Benefits of Silicon Carbide Schottky Diodes in Boost APFC Operating in CCM

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Abstract – Boost derived Active Power Factor Correction (APFC) imposes high stress on the main diode and main switch due to the high reverse voltage which may result in a very high reverse current. This study analyses the engineering requirements of the diode and transistor in APFC applications and compares a design that uses a fast silicon diode plus lossless snubber to a design with a Silicon Carbide (SiC) diode without snubber. The theoretical considerations where verified by comparing the performance of an ultra fast diode (MUR860, ON Semiconductor) with a lossless snubber to that of a SiC diode (SDP06S60, Infineon) without a snubber, in 1kW Boost APFC stage. The experiments confirm the conclusions of the theoretical prediction that the SiC is an excellent technological solution to Boost APFC stage operating under CCM conditions.

I. Introduction

Boost derived Active Power Factor Correction (APFC) circuits impose high stresses on the main diode and switch. This is especially true when the APFC stage operates in the Continuous Current Mode (CCM) in which the diode current does not drop to zero during the D_{off} period. Consequently, when the transistor is turned 'on' the silicon diode current will reverse direction and may reach very high values. The peak reverse current I_{pk} is a function of the reverse recovery process of the silicon diode (Fig. 1) and of the total inductances L_{stray} of the circuit (Fig. 2). The magnitude of the peak reverse current can be limited by adding a di/dt snubber that includes inductor (L) in series with the diode (Fig. 3). In this case, both the peak reverse current and the energy trapped in the snubber inductor will be smaller. This is due to the fact that the trapped energy is:

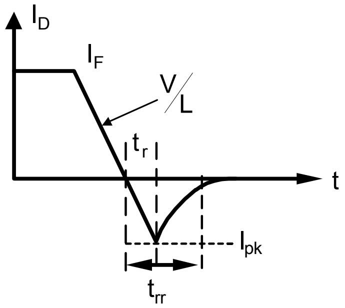

Fig. 1. Reverse recovery of a Silicon diode.

$$E_t = \frac{L I_{pk}^2}{2} \qquad (1)$$

while I_{pk} is proportional to V_o/L. Consequently, the larger the L the smaller is the trapped energy. An auxiliary network such as the one

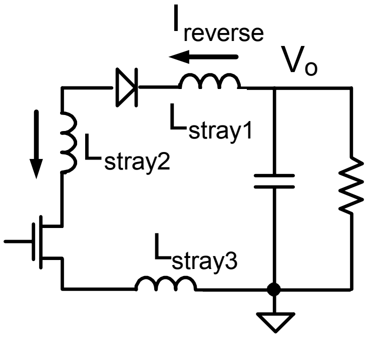

Fig. 2. Turn 'on' instance of a Boost APFC.

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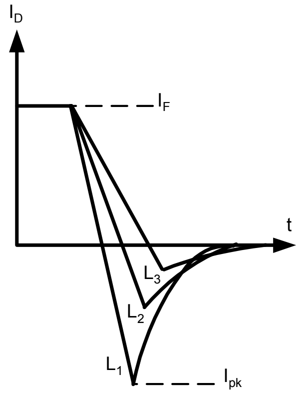

Fig. 3. The effect of series inductance on the reverse recovery process. $L_3 > L_2 > L_1$.

energy. An auxiliary network such as the one shown in Fig. 4 [2, 3] can recover this energy. Similar types of lossless snubbers have been used in the industry in recent years to remedy the adverse effects of the reverse recovery of silicon diodes.

The commercial introduction of the Silicon Carbide (SiC) Schottky diodes (Infineon) changes the pictures completely. As will be detailed in the paper, these fast diodes have negligible stored junction charge. Consequently, the reverse recovery current is very small and the behavior is more like a capacitor rather than the classical reverse recovery process found in silicon diodes [1]. The objective of the study was to compare the performance of a fast silicon diode with lossless snubber, to that of a SiC diode in Boost APFC circuit, which is one of the most demanding application.

II. The Lossless Snubber

The basic configuration of the lossless snubber applied in this study is given in Fig. 4 [3]. Its main purpose is to limit the reverse recovery current and to recover the energy trapped in the snubbing inductor L_s. At turn on of Q, L_s limits di/dt and when the diode ceases to conduct the energy trapped in L_s is moved to C_s. At turn off of Q, D_1,D_2 clamp the drain of Q to V_o and the energy stored in C_s is transferred first to L_s and then to the output. Details are given in [3] which also discuss the tapped inductor version of the snubber (Fig. 5). The purpose of the tap is to provide extra DC voltage to the resonant circuit so as to make sure that the main current will pass via D_o during T_{off}.

Since the operation of the snubber relies on the proper operation of its resonant behavior, ample time must be given to the resonant process to complete. For example, if L_s does not transfer all the trapped energy to C_s (just after the reverse recovery process) the current may build up, leading to a fault. Hence, the operation of the snubber relies on having sufficient time for the process to complete during turn on and turn off. This leads to a restriction concerning the minimum permissible T_{on} and T_{off}. The exact timing of the resonant cycle depends on the operating or conditions [2], but the order of magnitude is approximately a quarter of the resonant period. i.e.

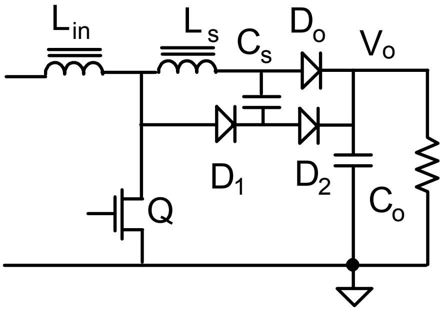

Fig. 4. Basic configuration of a Boost converter with lossless di/dt snubber.

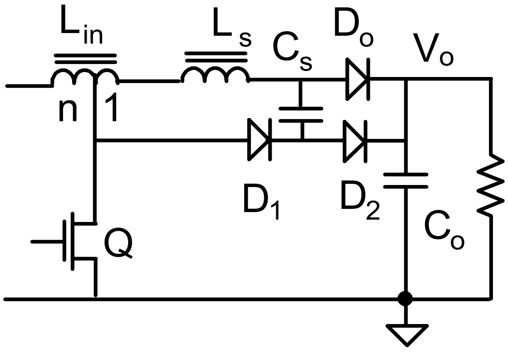

Fig. 5. Tapped inductor version of the lossless snubber.

$$T_{\min} \approx \frac{\pi\sqrt{L_s C_s}}{2} \tag{2}$$

The minimums ON and OFF times restrict the permissible range of the duty cycle. The main problem is the limitation of T_{off} that sets the limit for the maximum peak input voltage. In Boost converter:

$$\frac{V_o}{V_{in}} = \frac{1}{D_{off}} \tag{3}$$

And therefore:

$$Vin_{pk}(max) = V_o f_s (1 - T_{on}(min)) \tag{4}$$

Where f_s is the switching frequency.

This limitation is more significant as the switching frequency increases. Consequently, if a high switching frequency is desired, either L_s C_S need to be made smaller. Making the inductor smaller will increase the reverse recovery current and will increase the voltage across C_s just after turn-on. This will increase the reverse voltage of the output diode and may require a diode with a larger blocking voltage. Similarly, decrease in the value of C_s will also increase the voltage across it.

An estimation of the practical limitations of the switching frequency can be obtained by the following approximate analysis.

The peak reverse current of the diode will be (Fig. 1):

$$I_{pk} = \frac{V_o}{L_s} t_r \qquad (5)$$

Where t_r is as defined in Fig. 1.

The maximum voltage of the snubber capacitor (V_C(max)):

$$V_C(\max) = I_{pk}\sqrt{\frac{L_s}{C_s}} \qquad (6)$$

or, by applying (5):

$$\frac{V_C(\max)}{V_o} = \frac{t_r}{\sqrt{L_s C_s}} \qquad (7)$$

and from (2):

$$\frac{V_{Cc}(\max)}{V_o} = \frac{\pi t_r}{2T_{\min}} \qquad (8)$$

which implies

$$T_{\min} \approx \frac{\pi t_r}{2\dfrac{V_C(\max)}{V_o}} \qquad (9)$$

An example of the constraint imposed on the switching frequency we shall assume the followings:

$V_C(\max) = M\, V_o$ (10)

$1/T_{\min} = P\, f_s$ (11)

where

M, P < 1 (12)

Using these definitions:

$$f_s = \frac{P\,M}{\pi\, t_r} \qquad (13)$$

Considering a practical case: t_r=50nS; P=0.1; M=0.2, we find:

$f_s \approx 125$kHz

This numerical example clearly shows that the snubber technology is restricted to rather moderate switching frequencies. Higher switching frequencies can be reached by using faster diode, or using a diode with a higher breakdown voltage. Both will increase the cost of diode to be added to the extra components needed for implementing the lossless snubber.

III. The Silicone Carbide Schottky Diode

Unlike the case of a Silicone diode, the Silicone Carbide Schottky (SiCS) diode behaves more like a non-linear capacitor rather than a PN junction. That is, the charged energy in the SiCS is primarily a charge associated with a capacitor. Consequently, the diode's turn-off process entails a removal of a constant charge, practically independent of di/dt. The charge for a 600V 6A diode is (SDP06S60, Infineon) is Q_d=21nC for a forward current of 6Amp [4]. Assuming that all the energy associated with this charge is dissipated, the power loss due to this charge removed from the output V_o at f_s will be:

$P_{dq} = Q_d\, f_s\, V_0$ (14)

At 100 kHz and 380V output voltage this would translate into about 0.8W. However, as the frequency increases, the dissipated power could be significant (8W at 1MHz). Conceivably, this charge could be circulated in a lossless manner by using a snubber similar to one shown in Fig. 5. Assuming that all energy is transferred to the snubber capacitor C_s, the maximum voltage across it will be:

$V_C(\max) = Q_d\, C_s$ (15)

For example, a 1nF capacitor will develop a 21V voltage for the 21nQ charge, increasing only slightly the reverse voltage on main diode.

However, to pursue this snubber idea for the SiCS diode at very high switching frequencies, one would need extremely fast diodes for D_1, D_2 (Fig. 4, 5). This approach was not pursued in this study.

An additional point that needs to be mentioned is that the forward voltage drop of the SiCS diode is somewhat larger than that of the Silicone diode. Furthermore, the voltage drop increases with junction temperature, opposite to behavior of the Silicone diode. This increase in voltage offsets to some degree the reduction of switching losses. However, since the power loss associated with the forward drop is not frequency dependent, the performance of the SiCS will be clearly superior to Silicone diodes at very high switching frequencies.

IV. Experimental Results

The experiments were designed to compare the performance of an ultra fast diode (MUR860, ON Semiconductor) with a lossless snubber to that of a SiC diode (SDP06S60, Infineon) without a snubber, in 1kW Boost APFC stage. The MUR860 is relatively slow as compared to recently introduced super fast diodes that are more expensive. Output bus voltage was nominally 375V. The input was 220VAC in normal APFC operation or 155VDC when oscilloscope traces were recorded. Switching frequency was 120kHz. The power MOSFET was IRFP460. Snubber components (Fig. 5) were: L_s = 7uH; C_s=0.1uF; D_1,D_2=MUR406; n=7. Fig. 6 shows the Silicone diode and main switch currents at turn 'on', when the circuit was operated without a snubber. In this case, the output voltage was limited to 98V to prevent damage to the circuit. At turn 'on' the transistor carries the diodes current plus the inductor current. Here the peak reverse current reached 4Amp which implies that for 375V output the peak current would have reached 14Amp for the nominal experimental forward current of 1.5Amp. The performance with the silicone diode and snubber is much better (Fig. 7), the maximum reverse current reached 3.8 Amp for the nominal 375V output. This peak is tolerable especially since the snubber circulated the trap energy in the inductance.

The performance of the SiC diode is superior to the silicone diode plus snubber solution (Fig. 8). Peak reverse current is less than the 2Amp (under same condition) and the reverse process is very short (less than 25nS).

The study also examined the switching process of the main switch with the silicon diode and snubber solution and when the SiC diode is used. In the case of the silicone diode with snubber, we find at turn-on a quick drop in the MOSFET voltage V_{DS} (Fig. 9). The peak current reflects the peak reverse current of the diode. It should be noted though that at the instance of the peak, the drain voltage is already low. In the SiCS diode case (no snubber) (Fig. 10), we

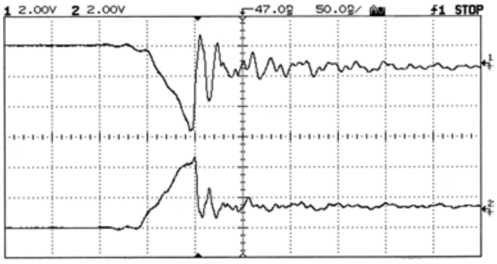

Fig. 6. Silicon diode current (upper trace) and transistor current (lower trace) in Boost APFC without snubber. V_o = 98V; Horizontal scale: 50nS/div. Vertical scale: 2A/div.

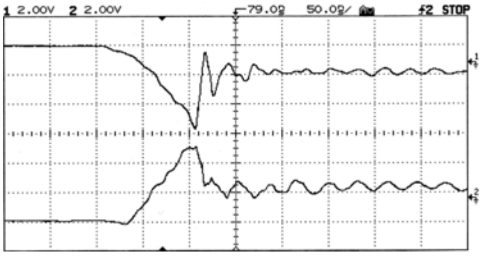

Fig. 7. Silicon diode current (upper trace) and transistor current (lower trace) in Boost APFC with lossless snubber. V_o = 375V; Horizontal scale: 50nS/div. Vertical scale: 2A/div.

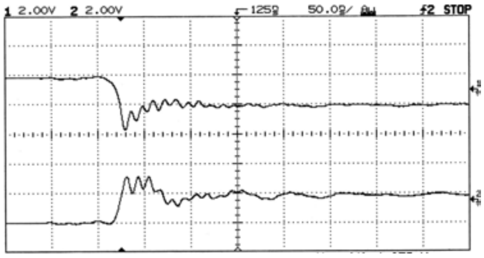

Fig. 8. Silicon Carbide Schottky diode current (upper trace) and transistor current (lower trace) in Boost APFC with lossless snubber. V_o= 375V; Horizontal scale: 50nS/div. Vertical sale: 2A/div.

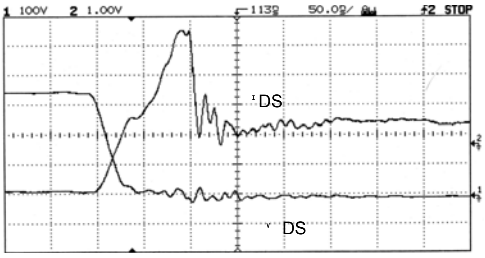

Fig. 9. MOSFET voltage and current when operated with Silicone diode and a lossless snubber. Vertical scales: 1A/div &100V/div. Horizontal scale: 50nS/div.

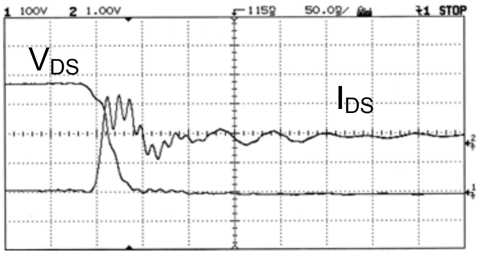

Fig. 10. MOSFET voltage and current when operated with SiCS diode. Vertical scales: 1A/div &100V/div. Horizontal scale: 50Ns/div.

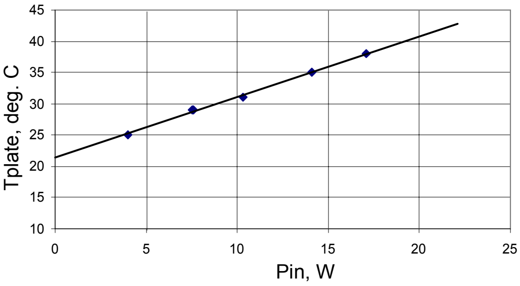

Fig. 11. Heatsink calibration curve.

observe a slower drop of the MOSFET voltage. This is due to the fact that the attenuating effect of L_s is now absent. The peak voltage of the transistor is lower but, at the peak, the voltage of the transistor is still relatively high. This process is a reflection of the fact that the energy loss associated with the average current due to the stored charge of the SiCs diode now dissipates in the transistor.

The heatsink of the experimental set up was calibrated by the method detailed in [3]. It entails the measurement of the temperature rise as a function of the power dissipated by the devices attached to the heatsink. The calibration curve is shown in Fig. 11. Applying this procedure it was found that for a 350W power level the temperature rise for the case of Silicone diode plus snubber and for the case of SiCs diode without snubber, was about the same: 32°C. This corresponds to about 10W dissipation.

V. Discussions and Conclusions

The superior reverse recovery process of the SiCS diode which is characterized by short and small reverse current, eases the design of the Boost APFC stage. Losses will be lower and there is practically no need for a snubber to protect the circuit against over-current and over-voltage peaks.

This paper concentrated on the comparison between the SiCs diode and a (relatively slow and hence low cost) Silicone diode plus a snubber. It is fair to assume that the SiCS technology will be more expensive than the silicone technology and hence a low cost Silicone diode plus snubber may be comparable and even of lower price than the SiCS diode. Consequently, for switching frequencies of about 100kHz, the SiCS may not have a significant advantage over the silicone diode. However, at higher switching frequencies the SiCS is no doubt a better choice both from the performance and economics points of views.

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