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# Offline Buck Converter with Tapped Inductor Offers Improved Performance

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## APPLICATION NOTE

## Introduction

For electronic and industrial equipment requiring non−isolated, offline, low power outputs, the simple buck converter appears ideal; however, the large differential input−to−output voltage can be problematic in terms of very low converter duty cycle, peak−to−average switching current ratios, and overall conversion efficiency. This application presents a solution that will overcome many of these issues without additional electronic circuitry. The solution involves a modification to the buck inductor in which a tap is added to the winding and the buck freewheeling diode is connected to the tap. This magnetic reconfiguration will convert the standard buck topology shown in Figure 1 to what is sometimes referred to as the "current−boosted" buck shown in Figure 2.

## Buck Converter Operation

A conventional offline buck converter with an output of 12 volts at 300 mA (3.6 watts) is shown in Figure 1. This example converter is configured around ON Semiconductor's NCP1014 monolithic current mode controller with integrated MOSFET for maximum circuit simplicity; however, it could also be configured with a discrete controller such as the NCP1216 and a separate MOSFET. Voltage regulation and feedback are accomplished via the simple network of Zener diode Z1, the associated resistors R2 and R3, and optocoupler U2. The optocoupler is necessary because the ground (pin 4) on the NCP1014 controller is at a switching node and optical feedback is the simplest and most economical way to overcome the associated dV/dts and high voltage issues associated with other types of discrete feedback and/or voltage offset circuits. The schematic also includes a simple conducted EMI filter comprised of C1, and pi−network C2, L1, and C3.

As with typical buck operation, the rectified offline voltage at bulk capacitor C3 provides a dc level to the drain of U1's internal MOSFET (pin 3), and is switched on and off at the source terminal (pin 4) and presented to the integrating circuit of L2 and C4. The L/C output filter averages the switched rectangular waveform to the desired output dc voltage at C4 via the voltage sensing/feedback of Z1/U2 and

pulse width modulation in U1. Freewheeling diode D5 provides for current continuity in L2 when the MOSFET in U1 is in the offstate.

The dc transfer function of the buck converter is given by Vout = D x Vin where D is the duty cycle (MOSFET on time divided by total switching period T) of the rectangular wave presented at L2's input. Vin is the dc voltage presented to the buck switching circuit. For a nominal input of 120 Vac and an output of 12 volts one can easily calculate the required duty cycle D for the internal MOSFET switch:

$$D = \frac{V_{out}}{(V_{in} \text{ ac} \times 1.4)} = \frac{12}{(120 \times 1.4)} = 0.07 \text{ or } 7\%$$

This is a very small duty cycle, which for a switching frequency of 100 kHz (T = 10 μs), amounts to an on time of 0.07 x 10 μs = 0.7 μs or 700 ns. This short on time duration is actually not much larger than the controller's internal propagation delay and leaves little room for pulse width dynamic range for load changes, and will certainly result in a sub−switching frequency pulse skipping mode of operation when the load drops below the level where L2's current becomes discontinuous. Operation in this mode may be acceptable as long as the output ripple of the supply is not excessive and/or audible noise is not present in the inductor.

Operation with low duty cycles also requires the inductance of the main output choke L2 to be higher if discontinuous conduction mode (DCM) is to be avoided at the lowest nominal output loading. This aspect of the inductor design is also related to the peak−to−average current ratio seen by the MOSFET. The peak current through the internal MOSFET of U1 is the sum of the output load current and the magnetizing current of L2. Under nominal line conditions (165 Vdc on C3), the peak magnetizing current at the end of a switching cycle is given by the familiar relationship of E = L x dI/dt. Rearranging the terms for dI gives dI = (E x dt)/L, which computes to the following magnetizing current for this example:

$$dI = \frac{[(V_{in} \text{ dc} - V_{out}) \times dt]}{L} = \frac{[(165 - 12) \times 0.7]}{750 \text{ μH}} = 143 \text{ mA}$$

Peak MOSFET current will be 300 mA (max load current) + 143 mA = 443 mA.

The nominal specified overcurrent trip level in the NCP1014 is 450 mA assuming no tolerance variation. So, the question here is how can we avoid the above mentioned low duty cycle issues and possibly get even more output current from this buck converter using the same semiconductors with minimal circuit changes.

**Solution**

A modification that will resolve the issues associated with low duty cycle and even allow a higher output current is shown in the tapped inductor buck schematic of Figure 2. By tapping the inductor at 25 percent from the output end and connecting the freewheeling diode at this node we can increase the new duty cycle of the MOSFET to approximately D' = 0.24 or an on time of 2.4 μs, and the output current can be increased by about three times, to almost 1 ampere. The relationships for the extended duty cycle D', and the peak current boosting effect, Iboost, are as follows:

$$D' = \frac{(N+1)}{[N + (\frac{V_{in}dc}{V_{out}})]}$$

where N is the turns ratio of the two windings on either side of the tap. In this case the winding on the left side or input side of the tap has three times as many turns as the winding on the output or freewheel side of the tap. The peak current boosting capability is given by:

$$I_{boost} = \frac{(N + 1)}{[(\frac{N \times V_{out}}{V_{in}\,dc}) + 1]}$$

The dc voltage input−to−output transfer function now becomes:

$$V_{out} = \frac{V_{in}dc}{[\frac{(N+1)}{D}] - N}$$

**Why It Works**

The statement that current cannot be abruptly discontinuous in an inductor is actually false as stated. The fact is, *the ampere turns product in an inductor cannot be discontinuous, i.e., NI must be a constant throughout the switching period T.* In the tapped inductor, the total number of inductor turns carries the current when the MOSFET is on, and this current will obviously have to be less than the specified overcurrent limit in U1. When the MOSFET shuts off, however, the current in the output side of the winding must increase abruptly to a peak level four times that of the on time current to satisfy the ampere turns equality since the output or freewheel diode winding has one quarter the number of turns of the entire winding. The current waveform typical of this transition is shown in Figure 3. Section A is the magnetizing ramp of the voltage across the entire inductor when the MOSFET switch is on. When the switch turns off, a current discontinuity is created at B where the current rises to a peak level defined by the full winding turns to freewheel diode winding turns ratio (4:1). The current ramp−down slope of C is defined by the value of the output

voltage plus freewheel diode voltage drop across the freewheel winding when the MOSFET is off, again by the relationship dI = (E x dt) /L. Note that L in this case is 1/16 of the full on−state winding inductance because inductance is proportional to $N^2$. Since the inductor integrates the waveform across it, the area under the offtime current waveform through the freewheel winding is larger than that of the ontime current waveform, and consequently the average output current will be higher. The differences seen by the MOSFET are, of course, the longer ontime (or D') in which it conducts current, and a higher turnoff voltage which will be mentioned below.

**Limitations and Practical Considerations**

It is interesting to note that the current boosting benefits will diminish when the input−to−output voltage differential is reduced. Taking another look at the current boosting relationship, Iboost = (N + 1)/[(N x Vout/Vin dc) + 1], shows that as Vout approaches Vin, the denominator term becomes N + 1 and the whole expression reduces to unity in the limit so that no benefit is achieved. At very high input voltages the value of the expression approaches N + 1 and effective output current boosting can be achieved by tapping the inductor at some appropriate point. Note that this relationship gives the *peak* current boosting effect and that the actual output current increase is the *weighted average* of the current waveform profile due to the integrating effect of the inductor. Keep in mind that the freewheel diode will now have to be current rated to handle this increase in average output current.

The location of the tap on the inductor and how the tap node is derived is also important due to the detrimental effects of leakage inductance between the two sections of the windings. Tapping should be done by using multifilar winding techniques which allow symmetrical and interleaved windings that reduce leakage inductance. For inductor L2 of Figure 2, the coil should be made by flat winding (no twists) four windings simultaneously (quadrafilar with four "wires−in−hand"), and then connecting the four windings in a series aiding manner ("finish" of one winding to the "start" of the next.) The connection of the 3rd section to the 4th becomes the tap for the freewheeling diode. This winding technique guarantees a symmetrical "immersion" of all windings in the magnetic flux with minimal leakage inductance. For a lower input voltage the winding configuration could be done bifilar with just two windings and the tap is at the halfway point where the windings are connected in series−aiding. In this case N becomes 1 in the three above equations because the windings have equal turns. A good rule of thumb is to select a configuration that places the expanded duty cycle D' somewhere between 0.2 and 0.5. If D is greater than 0.25 using the conventional buck with D = Vout/Vin relationship, then a tapped inductor approach will probably not be beneficial. Practice has shown that tapping the inductor such that N is either 1, 2, or 3 (depending on the input−to−output voltage ratio) will usually produce satisfactory results.

Another consequence of the tapped inductor is an additional negative voltage excursion on the source terminal of the switching MOSFET in U1 because the freewheel diode is now unable to directly clamp this voltage to a diode drop below the output common rail. The additional negative voltage seen by the MOSFET will be the buck output voltage plus diode drop times the turns ratio of the full inductor winding with respect to the freewheel winding, or (12 + 0.8) x 4 = 52 volts approximately. The leakage inductance between the windings will also contribute a narrow spike which could have a similar amplitude or higher. With the multifilar coil winding techniques described above this spike should be minimal; however, depending on the MOSFET's voltage rating, an optional small R/C snubber (R4 & C8) from the switching node to the output common should all but eliminate the spike. Assuming a universal mains input at high line (270 Vac), the peak voltage seen by the MOSFET will be in the order of 500 volts or less which is well below the 700 volt rating of the NCP1014.

One other issue that should be mentioned which is affected by the tapped inductor is the ripple current rating of output capacitor C4. The abrupt current step in the inductor current at the moment of MOSFET turnoff will be seen by the capacitor and the rms value will be approximately one half that of the peak−to−peak current step. This is significantly greater than the rather "benign" triangle current waveform that the conventional buck output capacitor typically experiences. Depending on the capacitor ESR, it may be necessary to use multiple output capacitors in parallel not only to handle the increased ripple current but to also keep the peak−to−peak voltage ripple component appearing across the capacitor's ESR under control. For applications requiring very low output ripple, it may be necessary to use a two−stage "pi" network output filter with the addition of a small 4.7 μH slug inductor and another output capacitor following it.

### References

NCP1014 Data Sheet; ON Semiconductor Website (www.onsemi.com)

ON Semiconductor Design Notes DN06002, DN06011; ON Semiconductor Website

"Modern DC−to−DC Switchmode Power Converter Circuits", Chapter 8; By Rudolf Severns and Gordon Bloom; Van Nostrand Reinhold

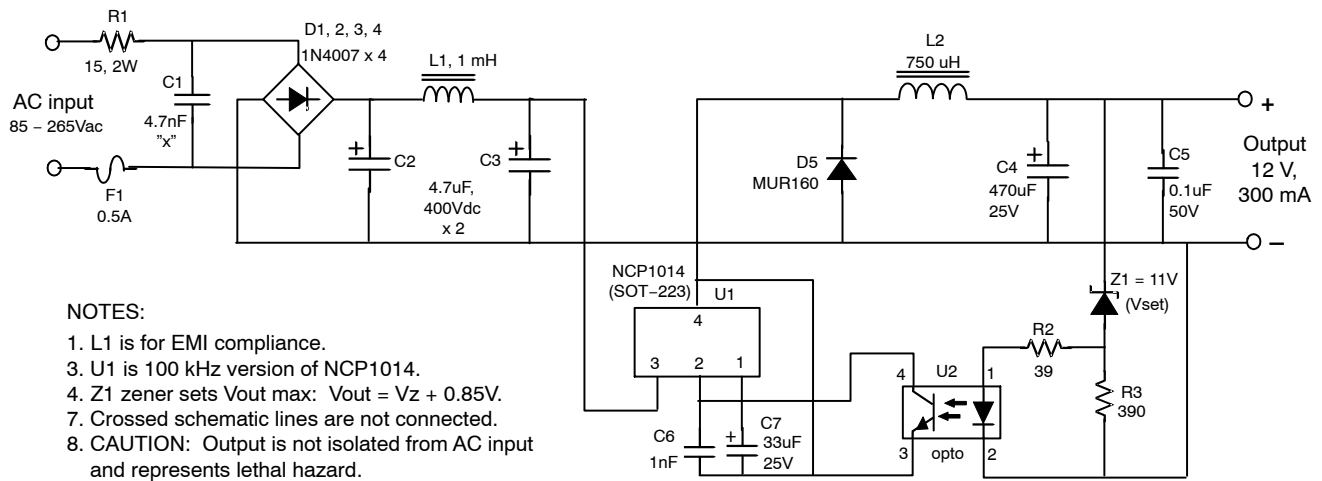ON Semiconductor Application Notes AND8190, AND8226; ON Semiconductor Website

NOTES:

1. L1 is for EMI compliance.
3. U1 is 100 kHz version of NCP1014.
4. Z1 zener sets Vout max: Vout = Vz + 0.85V.
7. Crossed schematic lines are not connected.
8. CAUTION: Output is not isolated from AC input and represents lethal hazard.

**Figure 1. Offline Buck with Conventional Inductor**
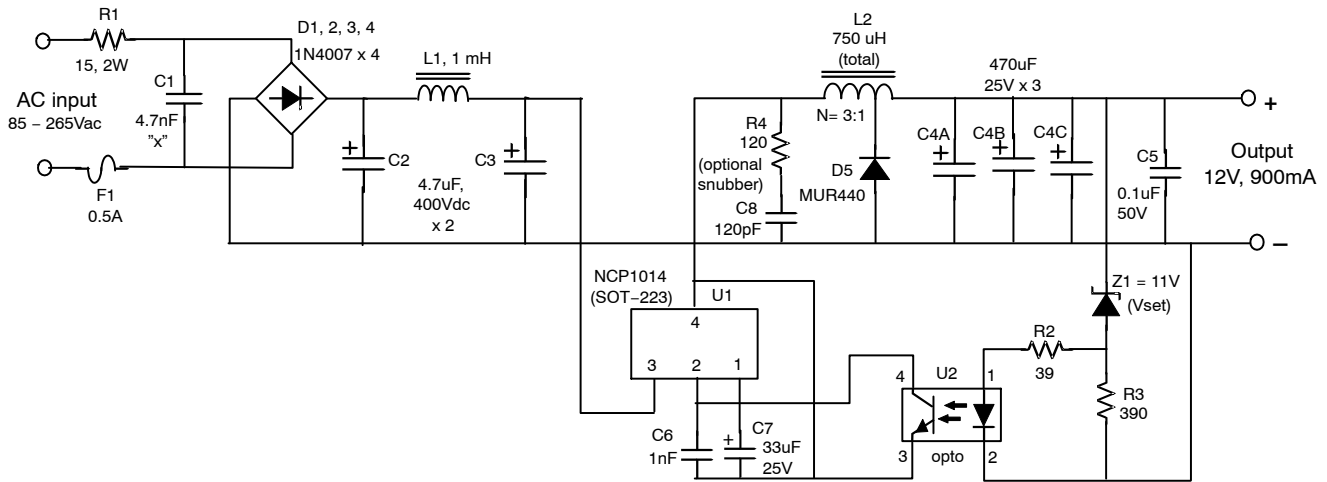
**Figure 2. Offline Buck with Tapped Inductor and Current Boosted Output**



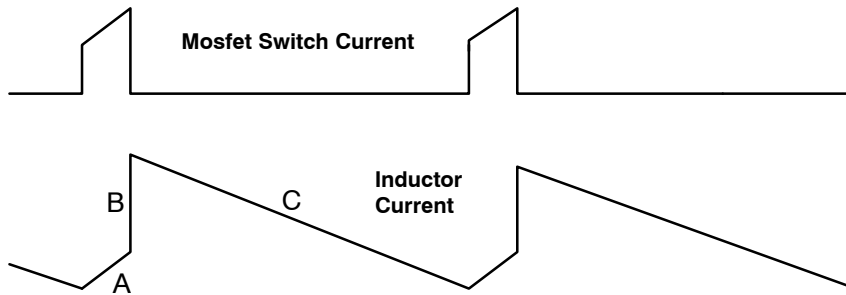**Figure 3. Tapped Inductor Current Profile**