

Article

Active Snubber Solution for an Interleaved Flyback Converter

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Abstract

This paper presents an energy-recovering active snubber in which the energy captured by the snubber capacitor is transferred back to the converter's input using an auxiliary inverting switching stage. The snubber operates independently of the main power stage and can therefore be applied to a wide range of isolated converter topologies without modifying their primary control or structure. The proposed snubber achieves an energy-recovery efficiency of approximately 80%, thereby reducing snubber-related losses by the same proportion. As a representative implementation, the concept was experimentally validated in a 550 W dual-phase interleaved DC–DC flyback converter, where it improves the overall converter efficiency by 1.6 percentage points and reduces total losses by 18% compared with a dissipative snubber solution. The proposed snubber supports a wide input-voltage range and is well suited for multiphase converters, as most of its components can be shared between phases.

Keywords: active snubber; flyback converter; leakage inductance; regenerative snubber

1. Introduction

Leakage inductance in isolated flyback-based converters leads to increased voltage stress and additional power losses, particularly in high-power applications. A snubber is usually used to limit the induced voltage to prevent the breakdown of the switching transistor. Although the approach is well understood, it remains a practical design challenge because the associated losses scale with switching frequency and power, and directly impact efficiency, thermal performance, and converter reliability. Simple dissipative approaches such as RCD snubbers are widely adopted due to their robustness and ease of implementation, but they inherently convert the captured leakage energy into heat, which becomes increasingly undesirable at higher power levels [1]. Consequently, significant research effort has concentrated on snubber configurations that recover the captured energy rather than dissipating it, with the aim of improving efficiency and reducing thermal stress [2].

Existing energy-recovery approaches differ primarily in how the snubber energy is returned to the power conversion process and in the extent to which they interact with the main converter operation. These differences result in trade-offs in circulating energy, operating voltage range, component count, and control complexity, which, in turn, affect their suitability for certain converters.

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Simply adding a capacitor to the RCD snubber can sometimes lead to efficiency improvement [3]; however, losses on the snubber resistor remain. A better approach is to transfer the energy stored in the snubber capacitor to the input capacitor, output capacitor, or transformer. The LC snubber uses an additional inductor and a diode to reverse the polarity on the capacitor when the switch is turned on. This enables later transfer of its energy to the transformer. Large voltage swings across the capacitor result in substantial circulating energy within the snubber, which can lead to significant losses in its components. A variant of this snubber uses an additional winding on the main inductor, eliminating the separate inductor [4]. A drawback of this solution is its limited input-to-output voltage ratio, which, in the case of a given output voltage, limits the minimum input voltage. Dzhunusbekov et al. reduced losses by adding components, but the limitation of the input-to-output voltage ratio remains [5]. To reduce excessive circulating energy losses, Vartak et al. modified the configuration by reversing the polarity of the auxiliary winding and adding a capacitor and two diodes on the secondary side [6]. However, this topology is patent-protected, which restricts its broader adoption in commercial designs. The LC snubber can also be applied to a two-switch flyback converter, which is suitable for higher input voltages [7]. Zhao et al. modified the snubber to transfer part of the energy to the supply of the control circuit [8]. The energy from the snubbing capacitor can also be transferred directly to the output using an additional transformer with two associated diodes [9]. However, in a multiphase converter, an additional transformer rated for the required isolation voltage is required for each phase.

A snubber can also be implemented using a capacitor and a controlled switch that allows the captured energy to be transferred back to the main inductor during the free-wheeling phase, creating what is commonly known as an active clamp circuit [10]. Unlike passive designs, this configuration requires an auxiliary control signal synchronized with the main transistor, which increases circuit complexity. Another variant utilizes an additional winding on the main transformer to discharge the snubber capacitor [11]. The energy from the snubber capacitor can also be used with another stage in a bridge-type converter [12].

Some implementations recover the captured energy by connecting the snubber capacitor in series with the source [13]. However, this approach may not be suitable for converters with high input currents due to an extended current path, increasing conduction losses. If the galvanic isolation is not required, the snubber capacitor can also be connected in series with the load [14] or the output capacitor itself can serve as a snubber capacitor [15]. Although these methods improve energy utilization, they introduce additional design and usability constraints.

In this paper, we present an efficient energy-recovering snubber solution, where the energy stored in the snubber capacitor is transferred to the converter's main input capacitor using an auxiliary switching stage that operates independently of the main converter. Consequently, the proposed snubber can be applied to a wide range of isolated converter topologies without imposing additional constraints on their primary control or structure. This concept is particularly advantageous in multiphase converters, where a single auxiliary stage can be shared among phases, where each phase retains a conventional configuration, like the one using an RCD snubber, simplifying their design and control. Since the snubber capacitor is discharged independently of the main inductors, the input-to-output voltage ratio is not directly limited by the snubber operation. The advantages can be summarized as follows:

- Greatly reduced losses, when compared to an RCD snubber;
- Possibility of a compact solution due to absence of a high-power resistor;
- Design independent from the main converter;
- Input-to-output voltage ratio not directly imposed.

The key characteristics of the reviewed snubber solutions, compared with the proposed one, are summarized in Table 1. Only solutions applicable to single-switch flyback converters and to parallel multi-phase converters are listed.

Table 1. Comparison of the existing snubber topologies to the proposed one. The number of components is given for a two-phase converter. An additional transformer is considered as two passive components (windings).

Active Snubber	Applicability to Parallel Multiphase Converters	Independent from the Main Converter	Wide Input–Output Voltage Ratio	Circulating Energy	Number of Passive and Active Components and Auxiliary Windings
LC	poor	yes	yes	high	4 + 4 + 0
[4]	poor	yes	no	high	2 + 4 + 2
[5]	poor	yes	no	low	4 + 10 + 2
[9]	poor	no	yes	low	6 + 6 + 0
[10]	poor	no	yes	low	2 + 2 + 0
[11]	poor	no	yes	low	2 + 6 + 2
proposed	good	yes	yes	low	2 + 4 + 0

We experimentally evaluated the presented snubber in a dual-phase flyback DC–DC converter, designed for PV monitoring in scientific research applications, where a wide variety of PV modules with different electrical characteristics are monitored. In such systems, the requirement to operate over an extended input-voltage range close to zero at maximum input current limits the applicability of many previously reported snubber solutions. Although maximum energy conversion efficiency is not the primary objective in research-oriented monitoring systems, minimizing thermal stress remains essential to reduce cooling requirements and enhance overall reliability and operational lifetime.

The rest of the paper is organized into three main sections. In Section 2, the topology of the proposed circuit is described. Section 3 describes the implementation of the circuit, including schematics, and gives performance results. Example usage of the circuit is presented in Section 4, together with performance improvement numbers.

2. Materials and Methods

The proposed active snubber was designed to recover the energy stored in the transformer’s leakage inductance and return it to the converter’s input capacitor, thereby reducing power loss and improving overall efficiency. Figure 1 illustrates the power flow in a DC–DC converter employing the proposed circuit. The active snubber recovers the leakage energy (B), which would otherwise be dissipated through the resistor of a conventional RCD snubber, and returns it to the input (A).

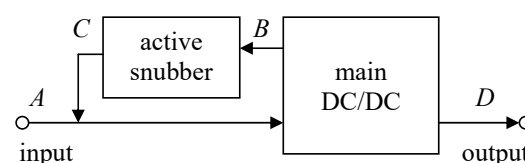


Figure 1. Block diagram of power flows in a converter employing the proposed circuit. A —input power, B —leakage inductance power, C —power recycled to the input, D —output power.

Total efficiency of the converter $\eta_T = D/A$ can be expressed as

$$\eta_T = \eta_M \cdot \frac{1}{1 - \eta_S \cdot l} \quad (1)$$

where $\eta_M = D/(A + C)$ is the efficiency of the main converter, $\eta_s = C/B$ is the efficiency of the active snubber, and $l = B/(A + C)$ is the relative leakage loss of the main converter. Note that the efficiency with the conventional RCD snubber equals η_M , whereas the fraction represents the efficiency gained by using the proposed circuit.

The proposed topology builds upon the conventional RCD snubber shown in Figure 2, where the negative terminal of the snubber capacitor (C_s) is connected to the positive terminal of the input capacitor (C_{IN}). Instead of discharging the C_s through the resistor, we propose an inverting switching regulator that transfers that energy to C_{IN} . The conceptual implementation of the proposed active snubber applied to a flyback converter is presented in Figure 3.

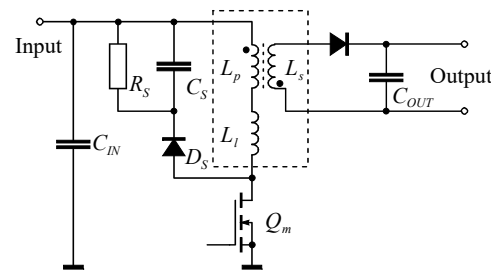


Figure 2. Basic flyback converter depicting transformer including leakage inductance L_l (in dashed rectangle) and an RCD snubber (R_s , C_s , D_s).

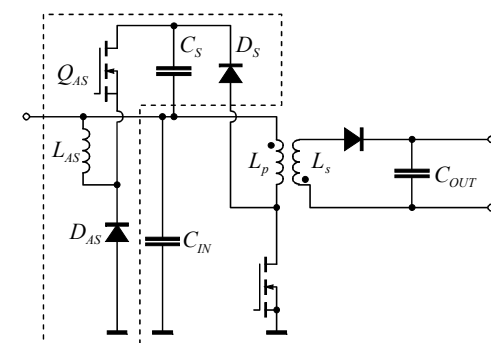


Figure 3. A flyback converter with an active snubber (dashed polygon on the left).

The energy transfer process begins by turning on the switch Q_{AS} , which connects the inductor L_{AS} to the snubbing capacitor C_s , as shown in Figure 4a by the red current path. This causes the current through the inductor to rise. When Q_{AS} turns off, the resulting voltage reversal across L_{AS} forward-biases the diode D_{AS} , transferring the energy from the inductor to the converter's input capacitor C_{IN} of the converter, as shown in Figure 4b.

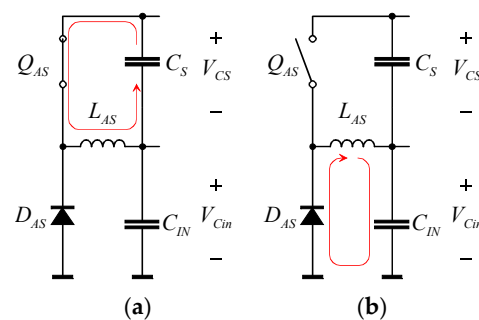


Figure 4. Two phases of operation of the active snubber with red curves showing current flow. The curves start at the element that drives the current. (a) In the first phase, Q_{AS} is turned on. (b) In the second phase induced voltage forward biases the diode.

In addition to reducing losses, this topology offers another advantage by enabling continuous regulation of power transfer simply by modulating the switching duty cycle. The duty cycle of Q_{AS} can be controlled by the voltage across C_s , effectively simulating Zener diode behavior. Because the control loop operates asynchronously with the main converter, the overall design remains simple and flexible.

It should be noted that the power transfer capability of the snubber decreases at low voltages across C_{IN} (V_{Cin}) due to the current limit imposed on Q_{AS} . Consequently, the snubber capacitor voltage increases; however, the increase is self-limiting because the snubber's power transfer is inherently reduced. It is important to emphasize that the peak voltage on the main switch is determined by the sum of the voltages across C_{IN} and C_s .

3. Results

We implemented the proposed snubber in a two-phase interleaved flyback converter rated at 550 W with an input voltage of up to 95 V and a primary winding flyback voltage of 52 V. To provide sufficient design margin, the switch (Q_{AS}) should have a voltage rating of at least 200 V. To reduce the discrete component count, we opted for an integrated circuit which includes as much functionality as possible. The required voltage rating exceeds the ratings of most integrated circuits designed for buck converters, but is well within the voltage range of commercial off-line flyback controllers that can also operate in other topologies.

We selected the TNY280 controller [16], which integrates a power switch and operates at 132 kHz using pulse-skipping modulation. The controller periodically turns on the switch Q_{AS} until a specific current value is achieved or a timeout expires. It typically operates in DCM and automatically reduces the peak current limit at light-load conditions. Based on these properties, we initially selected the inductor L_{AS} using the following equation:

$$L_{AS,CrCM} = \frac{V_{CS}}{I_p \cdot f} \cdot \frac{V_{CIN}}{V_{CS} + V_{Cin}}, \quad (2)$$

where I_p and f are peak inductor current and frequency of the controller, respectively. Increasing L_{AS} shifts operation towards CCM, thus improving power transfer with increased average inductor current. We selected inductance based on the lowest input voltage for full flyback converter power ($V_{Cin} = 32$ V) and voltage on C_s of 88 V. Considering TNY280's current limit of 750 mA and operation on the border between DCM and CCM, i.e., CrCM, gives 237 μ H. To allow for higher power, we chose the next higher standard inductance value of 330 μ H.

The snubbing capacitor C_s should be selected large enough for voltage jumps across it (ΔV_{CS}) to be negligible. The initial value can be calculated using the equation:

$$C_s = \frac{I_{snub}}{\Delta V_{CS} \cdot f}, \quad (3)$$

where I_{snub} is the input current to the snubber, which can be measured on the prototype and calculated from a known leakage inductance. In our case, we selected a 470 nF film capacitor.

The TNY280 is controlled via the enable pin (EN), which engages pulse skipping when pulled low. In standard applications, an optocoupler is connected to the pin in order to regulate the output according to a voltage reference on the secondary side. In our application, we regulate the voltage across the snubbing capacitor, which corresponds to the TNY280's input voltage. Since a higher voltage should result in a higher duty cycle of the TNY280 controller, regulation logic should be inverted. To achieve this, we used a bipolar npn transistor and resistor R_3 as shown in Figure 5. When the voltage across the snubbing capacitor (C_s) rises above the threshold set by the Zener diode ZD_1 , the optocoupler OC_1

starts to conduct and turns off the npn transistor, thus enabling the TNY280 controller. The controller is supplied from its drain pin by an internal regulator that only requires an external capacitor, which further simplifies our circuit.

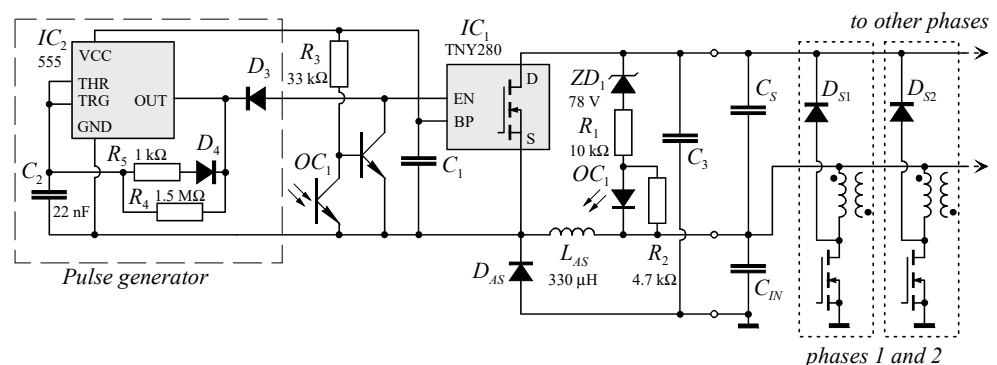


Figure 5. Snubber implemented with the TinySwitch controller (IC₁) and added pulse generator in the left dashed rectangle. On the right side, three terminals can be seen that connect the module part of the snubber (left) to the rest of the circuit.

The TNY280 controller includes several protective functions, such as a peak inductor current limit and an overload-protection timer that temporarily disables switching if the enable signal is continuously active for more than 64 ms. While this protection is beneficial in standard power supply applications, it is undesirable in a snubber circuit, which must operate continuously even if regulation cannot be maintained. To resolve this issue, we added a 555 timer circuit IC₂ [17], which generates short negative pulses that briefly disable the TNY280 controller and thus reset its overload timer. Values of C₂, R₄, and R₅ in Figure 5 define an approx. 22 μ s-wide pulse every 24 ms. Diode D₃ together with the npn transistor forms a negated wired OR logic gate that combines control signals from the timer and the optocoupler network. Please note that although the overload protection is disabled, the TNY280 remains protected by its current limit and temperature protection. As the current consumption of the 555 timer is low, it is powered directly from the TNY280.

For compactness and ease of integration, we implemented the active snubber as a modular circuit, as shown in Figure 6. The snubber and input capacitors were intentionally excluded from the module, and left on the main power board, since their close placement to the transformers and primary switching transistors is critical.

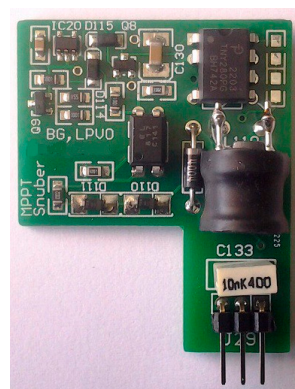


Figure 6. Photo of the prototype (approx. 1:1).

We evaluated the proposed snubber shown in Figure 5 separately to verify its functionality and measure the efficiency before implementing it into the flyback converter. The

test setup comprised a TTI PLH250 laboratory power supply and a Rigol DL3031A electronic load configured in a constant-current mode. The two instruments also served to measure voltages and currents. As shown in Figure 7, the snubber module was connected in a step-down configuration to prevent an uncontrolled rise in the output voltage if the load was accidentally disabled. In this configuration, the circuit maintains a constant voltage difference between the power supply (V_s) and the load (R_L). To smooth the current pulses, a 1 μF film capacitor was added at the input.

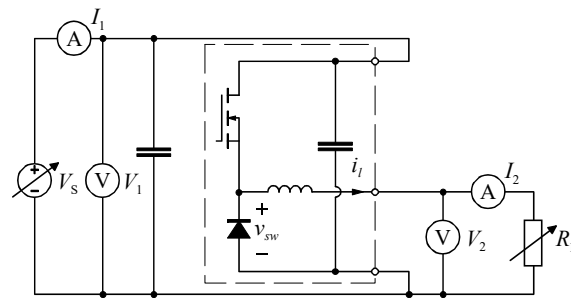


Figure 7. Efficiency measurement circuit. The snubber module is in the dashed rectangle. The left voltage source represents an adjustable power supply, and the variable resistor on the right is the electronic load.

Figure 8 shows the switching-node voltage and inductor current waveforms of the snubber module when operating at an input current (I_1) of 50 mA and output voltage (voltage across the input capacitor of the flyback converter $V_{Cin} = V_2$) of 35 V. In these conditions, the circuit operates in the Discontinuous Conduction Mode (DCM) with pulse skipping. The observed oscillations of about 1.2 MHz result from the L_s and parasitic capacitances in the circuit when the current through D_{AS} decays to zero.

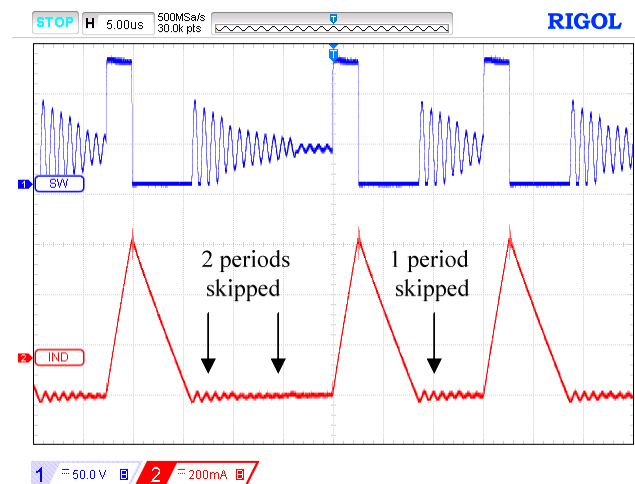


Figure 8. Voltage at switching node (v_{sw} —blue) and current through the inductor (i_l —red, AC coupled).

The circuit is used as an inverting converter, but measured as a step-down converter; therefore, efficiency must be calculated using a modified equation. As the snubbing capacitor is connected between D_s and the input capacitor, the input voltage is taken as $V_1 - V_2$. Similarly, the input capacitor is charged through D_{AS} ; therefore, output current is taken as $I_2 - I_1$. The equation for calculation of the snubber efficiency is therefore

$$\eta = \frac{I_1 \cdot (V_1 - V_2)}{(I_2 - I_1) \cdot V_2}, \quad (4)$$

where the input and output powers correspond to the energy flow from C_S to C_{IN} , respectively, and thus represent the share of power that is recuperated and therefore not dissipated on the resistor of the RCD snubber circuit. Performance was evaluated at several output voltages of the snubber ($V_{Cin} = V_2$), and the resulting efficiency curves are shown in Figure 9. Measurements show that the snubber efficiency exceeds 80% when operating at voltages that enable the flyback converter to operate at full power. Since the snubber circuit is powered from the drain and source terminals of the TNY280 controller, the efficiency figures also include the power of the control part. Due to the current limit on Q_{AS} , the capability of the active snubber is lower at lower voltages, but that does not limit its applicability, as the voltage stress of the converter's main switch is also reduced at lower V_{IN} , allowing for higher V_{CS} .

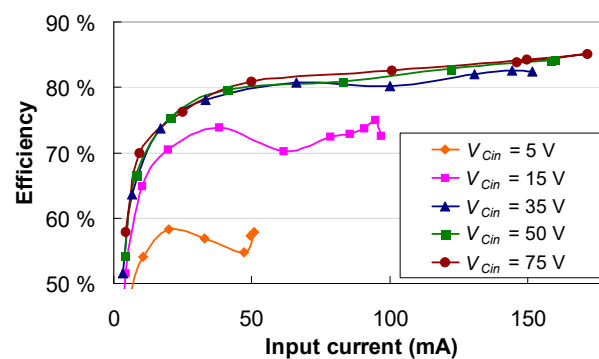


Figure 9. Efficiency of the proposed snubber vs. snubbing current at different voltages at the input of the power converter (V_{Cin}).

4. Discussion

We integrated the proposed snubber into a two-phase interleaved DC-DC flyback converter operating at 180° phase shift. It is intended for PV monitoring in research applications, where a wide variety of PV modules might be connected. The application requires a voltage range extending close to zero, thus eliminating many topologies, including forward topologies. The main parameters of the converter and its transformers are listed in Tables 2 and 3, respectively, and its inside can be seen in Figure 10.

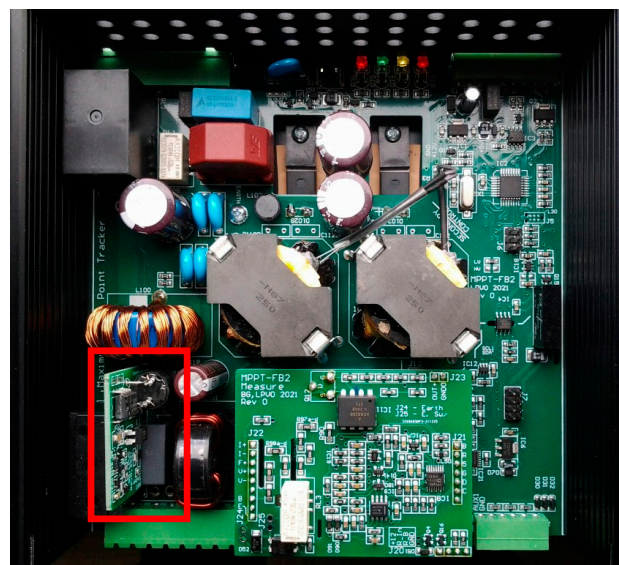


Figure 10. Photo of the implemented converter. The input is at the bottom left and the output at the top left. The snubber module is denoted by the red rectangle. Note that the snubber diodes and capacitor are hidden together with the main transistors under the module at the bottom center.

Table 2. Main parameters of the two-phase DC-DC converter.

Maximum input voltage	95 V
Minimum input voltage for nominal power	32 V
Maximum input current	17 A
Maximum input power	550 W
Nominal output voltage	250 V

Table 3. Main parameters of the main transformers.

Primary inductance	6.25 μ H
Saturation current	47 A
Secondary-to-primary turns ratio	24/5
Core size and material	RM14, N41

To determine the power drawn from the snubbing capacitor C_s , we connected an electronic load directly to the capacitor and operated the converter at the desired worst-case operating point. At full load (550 W and 498 W at the input and output, respectively), the maximum snubber power was 12 W at 88 V across the capacitor C_s . In the conventional RCD snubber, this power is entirely dissipated as heat. However, using the proposed circuit, more than 80% of this power is transferred back to the input and reused by the main flyback converter. As a result, the overall converter efficiency increased from 90.6% to 92.2% at full power and minimum input voltage. This corresponds to an 18% reduction in total losses and, therefore, in cooling requirements. The balance described is summarized in Table 4.

Table 4. Comparison of power flows in the converter under test. A–D markings are the same as in Figure 2.

Type of Snubber:	RCD	Active Snubber
Power at input terminals (A)	550 W	550 W
Power delivered to snubber (B)	12.1 W	12.3 W
Power recycled to input (C)	0 W	9.8 W
Power delivered to flyback circuit (A + C)	550 W	560 W
Power at output terminals of the converter (D)	498 W	507 W
Total losses (A – D)	52 W	43 W
Efficiency (D/A)	90.6%	92.2%

The converter efficiency further improves as the input voltage increases, reaching 93.8% at 50 V as shown in Figure 11. These efficiencies exclude the power consumption of auxiliary measurement and control circuits, which draw approximately 1 W (0.2% of the rated power) from a separate supply. The flyback converter can achieve rated power at an input voltage span of 1:2.9.

The operation of the proposed circuit is shown in Figure 12. It can be clearly seen that the snubbing capacitor (C_s) is charged (top trace) when one of the main transistors switches off (bottom two traces)—corresponding to the rising edge of its drain-source voltage. When the Q_{AS} is turned on, the snubbing capacitor is partially discharged to L_{AS} . The operation of the Q_{AS} can be seen in the voltage at the switching node (V_{SW}) (second trace) of the active snubber, where the high level indicates that the Q_{AS} is turned on. Pulse skipping can also be observed. Case (a) represents operation at two-thirds of the rated

power. Operation at low input voltages was also tested. Case (b) represents the point where operation of the snubber enters CCM. Note that, in this case, the circuit also exhibits pulse skipping; therefore, it is not running at full power. During the tests, the input voltage was further reduced to zero, and the circuit maintained a preset snubber capacitor voltage at all operating points.

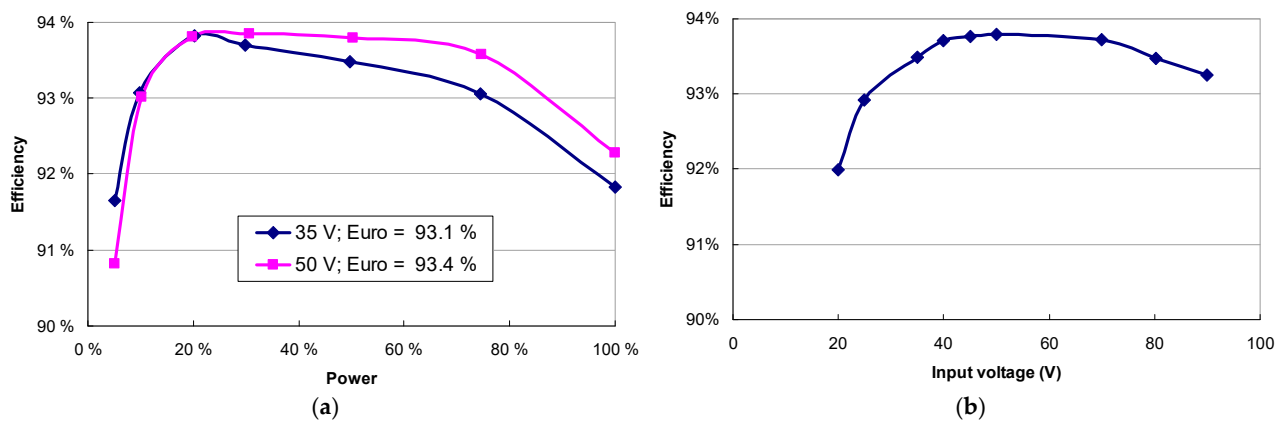


Figure 11. Efficiency of the flyback converter at constant output voltage of 250 V. (a) Measured at two different input voltages and varying power. Euro-weighted efficiency is also given. (b) Measured at 50% (275 W) of the rated power and different input voltages.

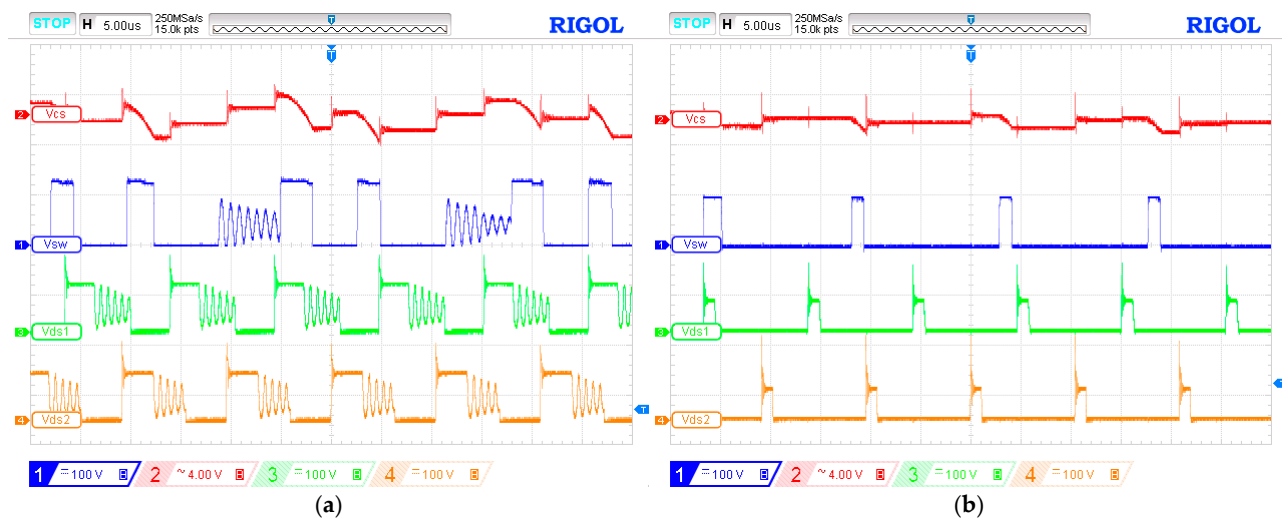


Figure 12. From top to bottom: voltages of the snubbing capacitor (AC coupled), switching node of the snubber, and drain-source of the two main transistors. (a) Measured at an input voltage of 41 V and power of 400 W. (b) Measured at an input voltage of 8 V and maximum input current (17 A).

5. Conclusions

We presented a regenerative active snubber implementation and its system-level integration in a multiphase flyback converter. The circuit builds on the idea of an RCD snubber by replacing the resistor with a switching regulator that transfers energy from the snubbing capacitor back to the input capacitor of the power converter, thereby increasing overall efficiency. The snubber operates independently of the main converter, thus simplifying the designs of the two and allowing easy integration into existing topologies. The circuit uses a simple control scheme and requires only a small number of power components, most of which can be shared among phases in a multi-phase configuration. Unlike many previously reported solutions, the proposed topology does not impose direct limits on input-voltage ratio, making it suitable for a wide range of operating conditions. The

prototype was implemented in a 550 W two-phase interleaved flyback converter used in a maximum-power-point tracker for photovoltaic monitoring applications with a maximum input voltage of 95 V. The active snubber increased its efficiency from 90.6% to 92.2% and reduced total losses by approximately 18% when compared with the converter with an RCD-type snubber operating at full power. The proposed concept can be readily extended to converters with higher input voltages, possibly up to 350 V, as the voltage rating of the TNY280 is 700 V. Adapting the design to other power levels is also possible. However, the TNY280 is the most powerful device in its series. Therefore, to increase power capability, a different series should be considered. The TinySwitch-5 series includes parts rated up to 3240 mA [18], which is more than four times the current of the TNY280 used in this work. Note that the TinySwitch-5 series has a different control scheme, thus requiring circuit modification. The concept can also be applied to many other isolated topologies requiring efficient energy recovery.

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Abbreviations

The following abbreviations are used in this manuscript:

DC	Direct Current
RCD	Resistor-Capacitor-Diode
PV	Photovoltaic
DCM	Discontinuous Conduction Mode
CCM	Continuous Conduction Mode
CrCM	Critical Conduction Mode

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