on the choice of the RG chosen to reduce the di/dt and therefore the levels of EMI of the converter. As described in AN628 (please refer to *2*) a gate resistance of 15 Ω has been selected for turn-on, while a diode is used for a fast turn-off.

- The maximum "on state" power dissipation evaluated at the minimum input mains voltage is:

**Equation 1**

$$P_{ON-MAX} = I^2_{Qrmsmax} \cdot R_{on-max} = (2.15)^2 \cdot 0.38 = 1.76\ W$$

- The switching (on + off) losses can be estimated as:

**Equation 2**

$$P_{SW} = P_{crossover} + P_{REC} = t_{cr} \cdot V_{out} \cdot f_{sw} \cdot I_{rms} + P_{REC}$$

where, $P_{crossover}$ are the switching losses due to the crossover time of the power MOSFET while $P_{REC}$ is the contribution due to the diode recovery.

In general $P_{REC}$ depends on the di/dt value of the current MOSFET at turn-on (and this depends on the RG value selected and the intrinsic capacitance of the MOSFET) because this di/dt sets the value of $I_{RM}$ on the boost diode recovery current. To take into account the boost diode recovery effect, for the silicon diode, an easy approach is to compute two times the current value (at turn-on). This means that $P_{SW}$ is 1.5 times the $P_{crossover}$ value, (see AN628), but for the SiC diode we can suppose (thanks to superior switching performances) that the $P_{REC}$ value is negligible.

**Equation 3**

$$P_{SW} = (15ns \cdot 400V \cdot 100kHz \cdot 2.15A) = 1.3\ W$$

The capacitive losses at turn-on to be added are:

**Equation 4**

$$P_{capacitive} \approx \frac{10}{3} \cdot C_{OSS} \cdot V^{1.5}_{out} \cdot f_{sw} = \frac{10}{3} \cdot 230pF \cdot (400)^{1.5} \cdot 100kHz = 0.6\ W$$

where $C_{oss}$ is the drain capacitance at $V_{DS}$= 25 V.

To reduce the switching losses at turn-off, a RCD snubber is used and in order to keep the junction temperature at a safe level at worst case condition, low-line input voltage (88 V) and full load (200 W), a small heatsink is used.

# 3 Booster diode

The booster diode is selected to withstand the output voltage and current. Moreover, it has to be as fast as possible in order to reduce the power switch losses (please refer to 3 in Bibliography on page 18). The STPSC806D (600 V/8 A) SiC diode matches these specifications and is especially suitable for this application. This part offers the best solution for the continuous current mode operation due to its very fast recovery time, 15 ns typical. The diode power losses can be split in two contributions: conduction losses and switching losses.

The conduction losses can be estimated by:

**Equation 5**

$$P_{Don} = V_{to} \cdot I_{out} + R_d \cdot I^2_{Drms}$$

with

**Equation 6**

$$I_{Drms} = \frac{P_{out}}{V_{lpk}} \sqrt{\frac{16 \cdot V_{lpk}}{3 \cdot \pi \cdot V_{out}}}$$

The switching losses are:

**Equation 7**

$$P_{sw} = V_{out} \cdot Qrr \cdot f_{SW}$$

where

- $V_{to}$ = threshold voltage
- $R_d$ = differential resistance
- $V_{lpk}$ = line voltage peak value
- $V_{out}$ = DC output voltage
- $I_{Drms}$= RMS value of diode current
- Qrr= total inverse recovery charge of diode

At low-line input voltage the conduction losses are bigger with respect to the case of high-line voltage while the switching losses are always negligible due to the small value of Qrr for every value of di/dt of current imposed by the MOSFET (at turn-on). The last instance is not true for the silicon diode, because Qrr is bigger and greatly depends on the di/dt value.

Furthermore the silicon diode performance are temperature-dependent (Vf, recovery current, etc.), while the SiC diode has the same behavior also for high temperature (please refer to 1 in Bibliography on page 18). In the worst case:

**Equation 8**

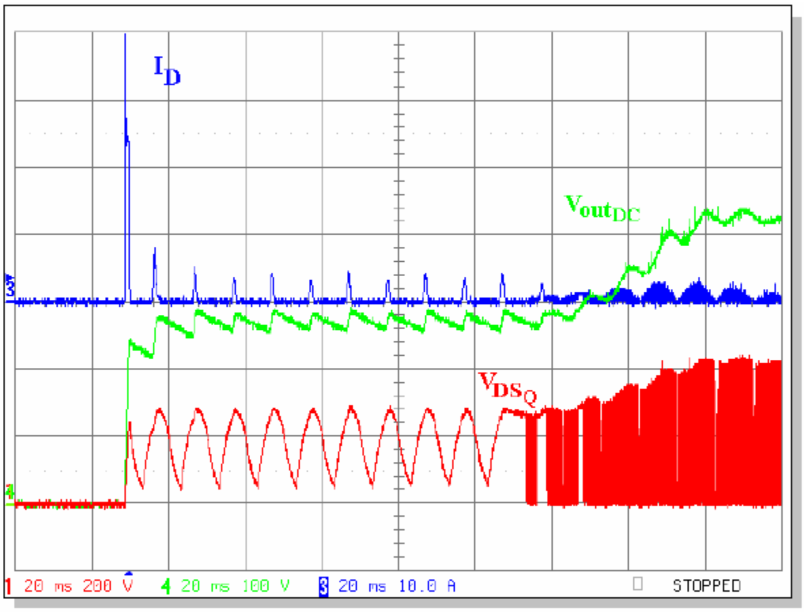
$$P_{Don} = V_{to} \cdot I_{out} + R_d \cdot I^2_{Drms} = 0.9V \cdot 0.5A + 0.065\Omega \cdot 1.28^2 A^2 = 0.55\ W$$

**Equation 9**

$$P_{SW} \cong 0\ W$$

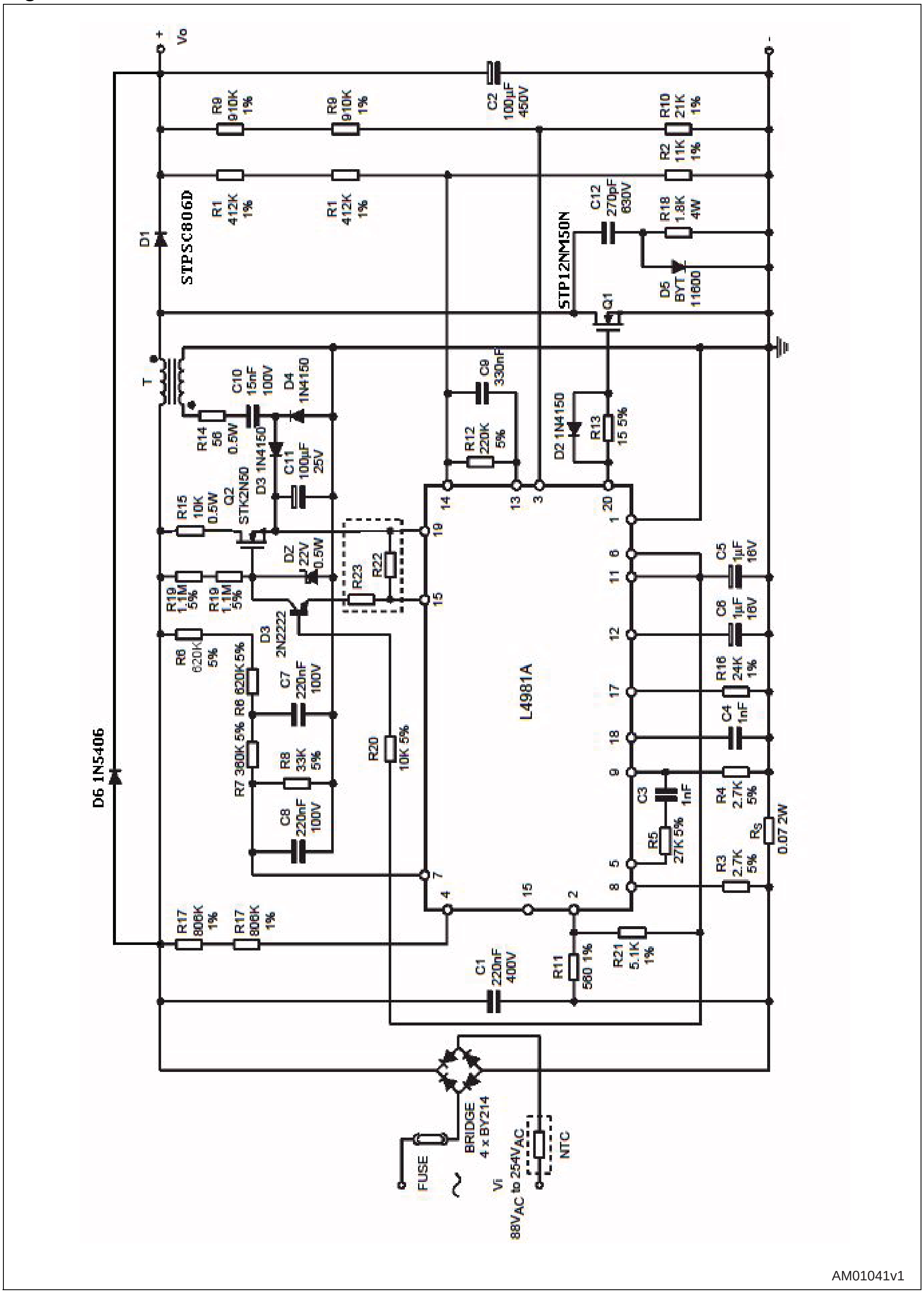
Another important parameter to take into account for the choice of boost diode is the $I_{FSM}$ value. At startup the output capacitor sinks much current (it is discharged) and the boost diode must conduct high peak level current. In this application at startup, the max peak current in the diode is about 40 A, therefore, a bypass diode must be used, (1N5406 standard diode low cost), with a high $I_{FSM}$ value, because the SiC's $I_{FSM}$ value guaranteed in the datasheet is 30 A.

**Figure 1. Current diode ID at startup**



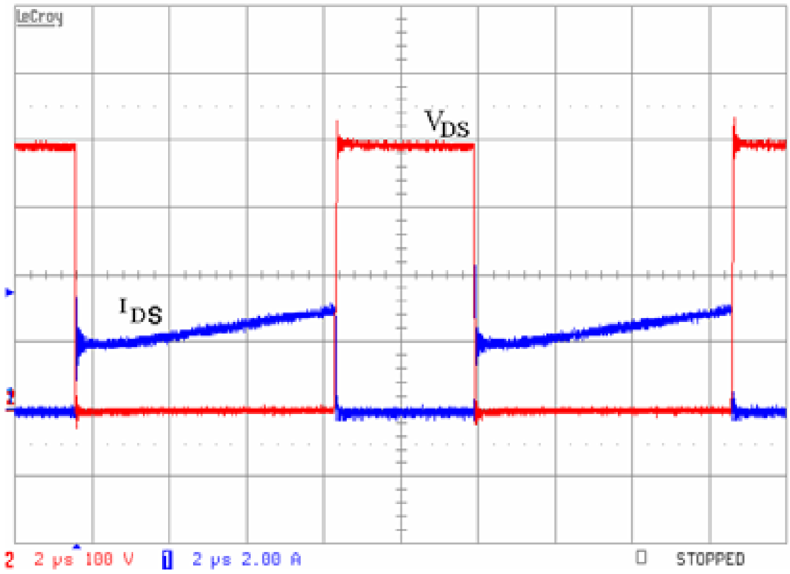

The other components have been designed with the criteria already described in other application notes and their values are given in the schematic (*Figure 2*).

**Figure 2. 200 W evaluation board circuit**



In *Figure 3* a switching cycle of the MOSFET device is reported, while in *Figure 4*, *5*, *6*, *7* and *Figure 8*, *9*, *10* and *11* are showed the turn-on and the turn-off MOS waveform for several input voltage and in full load condition (400 V/ 0.5 A).

**Figure 3. Switching cycle waveforms for MOSFET**




In the *Table 1* are reported the energy loss at turn-on and turn-off versus Vin.

**Table 1. MOSFET energy losses using SiC diode**

| Vin [Vac] | Eon [uJ] | Eoff [uJ] |
|---|---|---|
| 88 | 14.1 | 6.3 |
| 110 | 12 | 6 |
| 220 | 9 | 6 |
| 264 | 9 | 5.9 |

We observe that the value of switching losses in the worst case (Vin=88 Vac) is very close with the value estimated in the design procedure equal to the sum of (*Equation 3*) and (*Equation 4*):

**Equation 10**

$$P_{SW} = (Eon + Eoff) \cdot fsw = (14.1 + 6.3)uJ \cdot 100kHz = 2.04\ W$$

**Figure 4. Turn-on switch (with SiC diode) - Vin = 88 Vac**

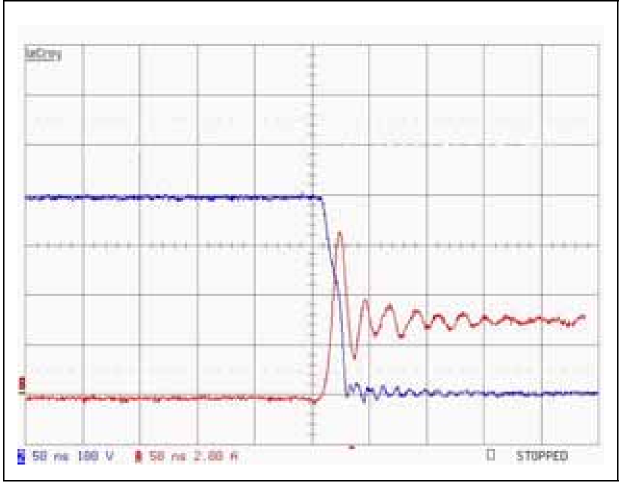



**Figure 5. Turn-on switch (with SiC diode) - Vin = 110 Vac**

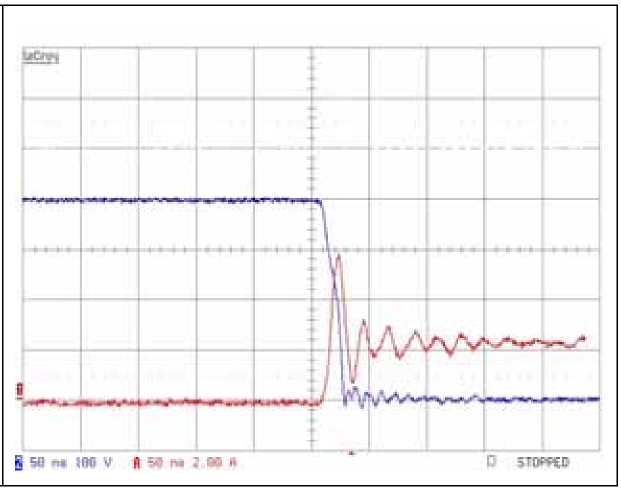



**Figure 6. Turn-on switch (with SiC diode) - Vin = 220 Vac**

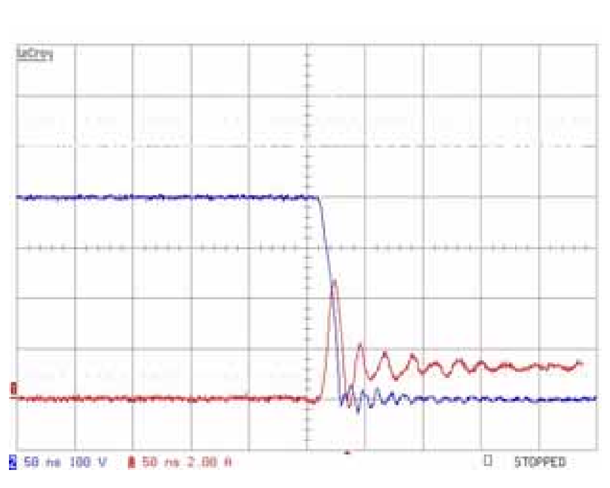
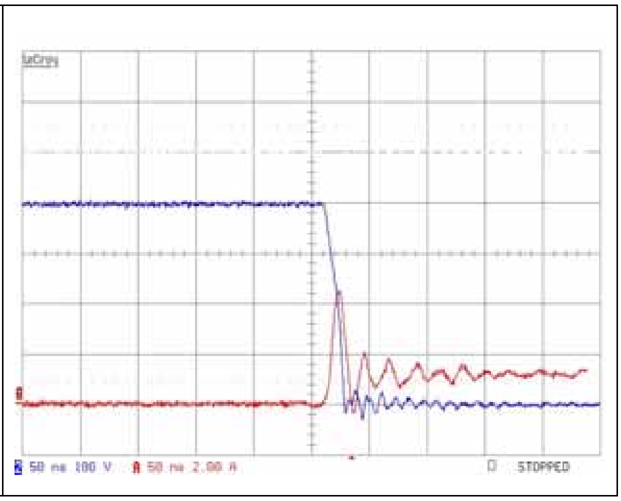



**Figure 7. Turn-on switch (with SiC diode) - Vin = 264 Vac**




The di/dt value at turn-on measured in the application, due to the Rg value selected is 450 A/µs.

**Figure 8. Turn-off switch (with SiC diode) - Vin = 88 Vac**

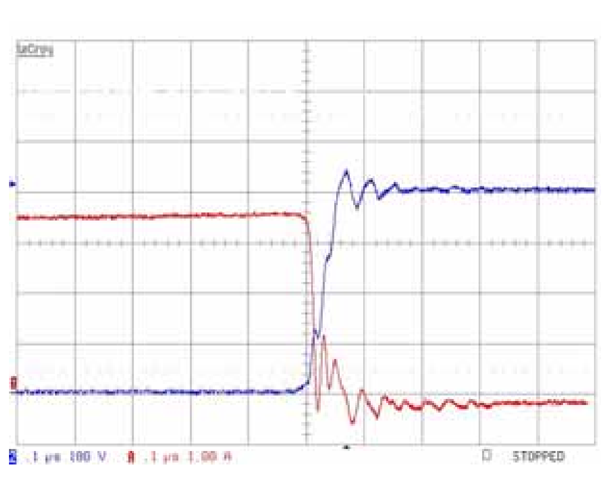



**Figure 9. Turn-off switch (with SiC diode) - Vin = 110 Vac**

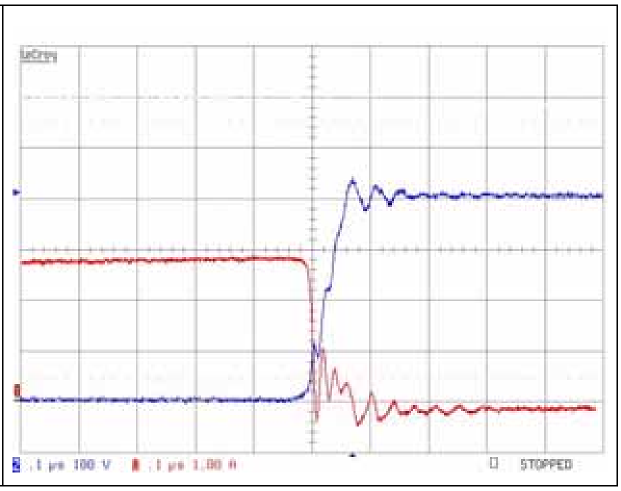



**Figure 10. Turn-off switch (with SiC diode) - Vin = 220 Vac**

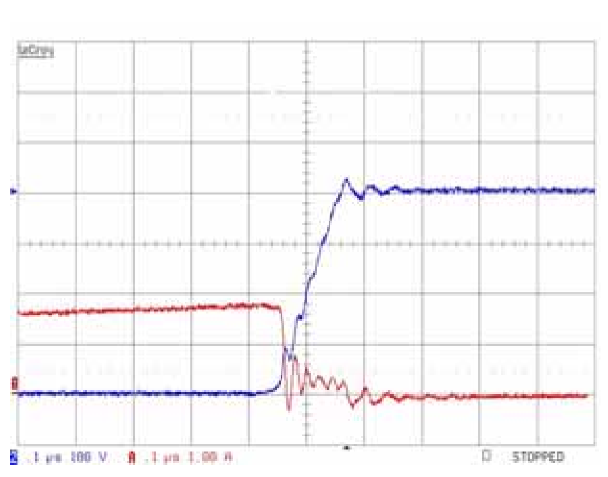
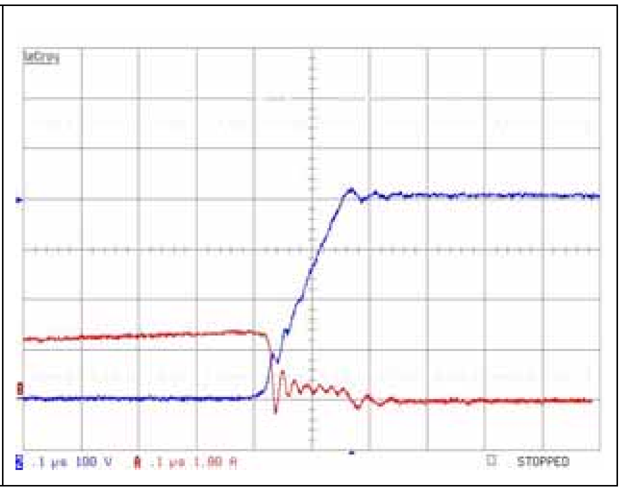



**Figure 11. Turn-off switch (with SiC diode) - Vin = 264 Vac**




For comparison purposes, the same measurements are performed using a fast silicon diode used in this application (STTA506D, as described in AN628) as the boost diode instead of SiC. *Figure 12*, *13*, *14*, *15* and *Figure 16*, *17*, *18*, *19* show the turn-on and the turn-off MOS waveform for several input voltages and in full-load condition (400 V/0.5 A).

Figure 12. Turn-on switch (with Si diode) - Vin = 88 Vac

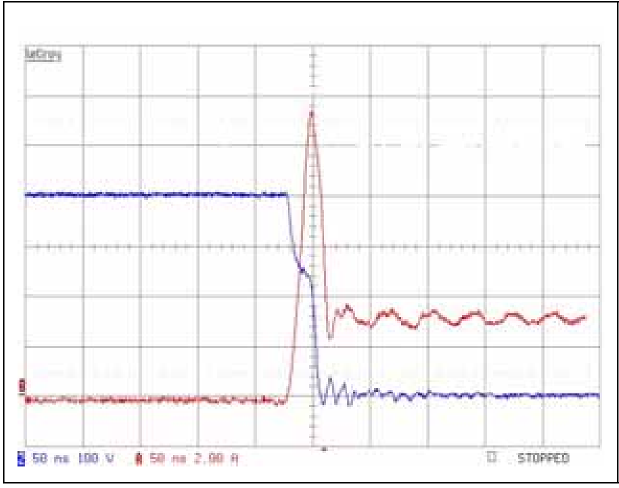



Figure 13. Turn-on switch (with Si diode) - Vin = 110 Vac

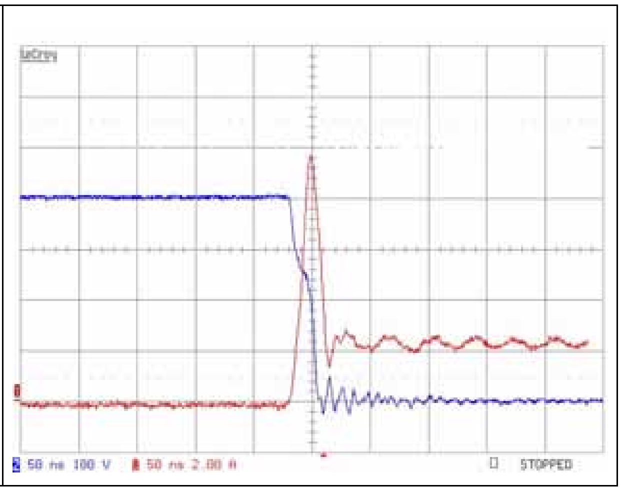



Figure 14. Turn-on switch (with Si diode) - Vin = 220 Vac

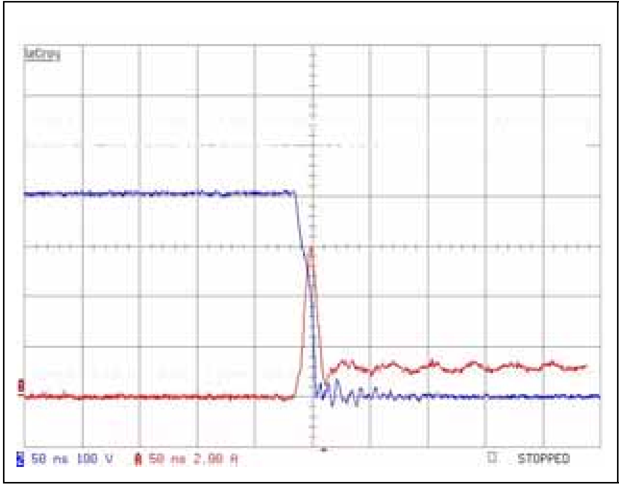



Figure 15. Turn-on switch (with Si diode) - Vin = 264 Vac

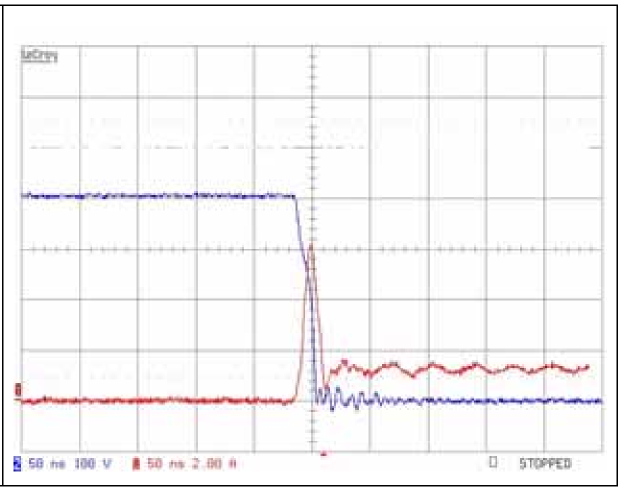


Figure 16. Turn-off switch (with SiC diode) - Vin = 88 Vac

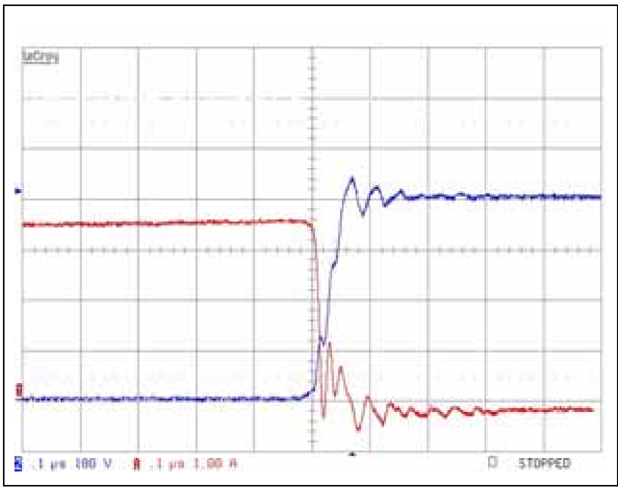


Figure 17. Turn-off switch (with SiC diode) - Vin = 110 Vac

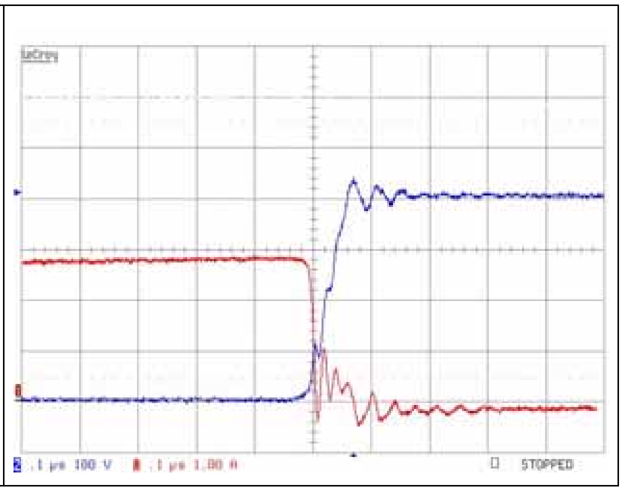


Figure 18. Turn-off switch (with SiC diode) - Vin = 220 Vac

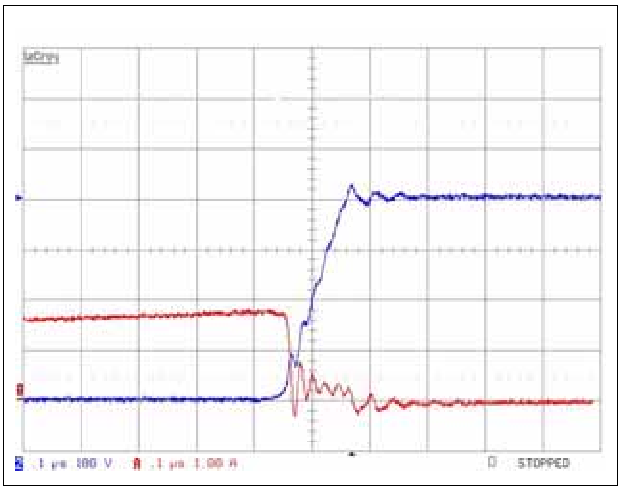


Figure 19. Turn-off switch (with SiC diode) - Vin = 264 Vac

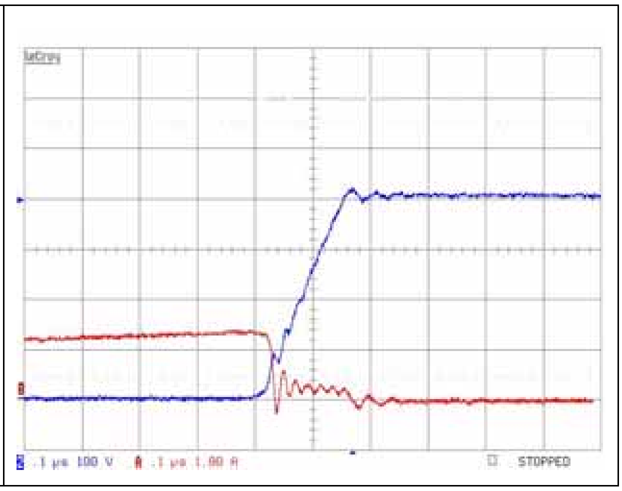


*Table 2* gives the energy losses at turn-on and turn-off versus Vin.

Table 2. MOSFET energy losses using Si diode

| Vin [Vac] | Eon [uJ] | Eoff [uJ] |
|---|---|---|
| 88 | 37.3 | 4.7 |
| 110 | 26.7 | 4.6 |
| 220 | 12.82 | 5.1 |
| 264 | 13.77 | 5.3 |

**Figure 20. Turn-off switch (with Si diode) - Vin = 88 Vac**

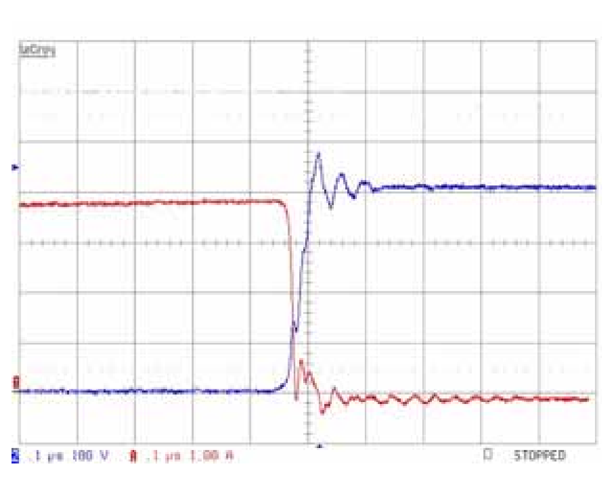


**Figure 21. Turn-off switch (with Si diode) - Vin = 110 Vac**

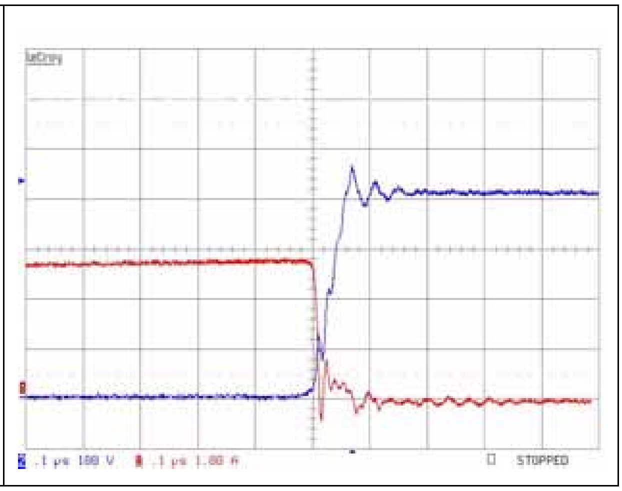


**Figure 22. Turn-off switch (with Si diode) - Vin = 220 Vac**

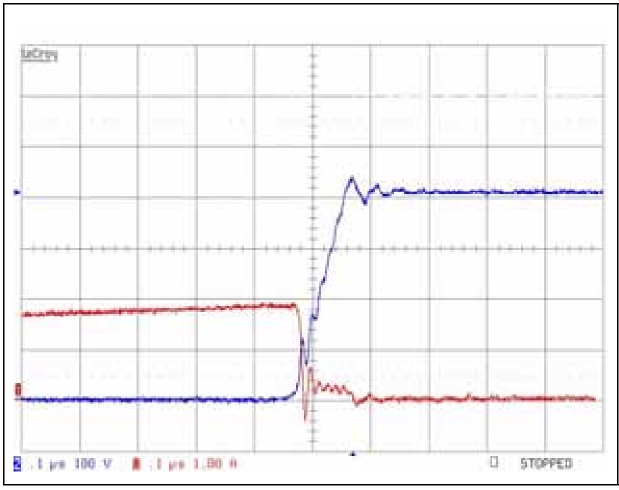
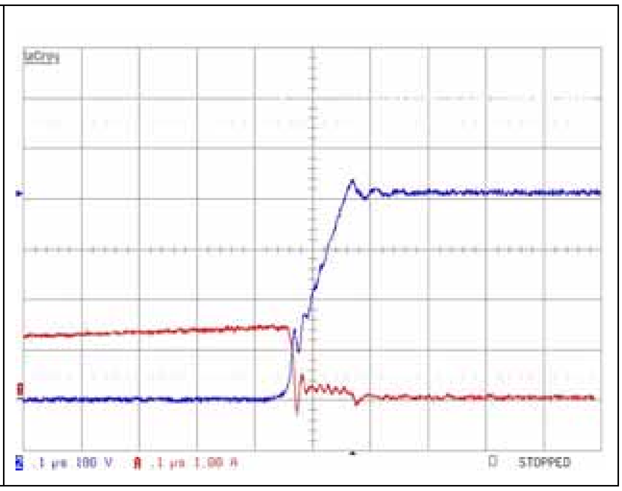


**Figure 23. Turn-off switch (with Si diode) - Vin = 264 Vac**



The turn-on switching of the MOSFET is strongly influenced by the diode recovery so the SiC diode leads to a reduction of the turn-on losses of the switch. The turn-on switching waveforms for the silicon diode case highlight the current peak at turn-on as shown in *Figure 24*. In *Figure 25* this is evident as the SiC diode allows a strong reduction of the current peak.

**Figure 24. Turn-on switch comparison (Vin = 88 Vac) - Si diode**

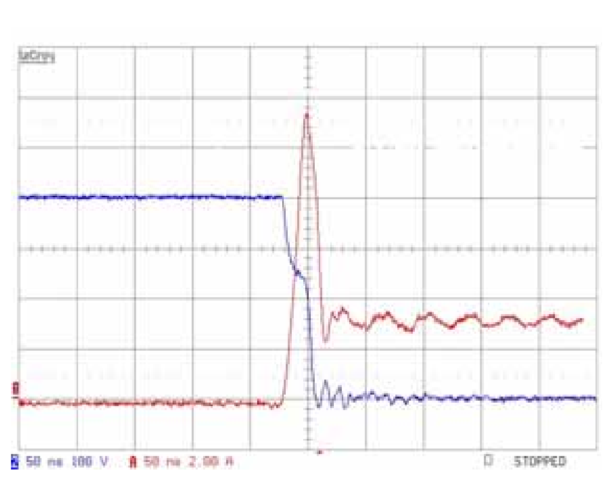
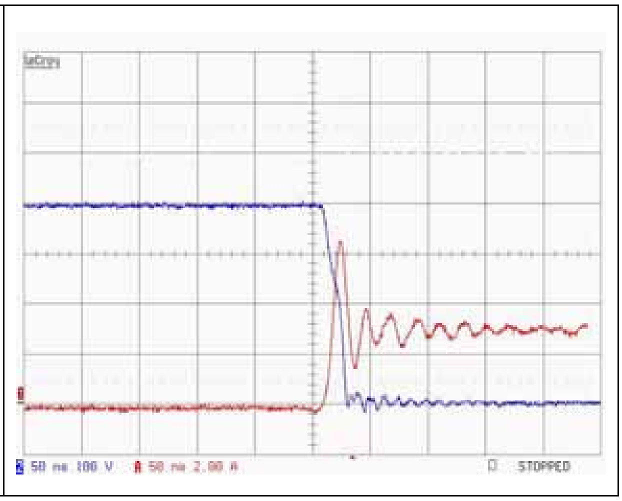


**Figure 25. Turn-on switch comparison (Vin = 88 Vac) - SiC diode**



The impact of the different device choices in the PFC converter performances has been investigated at different values of the input voltage. The PFC demonstration board performance has been evaluated, testing the following parameters: PF (power factor), THD (percentage of current total harmonic distortion), η efficiency). Furthermore a thermal analysis has been conducted. The experimental results are summarized in *Table 3* and *4*, where it is possible to compare the converter performances of the two cases of study.

**Table 3. Experimental measurements results of the PFC converter with SiC diode**

| MD2 and SiC diode | | | | | | |
|---|---|---|---|---|---|---|
| $V_{in}$ [$V_{AC}$] | $V_{out}$ [V] | $I_{out}$ [A] | $P_{in}$ [W] | THD % | PF | η [%] |
| 88 | 391.81 | 0.506 | 215.2 | 3.4 | 0.999 | 92.21 |
| 110 | 392.77 | 0.508 | 213.5 | 1.8 | 1 | 93.45 |
| 220 | 394.67 | 0.510 | 211.5 | 3 | 0.998 | 95.16 |
| 264 | 394.96 | 0.510 | 210.4 | 4.3 | 0.997 | 95.73 |

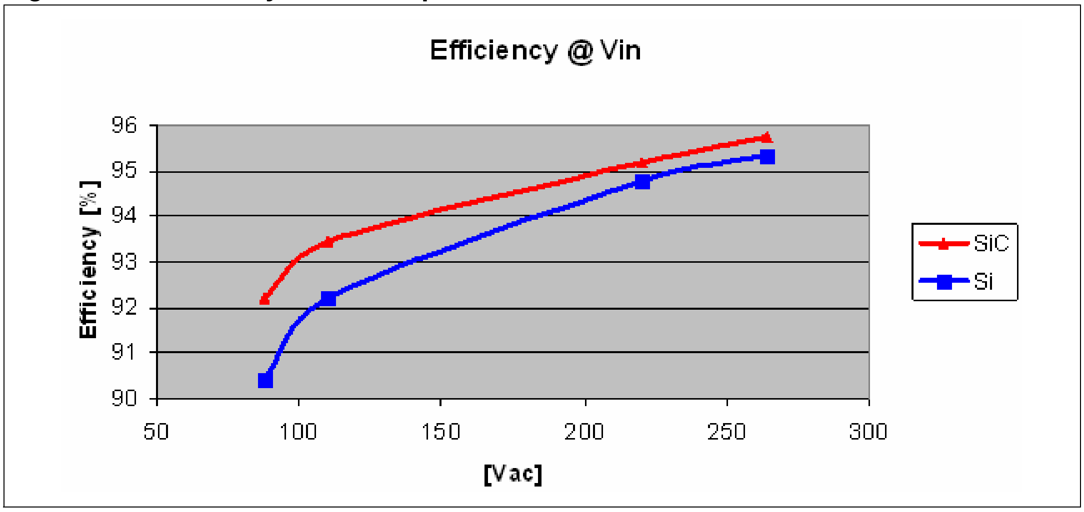
**Table 4. Experimental measurements results of the PFC converter with fast silicon diode**

| MD2 and Si diode | | | | | | |
|---|---|---|---|---|---|---|
| $V_{in}$ [$V_{AC}$] | $V_{out}$ [V] | $I_{out}$ [A] | $P_{in}$ [W] | THD % | PF | η [%] |
| 88 | 396.51 | 0.512 | 224.5 | 3.7 | 0.999 | 90.42 |
| 110 | 398.26 | 0513 | 221.8 | 1.2 | 1 | 92.23 |
| 220 | 401.74 | 0.516 | 219.1 | 2.3 | 0.998 | 94.76 |
| 264 | 402.21 | 0.517 | 218.5 | 3.9 | 0.997 | 95.31 |

*Figure 26* compares the efficiency curve versus Vin for the two cases. At high-line input voltage the difference of efficiency is smaller because the switching losses in the silicon

diode decrease (the current in the boost diode decreases) while the switching losses in SiC diode are always negligible. Furthermore as the current diode decreases also, the losses due to the diode in the MOSFET decrease.

**Figure 26. Efficiency curve comparison**




The difference in terms of efficiency is also evident if we consider the thermal behavior of power devices. In *Figure 27* we can observe the thermal maps for the MOSFET and Sic diode compared with the same MOSFET and Silicon diode in the worst case in terms of losses (Vin = 88 Vac). We note that the MOSFET and diode are compared using the same heatsinks.

**Figure 27. Thermal maps comparison - Si diode**

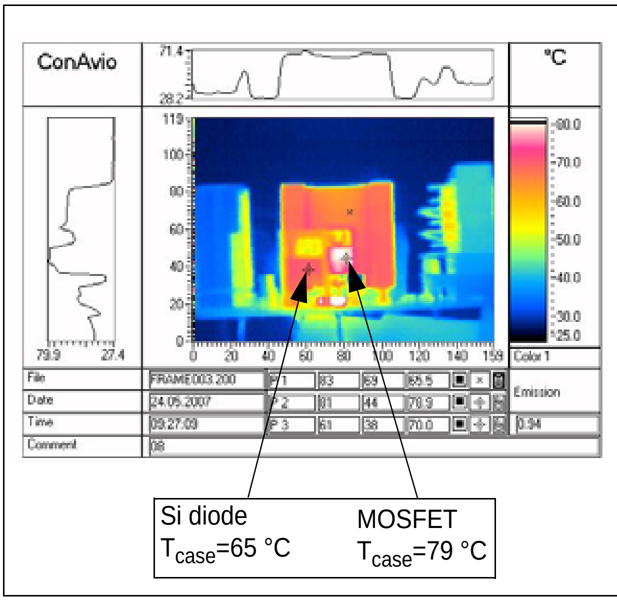
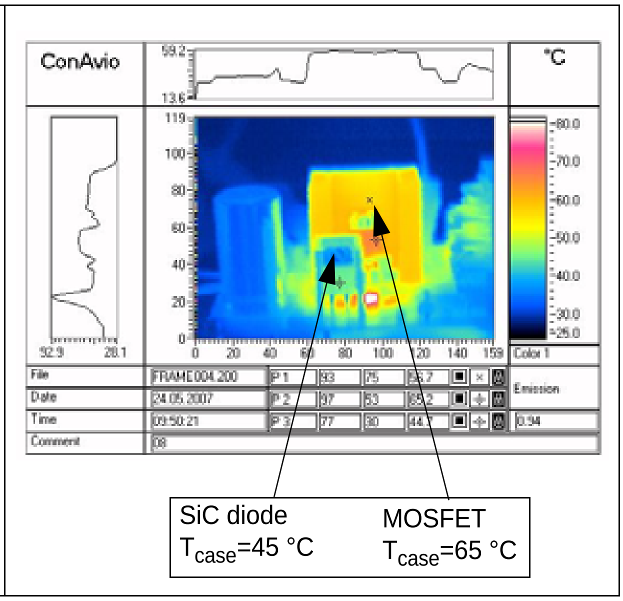



**Figure 28. Thermal maps comparison - SiC diode**




The difference in terms of temperature is 15 °C for the MOSFET and 20 °C for the diode. This is an important result for reliability as well as in terms of efficiency of the system.

These results allow using a smaller heatsink, saving cost and space.

# 4 Conclusion

In this application note an experimental investigation of the advantages and drawbacks related to the use of new devices of the last generation has been carried out in a continuous-current-mode PFC converter. In particular, the latest MOSFET MDmesh$^{TM}$ II and a SiC Schottky diode have been used. The experimental results show that the power converter using the new devices gets better switching performances and increased efficiency with respect to the case that uses the same MOSFET and an ultrafast silicon diode. The better performance in terms of efficiency and thermal behavior allow using smaller heatsinks, saving cost and space. The no-reverse recovery for the SiC diode allows using a lower gate resistance (high di/dt) optimizing the MOSFET power losses without introducing high level EMI. In this case we have a high value of di/dt (the recovery current of the SiC diode is smaller for every value of di/dt) , but the switching losses are reduced in the MOSFET ( turn-on is faster with Rg = 0 $\Omega$) with respect to the case of the silicon diode where large values of $I_{RM}$ (dependent on di/dt) and the EMI problem limits the choice of Rg.

# 5 Bibliography


1. SiC Diodes and MDmesh™ 2nd generation devices improve efficiency in PFC Applications; CIPS 2006 conference proceedings , pag.195-199
2. Application note 628: designing a high power factor switching preregulator with the L4981 continuous mode.
3. Application note: Turboswitch™ in a PFC boost converter.

# 6 Revision history

**Table 5. Document revision history**

| Date | Revision | Changes |
|---|---|---|
| 10-Mar-2008 | 1 | Initial release |
| 12-Sep-2008 | 2 | – STPS8600SIC replaced by STPSC806D<br>– Modified: *Figure 2* |