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# High frequency performance of snubber circuits in switchmode power supplies

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This paper investigates the experimental performance of three snubber circuits operating at a switching frequency of 100 kHz in a Cuk converter. The high frequency performance of two non-dissipative snubbers and one dissipative snubber are compared. It is shown that only one of the snubber circuits provides effective operation at 100 kHz, and is considered suitable for use at higher switching frequencies.

## 1. Introduction

The improved performance of switchmode power supplies is a direct result of the high frequency switching occurring in the power conversion process. The improvements obtained by raising the power supply's switching frequency are reduced energy storage element size and weight, improved transient response and easier containment and rejection of interference (EMI). This provides a reduction in equipment size and weight, but more importantly alleviates the inherent problem of interference generated by the switchmode process.

To operate at higher switching frequencies requires a reappraisal of the losses within the converter and a better understanding of the high frequency effects on circuit operation. Switching loss is a major circuit loss that increases linearly with frequency. The use of dissipative snubbers to control switching loss is limited to frequencies below 100 kHz due to their rising power losses. Non-dissipative snubbers are presently gaining the attention of power supply designers due to their reduction of switching losses. However, their operation has only been investigated at frequencies well below 100 kHz where parasitic device and circuit effects are negligible.

The high frequency performance of two non-dissipative snubbers and one common dissipative snubber is investigated in this paper at a switching frequency of 100 kHz.

## 2. Snubber circuits

A snubber circuit is included with the switch circuitry to provide stress relief for the switching device during commutation. A switchmode converter may require two snubber circuits to alleviate switching losses, one snubbing the turn-off transition and the other snubbing the turn-on transition of the switch. However, for many converter topologies the turn-off transition is the more severe case, and this paper considers only snubber circuits designed to provide stress relief at switch turn-off.

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(a)

(b)

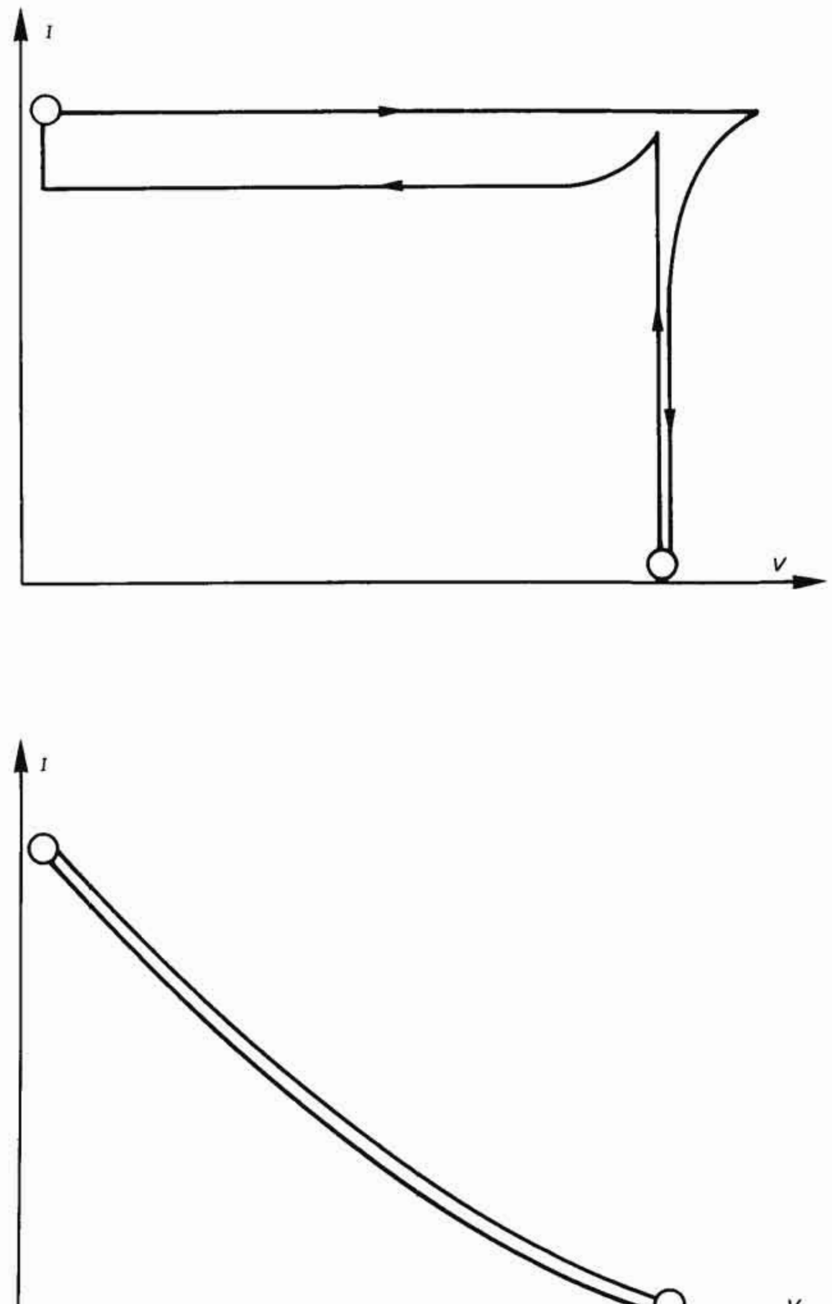


Figure 1. Switch load-line loci for (*a*) no snubber, and (*b*) with a snubber.

During the turn-off transition the snubber circuit acts as a bypass for the switch current, storing the accumulated bypass energy in a circuit reactor, and then releasing the energy (either dissipatively or non-dissipatively) during the time between switching transitions. A detailed review of snubber technology is given by Ferraro

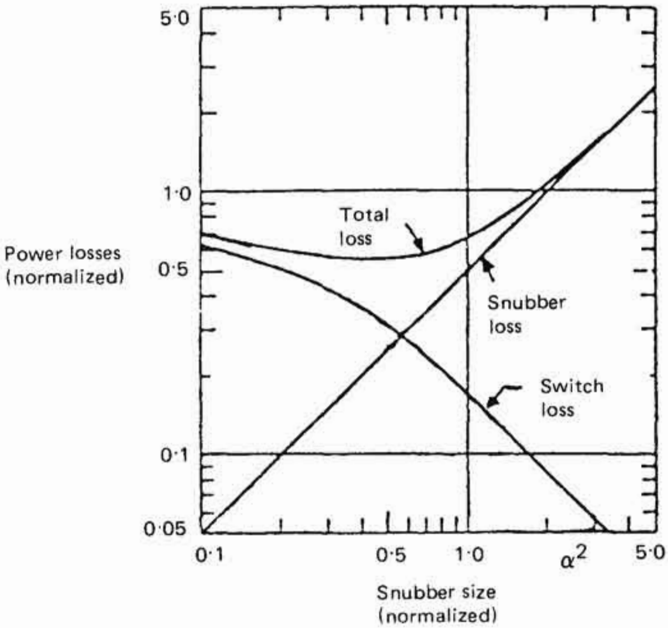


Figure 2. Switching losses as a function of snubber size.

(1982). The snubber performs the following essential functions for the switching device in a switchmode circuit:

1. Stress relief from concurrent switch voltage and current.
2. Switching power transfer.
3. Rate of rise control of the switch voltage and current.
4. Interference reduction.

The snubber alters the load line of the switch during commutation as shown in Fig. 1, reducing the switching loss power dissipation in the switch. The sum of the switch and snubber dissipation is the total switching loss for the circuit. An analysis of the switching loss by McMurray (1980) provides the results shown in Fig. 2, where it is seen that an optimum design can be configured that reduces the total switching loss compared to the unsnubbered case.

Dissipative snubbers transfer the switching power from the switch to a discharge resistor, where the power is lost as heat. The design of dissipative snubbers has been well reported in the literature (McMurray 1980, Calkin and Hamilton 1976, Skanadore 1977). For the common diode-capacitor-resistor snubber circuit shown in Fig. 3, the average power dissipation in the swich $P_q$ and discharge resistor $P_r$, are given by (Calkin and Hamilton 1976),

$$P_q = P_{\mathrm{off}} \cdot (\alpha^2/2 - 4\alpha/3 + 1), \qquad \alpha^2 \leqslant 1 \tag{1 a}$$

$$= P_{\mathrm{off}} \cdot \alpha^2/6, \qquad \alpha^2 > 1 \tag{1 b}$$

$$P_r = P_{\mathrm{off}} \cdot \alpha^2/2 \tag{2}$$

where $P_{\mathrm{off}}$ is the average turn-off power dissipation in the switch with no snubber and $\alpha$ is the normalized snubber size.

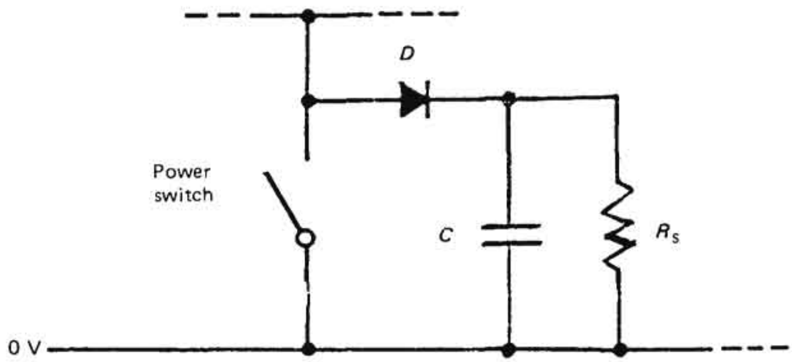


Figure 3. Diode-capacitor-resistor dissipative snubber circuit.

Non-dissipative snubbers transfer the switching power from the switch to another section of the converter, typically to the converters input or output. Various non-dissipative snubber designs have been reported in the literature using combinations of diodes, inductors and capacitors. It is advantageous for the snubber to both transfer power to the output, and to have a minimal count of passive and active components.

Domb *et al.* (1982) have reported on the analysis and design of the non-dissipative turn-off snubber network shown in Fig. 4. Depending on the actual combination of parameter values, four different modes of snubber operation are possible. One mode of operation is now described (mode 2) to illustrate the snubber operation. This mode returns energy to the power supply during the on-time of the period. The $C$-D1 network bypasses the switch current during turn-off, charging $C$ to some peak voltage $V_p$. Diodes D1 and D2 prevent any discharging of $C$ until the switch turns back on, at which time $C$ is connected in parallel with $L$. Current

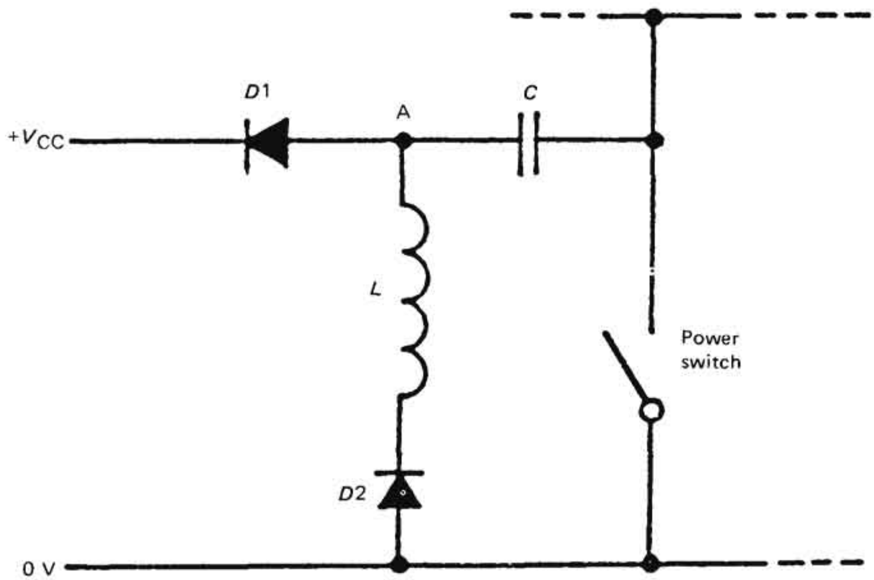


Figure 4. Non-dissipative snubber circuit reported by Domb *et al.* (1982).

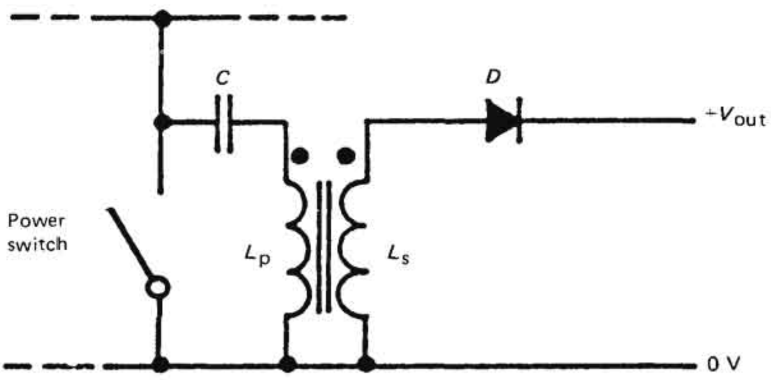


Figure 5. Non-dissipative snubber circuit reported by Ewing and Isbell (1982).

begins to rise in the $L$-$C$-switch loop until the voltage at point A forward biases D1, and the current in $L$ then flows back into the power supply ($+V_{cc}$). A complete set of design equations are given by Domb *et al.* (1982) but no experimental results were reported.

Ewing and Isbell (1982) report on the non-dissipative turn-off snubber circuit shown in Fig. 5. This circuit represents a near optimum handling of the turn-off energy, utilizing only one diode and passing the turn-off energy directly to the load. The $C$-$L_p$ network bypasses the switch current during turn-off, charging $C$ to some peak voltage $V_p$ as the voltage across $L_p$ is clamped by the constant voltage across $L_s$ as it delivers power to the load. At turn-on, $C$ is connected in parallel with $L_p$ and discharges resonantly through the $L_p$-$C$-switch loop. At the end of discharge, energy from $L_s$ begins flowing to the load through diode $D$. A complete set of design equations are given by Ewing and Isbell (1982) but no experimental results were reported.

More complex snubber designs for half-bridge and full-bridge converters have been reported. Lauritzen and Smith (1983) reported on a non-dissipative snubber used in a 1500 W half-bridge converter operating at 20 kHz that improved the converter efficiency by 4.7% at full output. The snubber also reduced the conducted interference levels of the converter by 10 dB between 2 MHz and 30 MHz. Williams (1984) reports on a 600 V, 100 A darlington switch and non-dissipative snubber that has achieved 95% energy recovery efficiency at a switching frequency of 100 kHz.

## 3. High-frequency converter losses

The switching power loss in a converter occurs at both the turn-on and turn-off transitions due to the rise and fall times of both voltage and current waveforms, as shown in Fig. 6 for the Cuk topology. Severe forced commutation occurs at both transitions and the switching losses can be expressed as,

$$P_s = f\left(\int_0^{t_{rv}} v \cdot i \cdot dt + \int_0^{t_{ri}} \dots + \int_0^{t_{fv}} \dots + \int_0^{t_{fi}} \dots\right) \tag{3}$$

where $f$ is the switching frequency and $t_r$ and $t_f$ are the rise and fall time intervals of the waveforms.

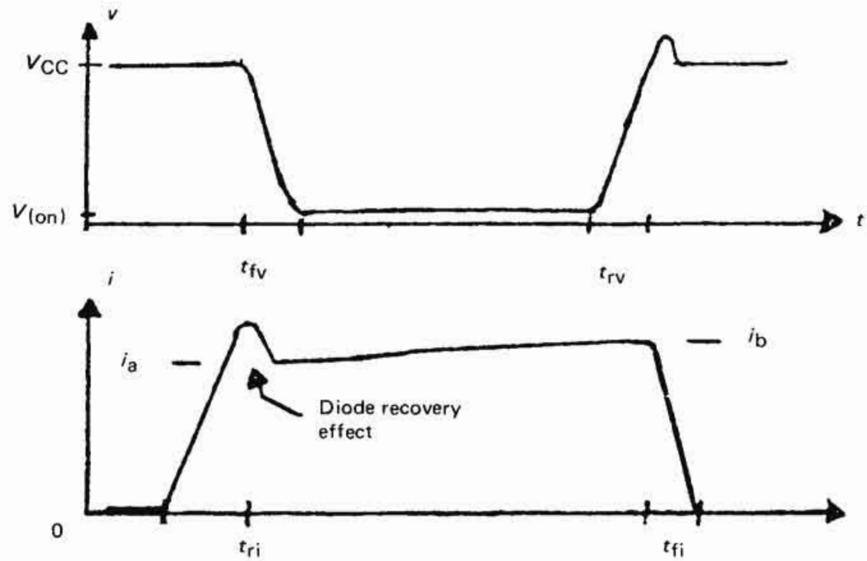


Figure 6. Switch waveforms for the Cuk converter.

An approximate expression for the switching losses can be formed by making the following assumptions:

1. Switch on-voltage is negligible, $V_{(on)} = 0$.
2. Diode recovery effects are negligible.
3. Input and output inductors are large so that $i_a \simeq i_b$.
4. Switch voltage and current waveforms change linearly.
5. No transient voltages or currents occur during the switching transitions.

Equation (3) can then be expressed approximately by,

$$P_s = V_{cc}/2 \cdot (I_{cc} + I_0) f(t_{ri} + t_{rv} + t_{fi} + t_{fv}) \tag{4}$$

The switching losses are therefore dependent on the input voltage $-V_{cc}$, input and output currents $-I_{cc}$ and $I_0$, switching frequency, load line and switching times.

A non-isolated 100 W, 25 V to 5 V Cuk converter was constructed with low loss, high frequency, passive components designed to handle the large magnitude pulse and ripple currents. Figure 7 shows the converter's circuit diagram and Table 1 gives the experimentally measured and the predicted circuit losses at 100 kHz and 500 kHz for the converter delivering 84 W to an external load. Experimental results

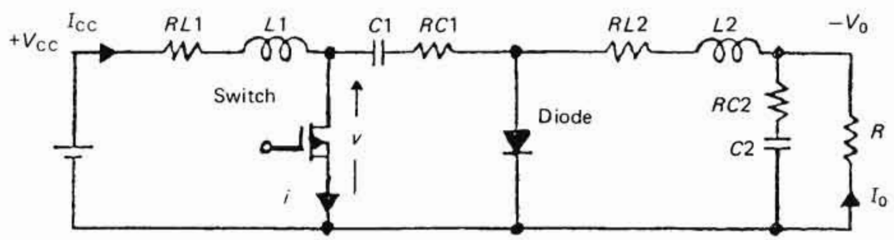


Figure 7. Cuk converter circuit diagram.

| Circuit component | | | Predicted parasitic loss (W) | |
|---|---|---|---|---|
| | | | @100 kHz | @500 kHz |
| $L1$ | 1·0 uH | $RL1$ | 0·17 | 0·12 |
| $L2$ | 5·0 uH | $RL2$ | 5·84 | 3·44 |
| $C1$ | 30 uF | $RC1$ | 2·43 | 2·39 |
| $C2$ | 220 uF | $RC2$ | 6·20 | 0.40 |
| Switch | 3 × IRF530 | $R_{on}$ (@60°C) | 5·82 | 5.62 |
| | | $P_s$ ($t$ = 40 nsec) | 4·34 | 21·87 |
| Diode | 60HQ100 | $V_{on}$ (=0·6 V) | 10·16 | 10·37 |
| Switch drive | | | 0·95 | 1·60 |
| Total predicted power loss | | | 35·91 | 45·81 |
| Total measured power loss | | | 37·4 | 44·6 |

Table 1. Predicted and experimentally measured circuit losses for the 25 V to 5 V Cuk converter delivering 84 W to an external load.

were obtained with a dissipative turn-off snubber network placed across the three MOSFETs to limit their peak drain to source voltage to under 100 V.

When operating at 500 kHz the input and output ripple currents are substantially reduced in magnitude compared with operation at 100 kHz. Two main frequency dependent effects are observed in Table 1:

1. Passive component power losses reduce at higher frequencies due to the lower ripple current magnitudes, even though the element values causing the power loss have increased, and
2. The switching loss in the MOSFETs has increased linearly with frequency and is the dominant contributor to the total power loss in the converter at 500 kHz.

In this topology the dissipative snubber is an effective network for providing stress relief for the MOSFET switch when switching loss power levels are low (< 10 W), however at switching frequencies above a few hundred kHz the increased power dissipation limits their use. The efficient operation of switchmode converters at switching frequencies above a few hundred kHz therefore requires the implementation of non-dissipative snubbers to alleviate switching losses.

## 4. High-frequency snubber operation

The experimental 25 V to 5 V Cuk converter was used to obtain photographs of the voltage and current waveforms of three snubber circuits. Component lead lengths within the converter have been extended to provide room for attachment of a current probe, resulting in increased parasitic inductances in the MOSFET drain and diode anode circuit legs. These parasitic inductances cause significant ringing at turn-off and turn-on and the converter's operating power level has been reduced accordingly to limit the increased peak voltage stress on the MOSFET.

Circuit waveforms of the Cuk converter with the dissipative snubber circuit given in Fig. 3 are shown in Fig. 8. The converter is operating in the discontinuous mode with the MOSFET drain current $i$ ramping from zero at turn-on to a maximum current of 14 A at turn-off. At turn-off the drain to source voltage $v$ rises to a transient peak of 90 V by the time $i$ starts to fall. During the current fall-time

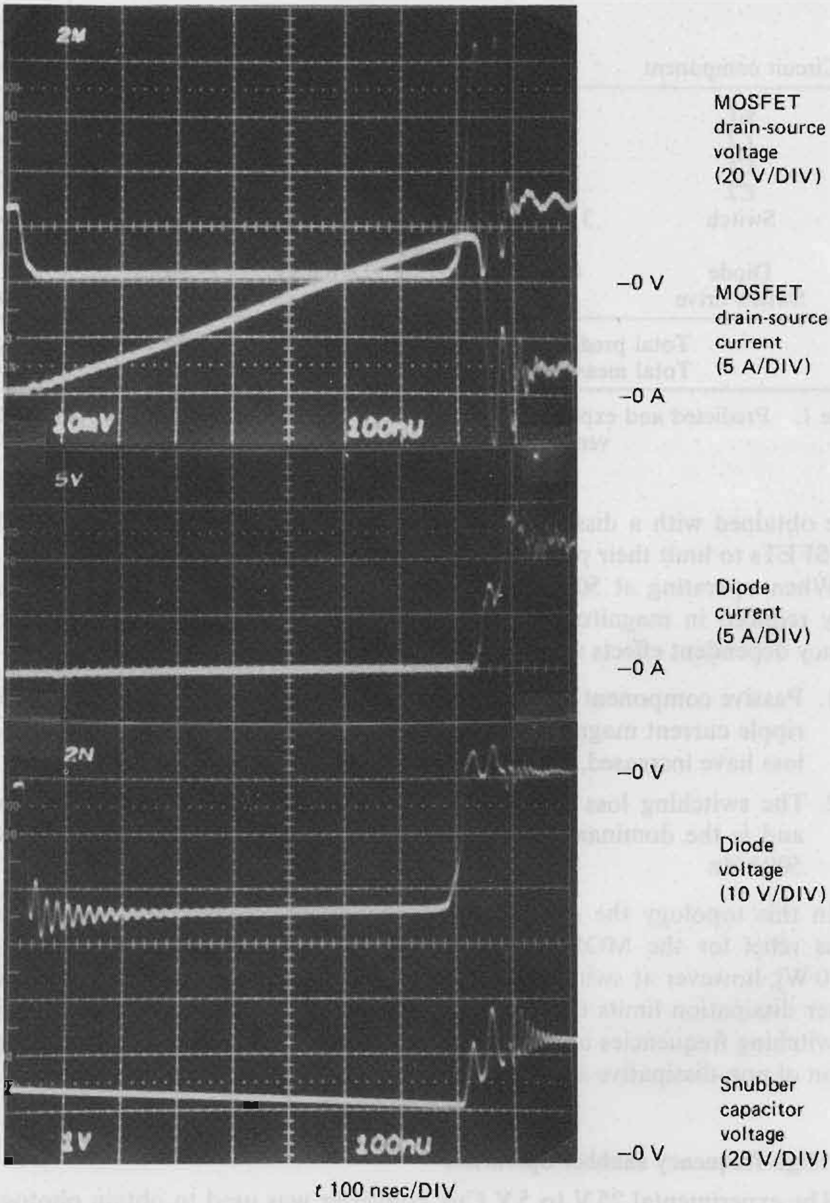


Figure 8. Dissipative snubber circuit waveforms.

the MOSFET voltage oscillates with large magnitude at a high frequency due to the parasitic drain inductance. The snubber diode then starts to commutate the MOSFET current and the MOSFET voltage settles rapidly to $V_{cc}$.

The snubber capacitor voltage $V_{cs}$ charges towards the peak MOSFET voltage at turn-off, but only reaches 55 V before $v$ falls and the snubber diode reverse biases. The snubber capacitor is unable to bypass most of the MOSFET drain current due to its own parasitic lead inductance. The snubber capacitor then discharges through $R_s$ to the source voltage $V_{cc}$ when the MOSFET is off, and to ground through the

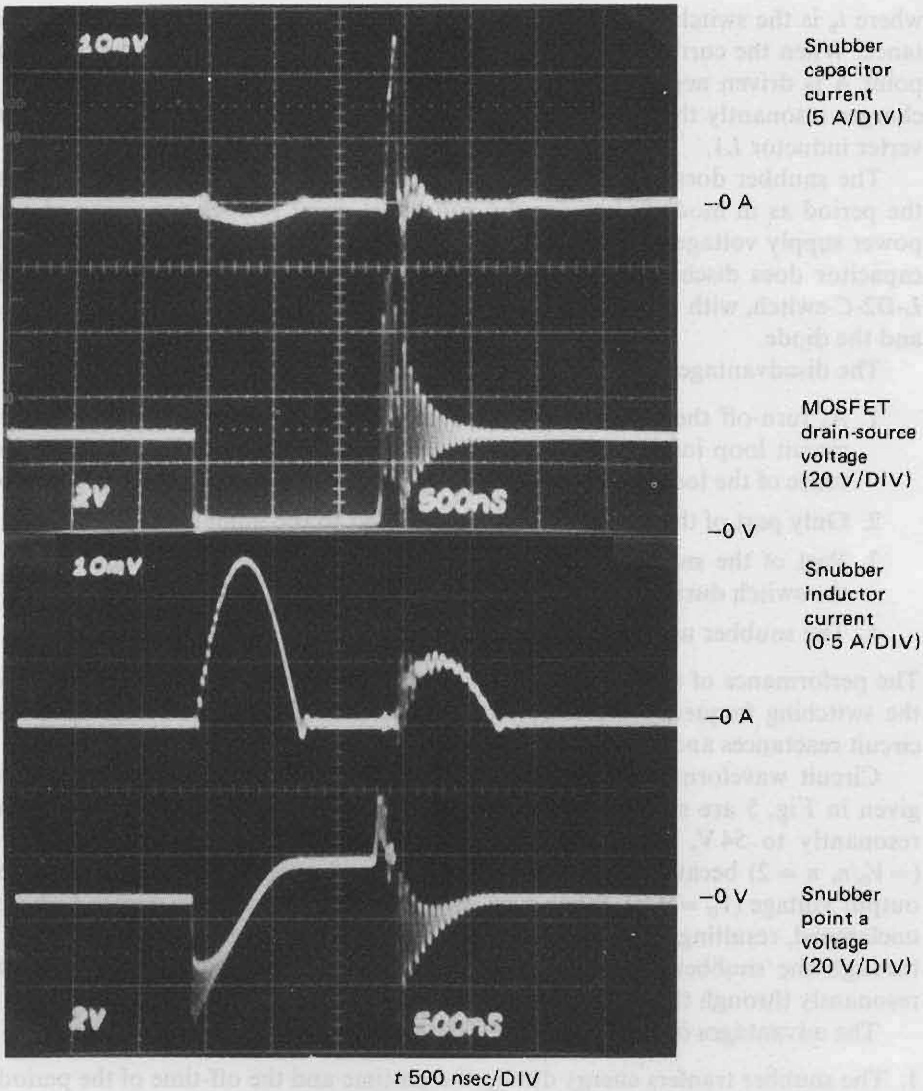


Figure 9. Domb-Redl-Sokal non-dissipative snubber circuit waveforms.

MOSFET when it is on. The capacitor voltage only discharges to 20 V before turn-off due to the small MOSFET duty cycle (D = 0·08).

The performance of the dissipative snubber at a switching frequency of 100 kHz is shown to be limited primarily by its resistive power loss, but also by parasitic snubber circuit inductance which limits the maximum capacitor voltage achieved during the turn-off transition.

Circuit waveforms of the Cuk converter with the Domb-Redl-Sokal snubber circuit given in Fig. 4 are shown in Fig. 9. The snubber operates only in mode 4, where the energy is returned to the power supply during the off-time of the period. In this mode the network *C-D*1 bypasses the switch current at turn-off, charging *C* to a peak voltage $V_p$,

$$V_p = V_{cc} + i_b(L_s/C)^{1/2} \tag{5}$$

where $i_b$ is the switch current at turn-off and $L_s$ is the parasitic drain circuit inductance. When the current through $L_s$ becomes zero, $v$ drops to $V_{cc}$ and the voltage at point A is driven negative. This forward biases $D2$ and the snubber capacitor discharges resonantly through $D2$-$L$-$C$-$L_s$ and into the power supply via the Cuk converter inductor $L1$.

The snubber does not return energy to the power supply during the on-time of the period as in mode 2, because the voltage at point A does not swing above the power supply voltage $V_{cc}$, thereby keeping $D1$ reverse biased. However, the snubber capacitor does discharge current resonantly during the on-time through the loop $L$-$D2$-$C$-switch, with the energy being dissipated within the parasitic loop resistances and the diode.

The disadvantages of the Domb-Redl-Sokal snubber are that:

1. At turn-off the snubber bypass current must flow through a physically large circuit loop incorporating $C$, $D1$ and the power supply. The parasitic inductance of the loop will then limit the turn-off energy bypassed by the snubber.
2. Only part of the snubber energy is returned to the input supply.
3. Part of the snubber energy is dissipated resonantly within the snubber and the switch during the on-time of the period.
4. The snubber uses two diodes to control the transfer of energy.

The performance of the Domb-Redl-Sokal snubber operating in a Cuk converter at the switching frequency of 100 kHz has been shown to be limited by the parasitic circuit reactances and the mode of snubber operation.

Circuit waveforms of the Cuk converter with the Ewing-Isbell snubber circuit given in Fig. 5 are shown in Fig. 10. At turn-off the snubber capacitor $C$ charges resonantly to 54 V, and the voltage across $L_p$ is clamped to approximately 2 V ($= V_0/n$, $n = 2$) because the snubber diode is conducting and $L_s$ is clamped to the output voltage ($V_0 = 4$ V). When turn-off is complete the voltage across $L_p$ becomes unclamped, resulting in resonant oscillations with transformer primary current flow through the snubber and the switch shunt capacitance. At turn-on $C$ discharges resonantly through the switch, transferring energy to the load.

The advantages of the Ewing-Isbell snubber are that:

1. The snubber tranfers energy during the on-time and the off-time of the period.
2. The snubber transfers energy to the output load.
3. The snubber capacitor is discharged fully before the start of the turn-off transition.
4. A minimal number of circuit components are used, with only one diode in the circuit.

The snubber does not exhibit any deleterious effects at the switching frequency of 100 kHz, however the transformer core losses may be significant as the resonant transfer of energy occurs at a frequency of 3 MHz, as shown in Fig. 10.

## 5. Conclusions

This paper has reported on circuit techniques for minimizing switching loss in switchmode converters operating at high switching frequencies. Switching loss

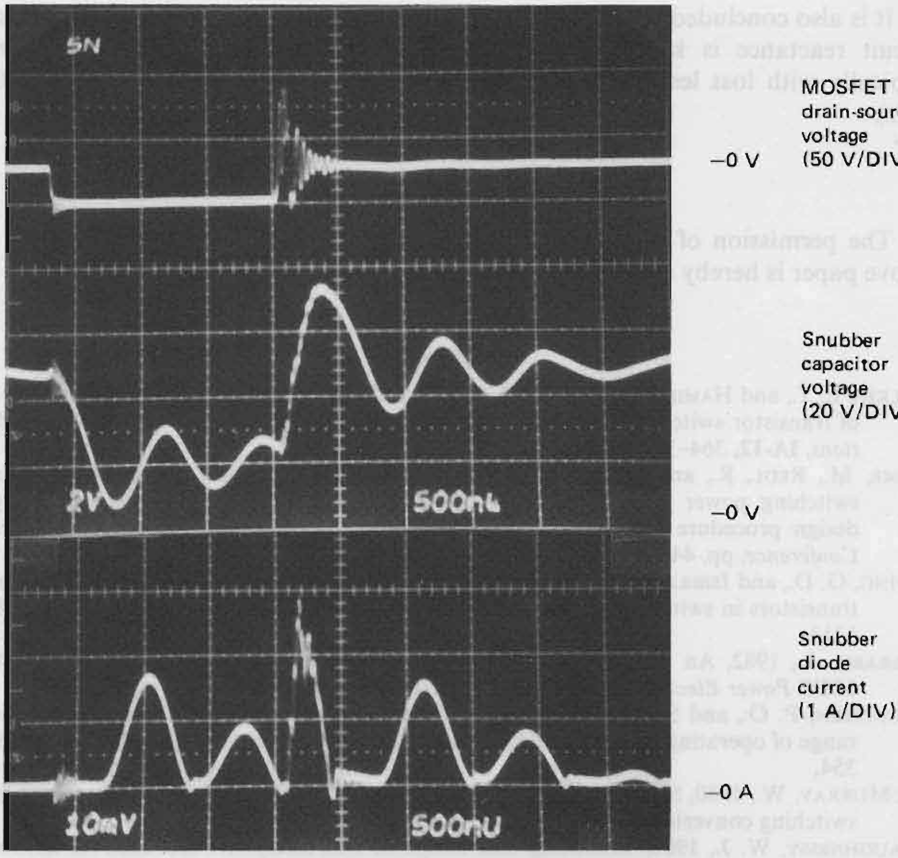


Figure 10. Ewing-Isbell non-dissipative snubber circuit waveforms.

increases linearly with frequency and is shown to be the dominant contributor to the total power loss in a Cuk converter at switching frequencies above a few hundred kHz. The improvements obtained by raising the converters switching frequency are reduced energy storage element size and weight, improved transient response and easier containment of both radiated and conducted EMI.

The experimental performance of three snubber ciruits has been investigated, when operating at a switching frequency of 100 kHz. It is shown that the Ewing-Isbell non-dissipative snubber provides effective operation at 100 kHz, and is considered suitable for use at higher switching frequencies. This snubber circuit provides a near-ideal transfer of switching energy to the output load with a minimum number of circuit components.

The performance of the Domb-Redl-Sokal non-dissipative snubber is limited by both the parasitic circuit reactances resulting from the circuit size, and the mode of switching energy recovery. When operating in the Cuk converter, the snubber returns part of the switching energy to the input supply and the remainder is dissipated resonantly in the snubber. It is concluded that this snubber is better suited to transformer isolated converters, where the snubber circuit operates in other modes.

It is also concluded that dissipative snubbers are suitable only when the parasitic circuit reactance is kept low and when the dissipated power loss is minimal (typically with loss less than 10 W and switching frequency below a few hundred kHz).

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