Analysis, Design, and Performance Evaluation of Flying-Capacitor Passive Lossless Snubber Applied to PFC Boost Converter

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Abstract - **A boost converter which employs a flying-capacitor passive lossless snubber to reduce the losses caused by the reverse-recovery characteristic of the boost rectifier is described. The passive snubber consists of a snubber inductor, two snubber rectifiers, and a snubber capacitor. The losses are reduced by inserting a snubber inductor in the series path of the boost switch and the rectifier to control the di/dt rate of the rectifier during it's turn-off. The snubber is analyzed and design guidelines are offered to achieve optimum performance. The proposed snubber is applied to a 500-W power factor corrected (PFC) boost converter which is designed to operate in the universal line range (90-264 V_{RMS}). Performance evaluations of the proposed snubber are made and compared to the conventional boost converter with respect to efficiency and device temperature.**

I. INTRODUCTION

In mid-to-high power off-line power supplies, the continuous-conduction-mode (CCM) boost converter is the preferred topology for implementing the front-end converter with active input-current shaping. However, since the dc-output voltage of the boost converter must be higher than the peak input voltage, the output voltage of the boost input-current shaper is relatively high. Due to the high output voltage, the converter requires the use of either a high-voltage, fast-recovery silicon (Si) rectifier, or a recently introduced silicon carbide (SiC) rectifier. At high switching frequencies, fast-recovery Si rectifiers produce significant reverse-recovery-related losses when switched under "hard" switching conditions [1]. These losses can be significantly reduced and, therefore, a high efficiency can be maintained even at high switching frequencies by employing a soft-switching technique [2]-[9]. Generally, SiC rectifiers exhibit no reverse-recovery-related losses. However, presently SiC rectifiers are offered at a significantly higher price than the fast-recovery type Si rectifiers which practically excludes them from being used in power supplies for consumer electronic products.

The key to achieve soft switching of the boost rectifier is to control its turn-off di/dt rate using a current snubber. Generally, the current snubber consists of a small inductor, which slows down the di/dt, and an active or passive network, which recovers the energy stored in the inductor in anticipation of the next switching cycle. The reset mechanism is considered lossy if the recovered energy is dissipated and (ideally) lossless if the energy is recycled or recirculated to either the input or output of the converter.

A passive reset network consists of combinations of diodes, capacitors, resistors, and inductors without the use of an additional switch. Generally, soft switching of the boost rectifier in a passive PFC circuit can be achieved with a lower component count than in an active PFC circuit, which makes it attractive at higher switching frequencies. However, zero-voltage turn-on of the main switch is not possible since the moment of turn-on is not anticipated by the passive snubber components. Therefore, the main switch operates under hard-switching conditions. Generally, this degrades the performance of the converter and makes it less attractive from a performance point of view. Nevertheless, passive snubber approaches are widely used since they are generally simpler to design and require fewer components, making them potentially more cost-effective than an active solution.

In this paper, a design oriented analysis is performed of a flying-capacitor passive lossless snubber [2]-[4] applied to a universal-input (90-264 V_{RMS}) power-factor corrected (PFC) boost converter. The limitations in operating range of the snubber are defined and practical design guidelines are offered to achieve optimum performance.

II. ANALYSIS OF OPERATION

The "flying-capacitor" passive snubber is shown in Fig. 1 [2]-[4]. It utilizes an inductor L_S as the turn-on current snubber with capacitor C_S and two rectifiers D_1 and D_2 as the reset network. Reverse-recovery energy is first stored in snubber inductor L_S during turn-on of main switch S and delivered to capacitor C_S at turn-off of rectifier D. This

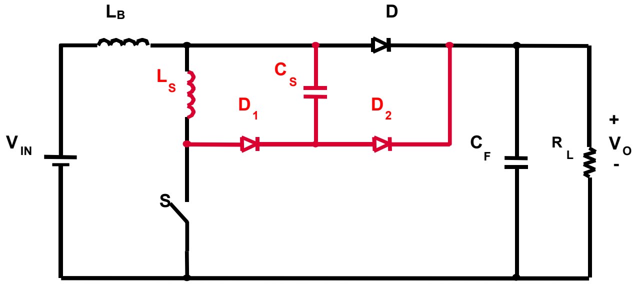
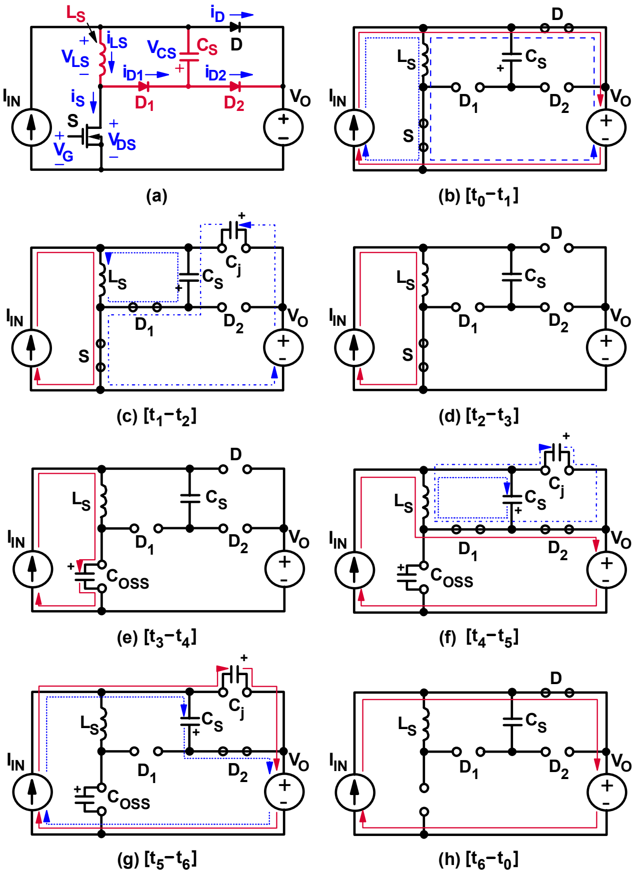


Fig. 1 Circuit diagram of "flying-capacitor" passive lossless snubber applied to boost converter.

energy is then used to reset the snubber immeadietly following turn-off of main switch S. Since reverse-recovery energy is never dissipated in a discrete resistor, but rather recirculated, it is considered to be ideally lossless.

To facilitate the explanation of the snubber operation, Fig. 2 shows the topological stages of the circuit in Fig. 1 during a switching cycle, whereas Fig. 3 shows the key switching waveforms. In order to simplify the explanation of the converter operation in Fig. 1, boost inductor L_B and input voltage source V_{IN} have been approximated as a constant-current source, I_{IN}, since it is assumed that inductor $L_B >> L_S$, while output capacitor C_F has been approximated as a constant voltage source V_O, since it is assumed that the output voltage is tightly regulated, as shown in Fig. 2(a). In addition, snubber diodes D_1 and D_2 are considered to be ideal (i.e., the junction capacitance's have been neglected). The junction capacitor C_j of D has not been neglected, though it is considered to be much less than the snubber capacitor C_S.

Prior to $t = t_0$, main switch S is off, boost rectifier D is on, and rectifier current I_D is equal to input current I_{IN}. Meanwhile, current I_{LS} is equal to zero, snubber diodes D_1 and D_2 are off, and voltage V_{CS} across snubber capacitor C_S is equal to zero, signifying that the snubber has been reset.



(a) (b) [t_0–t_1] (c) [t_1–t_2] (d) [t_2–t_3] (e) [t_3–t_4] (f) [t_4–t_5] (g) [t_5–t_6] (h) [t_6–t_0]

Fig. 2 Topological stages of "flying-capacitor" passive lossless snubber applied to boost converter.

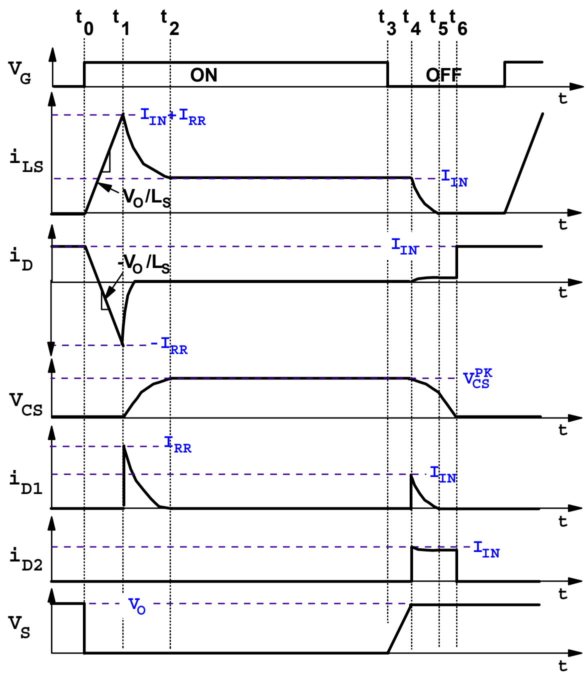


Fig. 3 Key switching waveforms of flying capacitor snubber.

At $t = t_0$ switch S is turned on, voltage V_{LS} is equal to V_O and current I_{IN} begins to commutate from boost rectifier D to switch S at a rate of V_O/L_S. Rectifier D does not turn off the moment current I_{IN} completely commutates to the switch, but instead, remains on until its reverse-recovery charge Q_{RR} is fully depleted. As a result, a reverse current flows through switch S at a rate of V_O/L_S until it reaches peak value I_{RR} at $t = t_1$.

At $t = t_1$, boost rectifier D turns off at the peak of the reverse current $-I_{RR}$, and switch current i_S is equal to $I_{IN} + I_{RR}$. Snubber diode D_1 turns on and junction capacitance C_j of boost rectifier D is effectively in parallel with snubber capacitor C_S. During $t_1 < t < t_2$ the reverse-recovery energy stored in inductor L_S resonates with capacitors C_S and C_j, causing voltage V_{CS} to increase. Since it is assumed that C $<< C_S$, the majority of the resonant current flows through capacitor C_S.

At $t = t_2$, voltage V_{CS} across snubber capacitance C_S reaches its peak value $V_{CS}^{PK} = I_{RR}\sqrt{L_S/C_S}$. Diode D_1 turns off and current $i_{LS} = i_S = I_{IN}$. During $t_2 < t < t_3$ boost rectifier D and snubber diodes D_1 and D_2, remain off and charge is stored in C_S. At $t = t_3$, main switch S turns off, and during $t_3 < t < t_4$, inductor L_S resonates with output capacitance C_{OSS} of main switch S causing drain voltage V_{DS} to increase.

At $t = t_4$, drain-source voltage $V_{DS} = V_O$ and snubber diodes D_1 and D_2 turn on, clamping it to the output voltage. During this interval, current

$$i_S = I_{IN} - \frac{V_{CS}}{\sqrt{L_S/C_S}}\sin(\omega_O t) = I_{IN} - I_{RR}\sin(\omega_O t),$$

assuming a lossless transferrance of energy between inductor L_S and capacitor C_S, and, where $\omega_o = 1/\sqrt{L_S(C_S + C_j)}$. In order for the snubber to reset, the resonant current $I_{RR}\sin(\omega_O t)$ must be greater than input current I_{IN}, allowing D_1 to turn off, as discussed in [2] and [4]. Otherwise, snubber diodes D_1 and D_2 remain on throughout the off time of switch S as they conduct current I_{IN}, and reverse-recovery-related losses associated with future switching cycles result now from two diodes instead of just one. Furthermore, the turn-off rate of snubber diodes D_1 and D_2 is limited only by circuit parasitic inductance, and, as a result, the reverse-recovery-related losses are more than two times the loss associated with boost rectifier D.

At $t = t_5$, current i_{D1} reaches zero and snubber diode D_1 turns off. Input current I_{IN} discharges capacitors C_j and C_S at the same rate (since they are in parallel) until, at $t = t_6$, diode D_2 turns off and boost rectifier D turns on. At $t = t_6$, charge has been completely removed from capacitor C_S, snubber diodes D_1 and D_2 are off, and no energy is stored in inductor L_S. As a result, input current I_{IN} flows through boost rectifier D until the start of the next switching cycle.

III. DESIGN GUIDELINES

The key to the design of the circuit shown in Fig. 1 is to minimize the circuits reverse-recovery-related losses in order to maximize system efficiency. From the previous circuit analysis, it is shown that the minimum reverse-recovery-related loss occurs when the turn-off di/dt rate of boost rectifier D is controlled by inductor L_S, and, furthermore, that snubber diode D_1 is forced to turn off, thereby eliminating the reverse-recovery-related loss associated with snubber diodes D_1 and D_2.

In order for snubber diode D_1 to turn off, a trade off is made between the value of snubber inductor L_S and the peak reverse-recovery-current I_{RR}, i.e., as the inductance of L_S increases, the reverse-recovery-related loss of rectifier D decreases, and the magnitude of current I_{RR} decreases. Peak reverse-recovery-current I_{RR} is a function of the rectifier characteristics, the forward current through rectifier D at the moment switch S turns on, and the slope of the current as it commutates from rectifier D to switch S, as discussed in [1]. Determining peak current I_{RR} from manufacturers data is unreliable since they often specify typical measurements for a limited number of operating points. Therefore, peak current I_{RR} should be determined experimentally.

Designing the snubber to reset when applied to wide input range converters, such as the PFC boost converter, is generally not possible, since the input current averaged over a switching cycle also varies over a wide range. Since peak-reverse-recovery current I_{RR} is a function of the forward current at the moment boost rectifier D turns off, it too varies over a wide range, making circuit optimization difficult. To achieve snubber reset at low input currents, as illustrated in Fig. 4 (a), the effectiveness of the snubber at high input currents is compromised. The alternative is to design the snubber to reset only at high input currents, as illustrated in Fig. 4 (b). This results in an efficiency improvement at high input currents and, in turn, a degradation of system efficiency at low input currents.

The addition of the snubber circuit shown in Fig. 1 to the conventional boost topology leads to additional component stress. The voltage stress of main switch S and snubber diode D_2 is equal to output voltage V_O (neglecting parasitic inductances), while the voltage stress of rectifier D and snubber diode D_1 is equal to the sum of the output voltage V_O and clamp voltage V_{CS}, i.e., $V_{S(max)} = V_{D1(max)} = V_O + V_{CS}$. However, with a careful selection of snubber capacitor C_S, the additional voltage stress of rectifier D can be small enough to permit the use of 600-V rectifiers, which is, generally, the industry standard for conventional boost rectifiers.

The device current stress of the power stage components is approximately the same compared to the conventional boost converter. When the snubber is properly reset, snubber diodes D_1 and D_2 conduct a resonant current, resulting in a small average current over a switching cycle. Generally, fast-

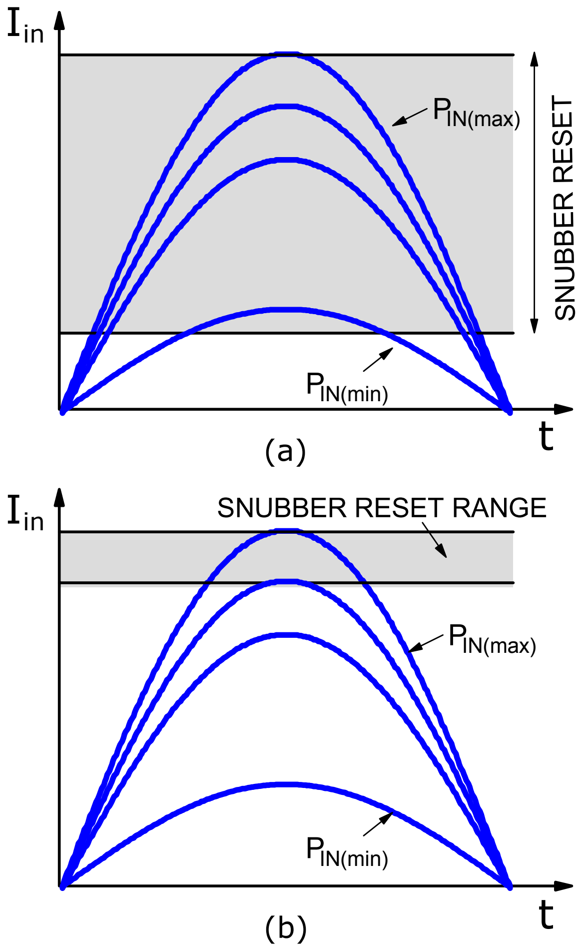


Fig. 4 Design optimization of "flying capacitor" passive lossless snubber applied to PFC boost converter: (a) Poor design, (b) Good design.

recovery, small signal diodes may be used. When the snubber is **not** designed to reset over a wide line and load range, as in the case of the PFC boost converter, the snubber diodes conduct not only a resonant current, but the full input current as well. In this case, the snubber diodes should be chosen to be of equal current rating to that of the boost rectifier, and, furthermore, thermal management of the snubber diodes must now be considered.

IV. PERFORMANCE RESULTS

The circuit shown in Fig. 1 was evaluated on a 500-W (380-V/ 1.32-A), universal line range (90-264 V_{RMS}) power factor correction circuit operating at 80 kHz. Though the converter was optimized at 500 W, the performance evaluation was extended to 650 W to illustrate the limited range of the snubber. Figure 5 shows the measured efficiencies of the experimental converter at the minimum line voltage (90 V_{RMS}) with and without the proposed snubber, along with the key component values. Figures 6 and 7 show temperatures of the main switch (S) and the rectifiers (D, D_1, and D_2) with and without the proposed snubber. As can be seen from Fig. 5, the passive snubber does not improve the conversion efficiency. From Figs. 6 and 7, it is shown that the greatest benefit in device temperature occurs at maximum rated output power $P_O = 500$ W compared to the conventional boost converter. At the maximum rated output power, the temperature improvement of S is 12 ^oC, of D is 10 ^oC and D_2 operates at approximately the temperature of the rectifier in the conventional boost converter. Fig. 8 (a) and (b) shows the voltage waveform across the snubber capacitor V_{CS} and the current waveform through the snubber inductor I_{LS} at two different instantaneous values of the input voltage V_{IN}, 90 V and $\sqrt{2}$ *90 = 127 V, respectively. From Fig. 8(a), it can be seen that I_{LS} is at the boundary of continuous and discontinuous conduction mode (i.e., $I_{RR} \approx I_{IN}$) whereas in Fig. 8(b), I_{LS} is continuous (i.e., $I_{RR} < I_{IN}$).

The temperature improvement of S at 650 W has decreased to 8 ^oC, the temperature improvement of D has improved to 18 ^oC, while the temperature of the snubber rectifier D_2 has increased 8 ^oC higher than the rectifier in the conventional boost converter! Figures 8(c) and (d) show that I_{LS} is continuous at both $V_{IN} = 90$ V and $V_{IN} = \sqrt{2}$ *90 V (i.e., $I_{RR} < I_{IN}$), which means that the reverse-recovery-related losses of the two snubber rectifiers are contributing to the degradation of the main switch temperature. The majority of the input current flows through D_2 during the off-time which explains why the temperature of D improves while the temperature of D_2 degrades.

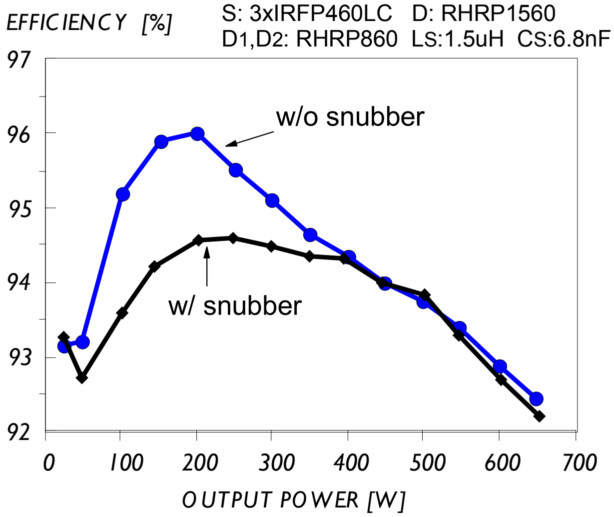


Fig. 5 Measured efficiency of the experimental boost converter at the minimum line voltage (90 V_{RMS}).

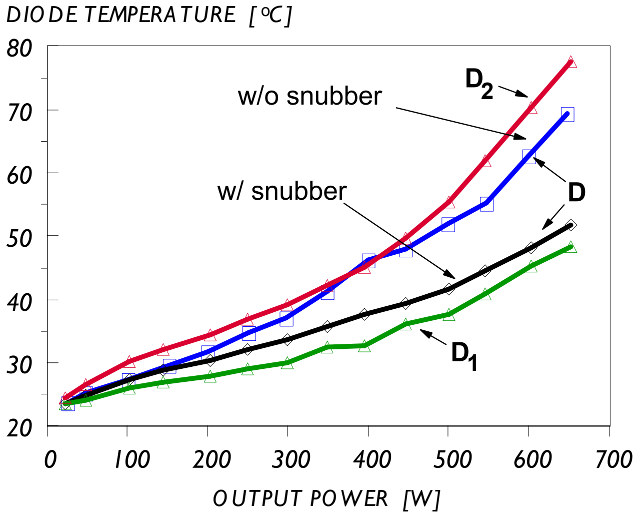


Fig. 6 Measured temperature of rectifiers D, D_1, and D_2 of the experimental circuit operating at minimum line voltage (90 V_{RMS}).

As shown in Fig. 5, the experimental circuit was designed with a snubber inductance value of $L_S = 1.5$ uH. The di/dt of the commutating current is then 250 A/usec, well above the

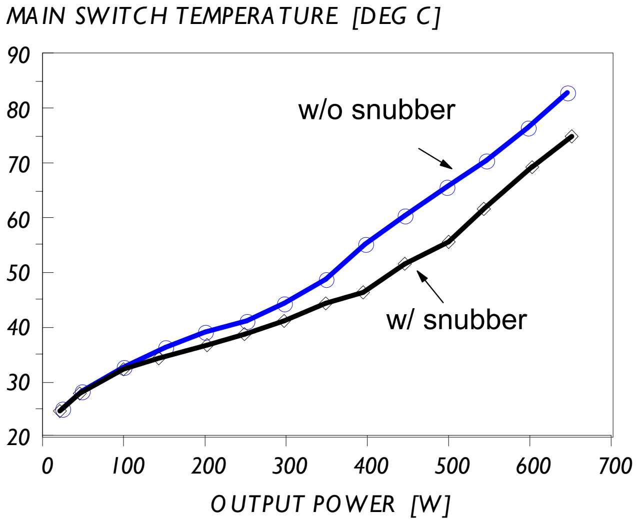


Fig. 7 Measured temperature of main switch of the experimental circuit operating at minimum line voltage (90 V_{RMS}).

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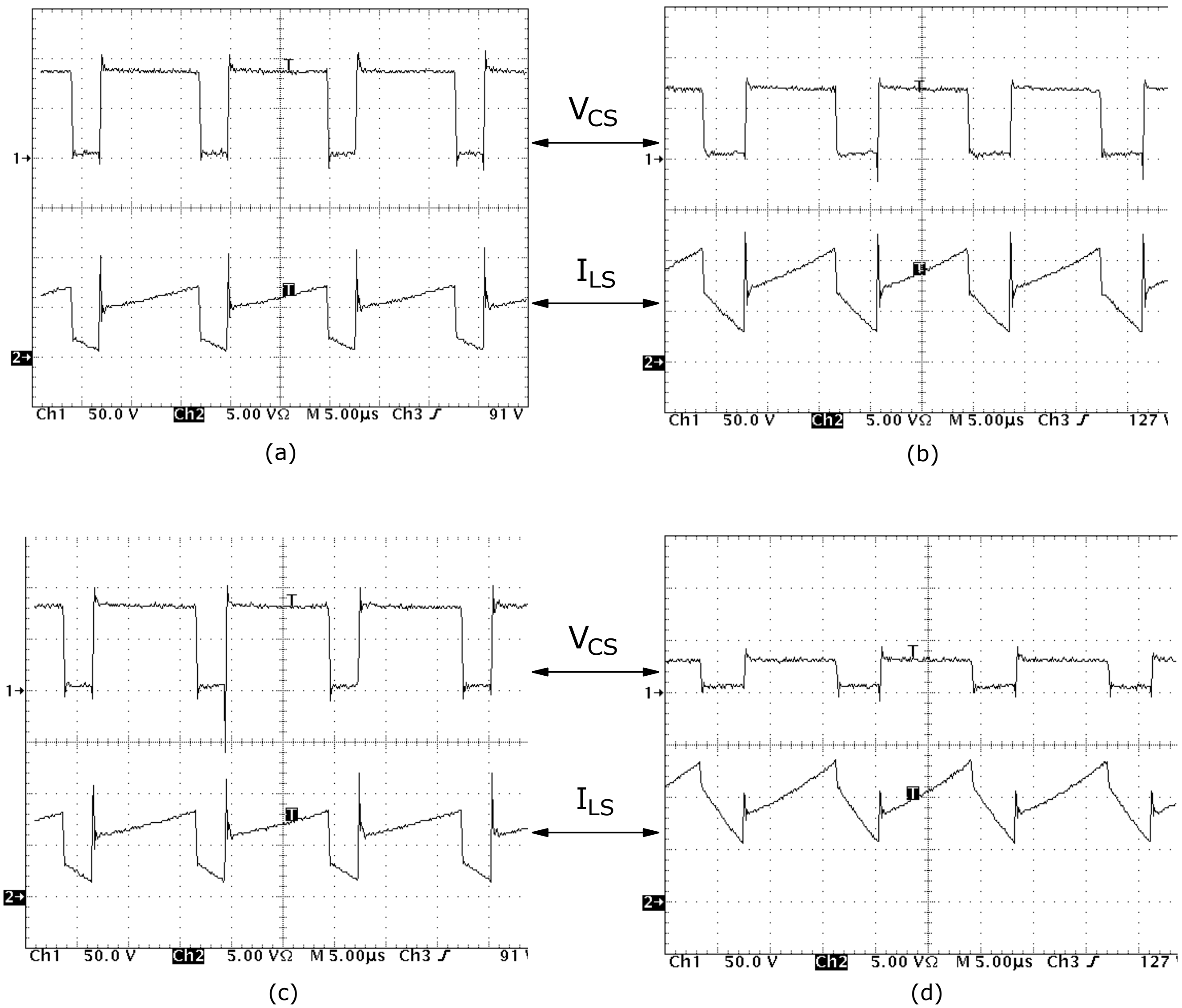

Fig. 8 Key switching waveforms of flying capacitor snubber applied to PFC boost converter: (a) P_O = 500 W, V_{IN} = 90 V (b) P_O = 500 W, V_{IN} = 127 V (c) P_O = 650 W, V_{IN} = 90 V (d) P_O = 650 W, V_{IN} = 127 V.

100 A/usec slope recommended by [1]. However as stated earlier, the design criteria is that $I_{RR} > I_{IN}$. Therefore as the output power increases, I_{RR} must increase. Generally, this can only be achieved by decreasing the snubber inductance. There comes a point when the snubber inductance becomes too low to offer any benefit over the conventional boost converter.

V. SUMMARY

The "flying-capacitor" passive lossless snubber, applied to the boost converter to reduce reverse-recovery related losses associated with the fast-recovery type boost rectifier, is simple to design, consists of very few additional components, and can offer improved system efficiency and device temperature. However, it is beneficial only within a narrow input voltage range and output current range, and, in fact, can be detremental to system efficiency when operating outside of this range. When applied to a boost converter with a wide input voltage range, such as a PFC boost converter, the snubber should be designed to offer maximum benefit at the worst case input/output condition (i.e., low line, full load). When applied to a 500-W PFC boost converter, the snubber was shown to exhibit a 10 - 12 Deg. improvement in device temperature, and no significant improvement in overall efficiency.

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