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Increasing Low Power Converter Efficiency with Resonant Snubbers

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Introduction

With energy requirements and costs constantly increasing, the demand for efficient power supplies obviously increases. Energy Star efficiency requirements for power conversion equipment are pretty much becoming the norm in the industry and world wide, and prospects indicate evolving and even tighter efficiency requirements in the future. The real problem in meeting the efficiency requirements has been in the low power realm of linear supplies where, in many cases, no hope at all exists in meeting them. As a consequence, off-line switchmode supplies are now rapidly replacing linear supplies and transformer “wallwarts” at low power levels even as low as a watt. This is evident in cell phone chargers, small set-top box supplies, modems and in commercial equipment such as garage door openers and white goods. However, designing switchmode supplies to meet the Energy Star requirements at low power levels is not easy. The reasons are multiple: 1) Cost – an absolute minimum cost is demanded for power supplies used in consumer items, severely limiting the components and sophistication of design; 2) Increasingly low output voltages such as 1.8, 2.2, and 3.3 volts severely impact the overall conversion efficiency, which now mandates the implementation of, say, synchronous rectifiers or other cost increasing techniques to achieve the desired efficiency; 3) The quiescent or standby current of the switcher control circuit now becomes a more significant fraction of the total output power, particularly in the case of single digit watt output power levels. This places an additional burden on the power supply control chip manufacturer to provide low operating power controllers at minimal cost. As one can imagine, all of the above factors are interrelated, so it becomes a challenging task for the power supply designer to bring all of these factors together and perhaps find the right combination of components and circuit “tricks” to meet the minimum efficient requirement.

Energy Star Efficiency Requirement (for active mode)

The Energy Star minimum average efficiency requirement (Tier 1 External Power Supplies, effective as of 1/1/2005) is defined as follows:

$$E_{\min} = [\ln(P_{\text{out}}) \times 0.09] + 0.49 \text{ for } 1 \text{ W} < P_{\text{out}} \leq 49 \text{ W}$$

Where P_{out} is the maximum output power of the power supply and \ln is the natural logarithm.

In order to get the average minimum efficiency, the efficiency of the supply must be measured at 25%, 50%, 75% and 100% of the rated output loading and then the average efficiency established. Notice that the full load efficiency may be acceptable, however, a poor efficiency at the 25% level (which is typical of low power converters), can essentially wreck the average efficiency number.

Typical Low Power Off-Line Converter

The schematic of Figure 1 shows a typical 12 volt, 16 watt modem supply utilizing ON Semiconductor’s NCP1027 monolithic current mode controller in a flyback topology. In flyback topologies such as this it is necessary to use some type of snubber circuit to limit the voltage spike on the switching Mosfet during device turn-off. This spike is caused by the leakage inductance or imperfect coupling of the transformer’s primary to secondary windings. The spike can be exacerbated in low power flyback converters because of the small size of the transformer and the associated less-than-ideal winding techniques that may be necessary to achieve acceptable operating flux densities and safety agency insulation requirements. Even though the amplitude of the voltage spike is defined by the relation $E=LdI/dt$, where the dI/dt term may be minimal due to the low power switch currents at this power level, the magnitude of L , which is the leakage inductance term, may still be relatively high due to the above mentioned non-ideal winding geometry constraints.

The RCD (resistor-capacitor-diode) snubber network composed of R2, R3, C5 and D5 is the conventional method of limiting the amplitude of the turn-off voltage spike. This network essentially clamps the amplitude of the voltage spike to a voltage somewhat higher than that of the dc bulk voltage of the converter depending on the residual charge on the snubber capacitor. To be effective for each switching cycle, the snubber capacitor must be discharged sufficiently to maintain a minimal charge level and the resistor R3 performs this function. Depending on the transformer’s leakage inductance, the power dissipation in this resistor can

be a very small fraction of a watt to several hundred milliwatts. This is energy wasted as heat and it can have a significant impact on the efficiency of the supply at low power levels. If this energy could be recycled back to the converter's input bulk capacitor C4, this would represent a savings of the energy normally dissipated as heat in resistor R3 and results in an increase in the supply's efficiency.

Non-dissipative, Resonant Snubber Circuit

Figure 2 shows an alternative to the classical RCD snubber network, using a non-dissipative resonant snubber. This resonant snubber not only recycles transformer T1's leakage reactance energy to the input bulk capacitor C4, but also provides a more effective shaping of the Mosfet's load line, thus lowering switching losses. At Mosfet turn-off, the leakage inductance energy of T1 is transferred to Cr and the rate of rise of the drain voltage (dV/dt) is slowed. When the Mosfet turns back on, capacitor Cr is discharged by transferring its energy to Lr in the resonant circuit formed by Lr/Cr. During the next off-period the energy is then transferred back to the bulk cap through the series diodes. This action can actually be best interpreted as a resonant "charge pump" in which the leakage inductance energy is returned to the bulk cap. The additional components include the small inductor Lr and another ultrafast diode. The overall converter circuit efficiency improvement will be several percentage points, particularly at light loads. This seemingly slight improvement may be all that is needed to meet the minimum Energy Star requirement. It should be noted that, in cases where the particular combination of leakage inductance and stray circuit capacitance produces significant ringing on the drain voltage waveform, changing the two fast recovery diodes to 60 Hz type diodes such as 1N4007 devices will actually help damp the ringing due to their slower recovery time. This will be of benefit for EMI considerations.

The calculations for obtaining the values of Cr and Lr in the circuit are straightforward. The capacitor value can be the same as that calculated for the RCD snubber network and is typically given by the following:

$$C_{r \text{ min}} = (I_{pk} * t) / V_{pk}$$

Where Ipk is the peak current seen by the Mosfet switch, t is the current fall-time in the Mosfet (typically 50 ns), and Vpk is the peak drain voltage seen by the Mosfet at turn-off. This latter value is just the minimum dc bulk voltage at low line plus the reflected flyback voltage determined by the

output voltage reflected through the transformer's turns ratio. For the case of this 16 watt supply, the peak Mosfet current is approximately 0.8 amps and the reflected peak voltage is just:

$$(V_{ac \text{ min}} * 1.4) + (V_{out} * N_p/N_s) = (120 \text{ Vac} * 1.4) + (12 \text{ Vdc} * 10) = 293 \text{ or } 300 \text{ Vdc}$$

Where Np/Ns is the turns ratio of the transformer which is 10 to 1.

Cr min then becomes: $(0.8 \text{ A} * 50\text{E-}9) / 300 = 0.133 \text{ nF}$; and to assure optimum snubbing a slightly higher value of 0.180 nF, or 180 pF was chosen.

The inductor should be chosen such that the snubber circuit's resonant frequency is at least 3 times the converter's switching frequency. Since the NCP1027 in this circuit is operating at 100 kHz, a 1.5 mH inductor was chosen, which, when used with the 180 nF capacitor yields a resonant frequency of approximately 300 kHz.

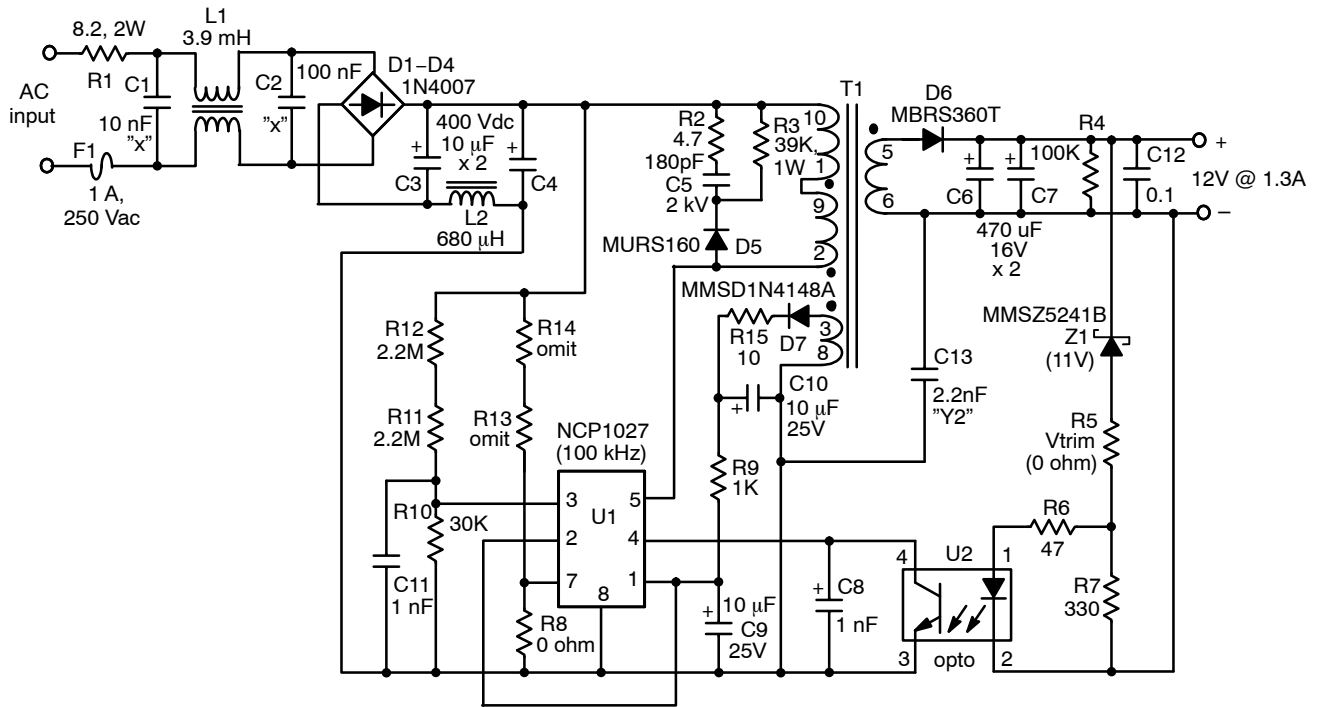
$$f = \frac{1}{2\pi \sqrt{L_r * C_r}}$$

One additional side benefit of the resonant snubber is the load line shaping that it provides to the Mosfet at turn-off. Because of the more effective discharging of snubber cap Cr, once the turn-off drain voltage reaches the dc bulk level, the rate of rise of the voltage (dV/dt) is stalled by the abrupt charging of Cr which lowers the switching losses in the Mosfet.

Results

The efficiency test results are shown in Figures 3 and 4. Figure 3 shows the efficiency curves with the traditional RCD snubber and Figure 4 shows the efficiency curves with the resonant snubber. Note that even though the circuit with RCD snubber in this example does meet the Energy Star minimum efficiency requirement of 74% (from $[\text{Ln}(16) * 0.09] + 0.49 = 0.74$), application of the resonant snubber increases the 120 Vac input efficiency by 2%. At 230 Vac the improvement is about 1%. If the supply had an output of 5 volts instead of 12 volts with a consequential lower average efficiency, the RCD may have been marginal and the use of the resonant snubber would have been imperative. The efficiency plots also show that light loading at 25% clearly impacts the average efficiency the most. This would mean that utilization of the resonant snubber would be even more advantageous at single digit power levels such as in cell phone chargers.

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NOTES:

1. L1 is Coilcraft E3491-AL common mode EMI inductor (3.9 mH)
2. L2 is Coilcraft part RFB0810-681L or similar (680 uH, 500 mA)
3. See Magnetics Data Sheet for T1 construction details.
4. R9 sets OVP trip level.
5. R8, R13, R14 for optional power limit feature (see NCP1027 data sheet.)
6. Z1 zener sets Vout: $V_{out} = V_z + 0.85V$; R5 is optional voltage trim resistor
7. R10 sets AC input brownout level.
8. R1 is optional inrush limiter.
9. U1 requires Aavid #580100W00000G clip-on DIP8 heatsink or similar.
10. Crossed schematic lines are not connected

Figure 1. 16 Watt, 12 Volt Output Modem Supply Schematic

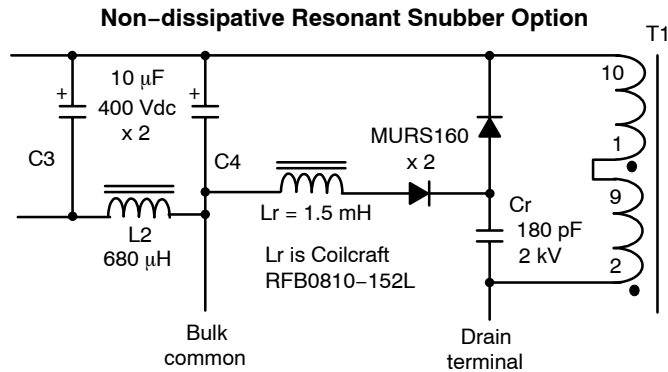


Figure 2. Resonant Snubber Circuit

Traditional RCD Snubber

Efficiency @ 25°C		
Load (%)	120 Vac (%)	230 Vac (%)
25	74	73
50	77	78.2
75	77.6	80
100	76.8	80.6
Average Efficiency	76.4	78.0
Minimum Efficiency per ENERGY STAR: [0.09 * Ln(16 W)] + 0.49	74	74

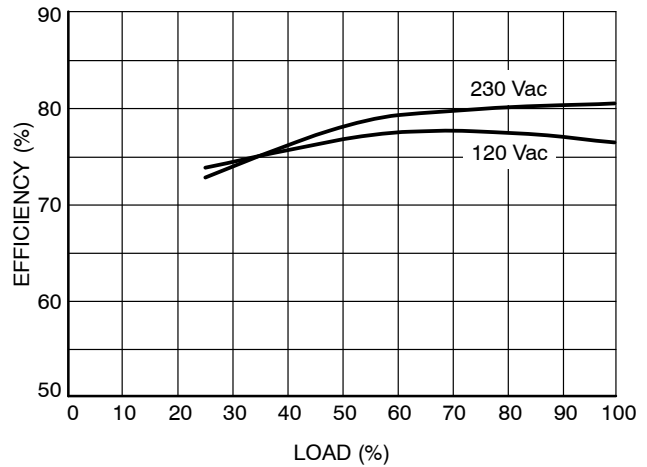


Figure 3. RCD Snubber Efficiency Plots

Non-Dissipative Resonant Snubber

Efficiency @ 25°C		
Load (%)	120 Vac (%)	230 Vac (%)
25	76.2	74.4
50	79	79.8
75	79	80.5
100	78.2	81
Average Efficiency	78.1	78.9
Minimum Efficiency per ENERGY STAR: [0.09 * Ln(16 W)] + 0.49	74	74

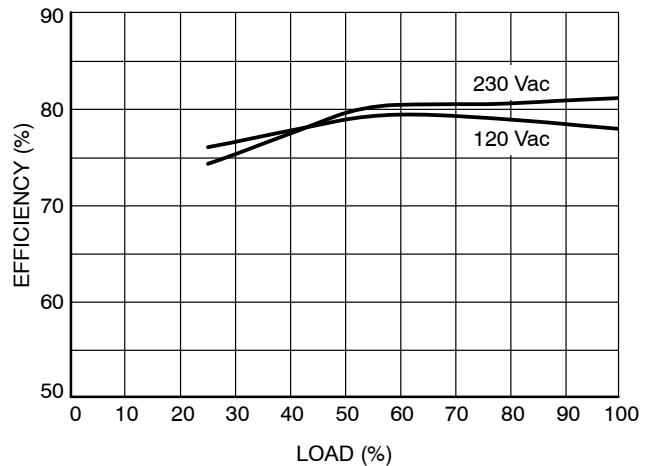


Figure 4. Resonant Snubber Efficiency Plots

References

ON Semiconductor Design Note DN06021/D; A 16 W, 12 Vdc Modem Power Supply; ON Semiconductor Website.

Snubber Circuits: Design, Theory and Application; Topic 2, Unitorde Power Supply Design Seminar SEM-900

Switching Power Supply Design, 2nd Edition by Abraham Pressman; Chapter 11; Turn-on, Turn-off Switching Losses and Snubbers, pages 413 to 426.

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