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# AND9043/D

# An Off-Line, Power Factor Corrected, Buck-Boost Converter for Low Power LED Applications

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## APPLICATION NOTE

### Introduction

This application note introduces a universal input, off-line buck-boost converter with inherent power factor correction (PFC) for driving constant current LED lighting applications. The converter is intended for series string LED applications where currents up to 100 mA are required with series forward voltage drops from 35 to 120 Vdc. LED applications include strip lighting, linear fluorescent replacements, and wall packs where AC line-to-output isolation is not required. The circuit design is also compatible with most existing triac dimmers and is applicable for power levels up to about 8 W maximum, depending on the output voltage and current combinations. The maximum open circuit output voltage is easily adjustable as well as the output current. The buck-boost circuit is designed around ON Semiconductor's NCP1014 series of monolithic switcher ICs and provides a very simple and low cost approach to LED lighting applications. The buck-boost inductor is also available as an off-the-shelf component.

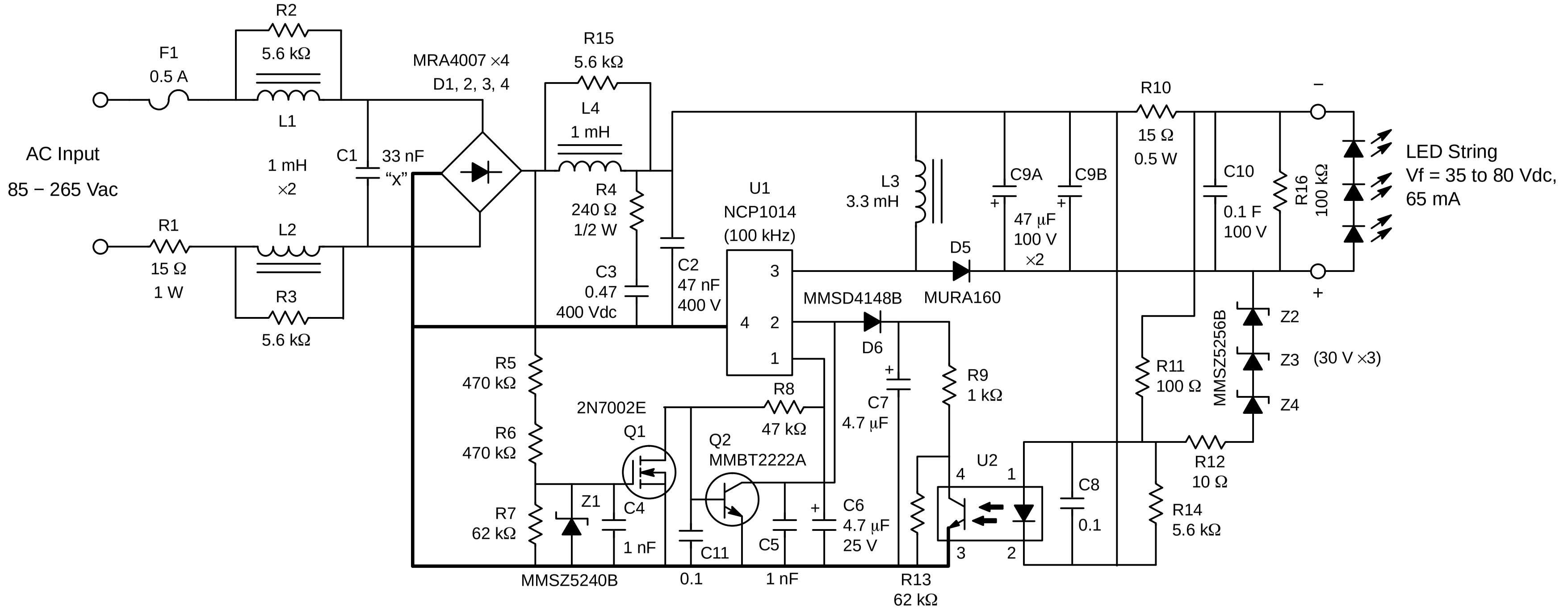
### Basic Circuit Operation

The NCP1014 buck-boost converter circuit is shown in Figure 1 and is configured for a 65 mA output with a Vf maximum of 80 V with the open circuit output clamped at about 90 V. The output current is set by current sense resistor R10 ($I_{out} = 0.95/R10$). The forward voltage drop of the photo diode in optocoupler U2 provides the effective reference voltage for current sensing.

The output current can be trimmed upward with R14. $V_{out}$ max is set by the total series Zener diode voltage of Z1 + Z2 + Z3 + 1 V. R16 is for discharging output caps C9A/B when the converter is off and provides a pre-load which helps set the minimum dimness level when triac dimming is used.

The buck-boost converter is configured around monolithic controller U1 (NCP1014), rectifier D5, inductor L3 and output capacitors C9A and C9B. The inductor L3 is operated in continuous conduction mode (CCM) to minimize the peak-to-average current ratio and to maximize overall circuit efficiency. Efficiency curves for various output Vf values and for both nominal line voltages are shown in Figure 2 below.

March, 2014 − Rev. 1



Notes:

1. Vout max set by Z2+ Z3 + Z4 (Vout = Vz + 1V)
2. I out max set by R10 (Iout = 0.95/R10); Imax = 100 mA
3. R14 is for trimming Iout (optional).
4. L1, L2, L4 are Wurth WE−TI 7447462102 or similar (1 mH).
5. L3 is Wurth part # WE−PD 7447709332 (or equivalent 3.3 mH inductor).
6. U1 should be heatsunk via ground tab (pin 4) to copper clad area.
7. Crossed schematic lines are not connected.
8. Thick lines are recommended ground plane/heatsink area.
9. For non−triac dimming applications R4, R5, R6, R7, R8, C3, C4, C5, Z1, Q1, and Q2 can be omitted. D6 can be replaced with a zero ohm resistor.

NCP1014 CVCC Off−line Buck−Boost with
Active PFC and Triac Dimming (Rev 9)

Figure 1. Buck-Boost Schematic

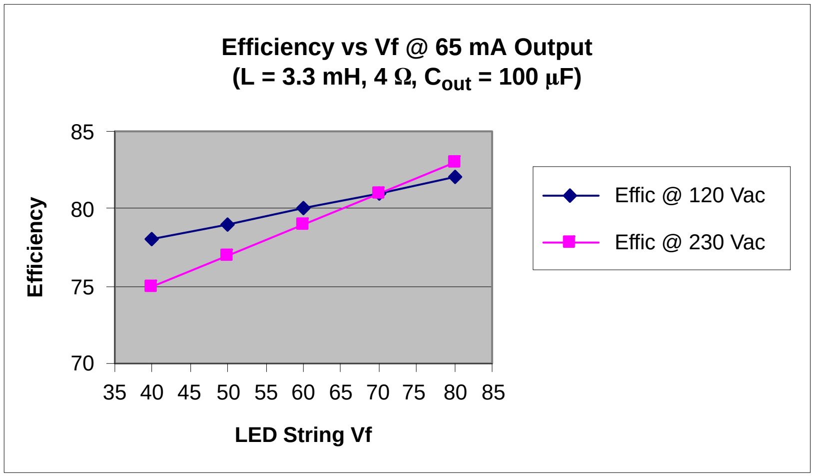


Figure 2. Efficiency versus Output Vf

The converter input circuit employs a conducted EMI filter comprised of L1, L2, L4, and C1. This filter is adequate for meeting FCC level B for conducted emissions as shown in the green plot (average) of Figure 3. This is for the maximum rated output current of 100 mA.

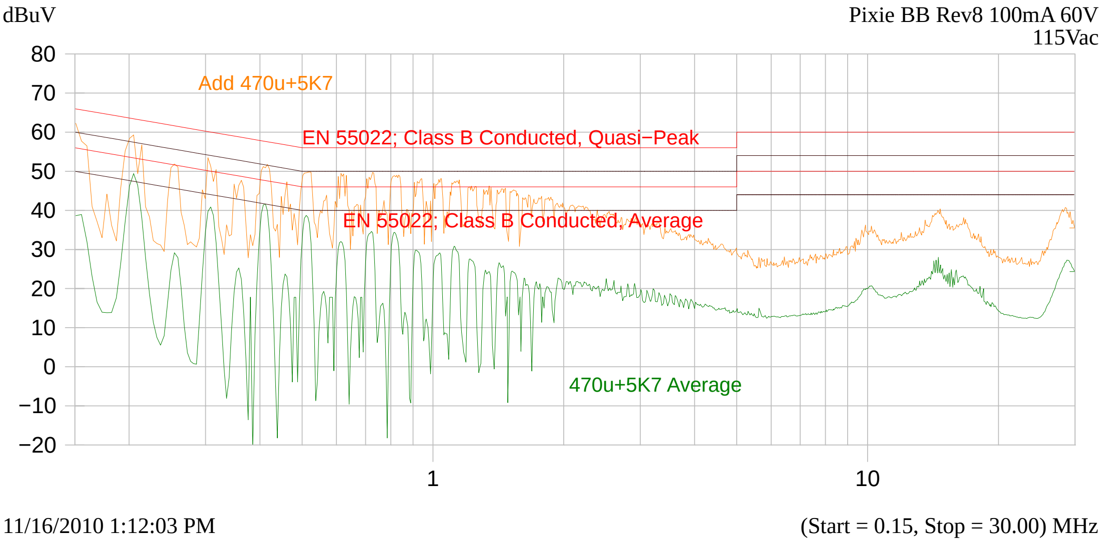


Figure 3. Conducted EMI for 100 mA with Vf = 60 Vdc (Green = Average; Orange = Peak)

By utilizing minimal input bulk capacity for C2, and low capacitance values for EMI “X” cap C1, relatively high power factor is achieved by switching the converter directly from the full-wave rectified line voltage. The unity gain bandwidth of the converter feedback loop is also set below 40 Hz via C7 and this also improves the through-put power factor. The power factor versus Vf for both nominal line voltages is shown in Figure 4 below:

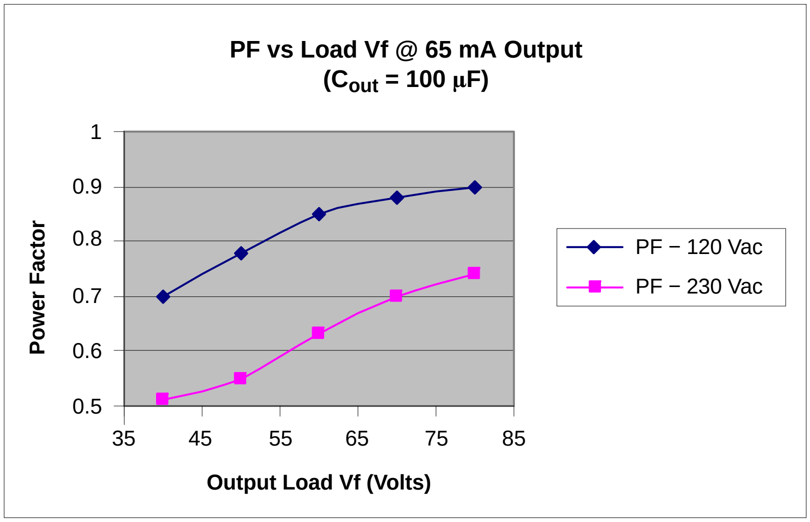


Figure 4. Power Factor versus LED Vf

Despite the simple, relatively low gain current sense and feedback design, current regulation over the typical Vf range is better than 4% as shown in Figure 5.

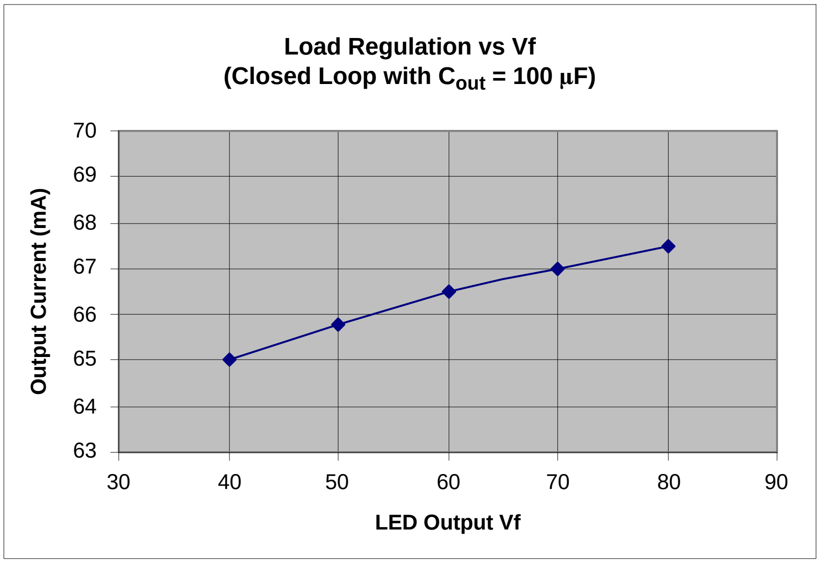


Figure 5. Current Regulation versus Vf

The 120 Hz output current ripple for 100 mA into an LED load with two 47 µF output capacitors in parallel (C9A/B) is shown in Figure 6. The output current ripple for a single output capacitor of 47 µF is shown in Figure 7. The scale is 50 mA per division vertically. The current ripple amplitude is dependent on the amount of filter capacity on the converter’s output, since the slow feedback loop causes this ripple to pass directly through the converter. It should be noted that the power factor and current regulation will degrade with decreasing output capacity. A minimum output capacity of about 47 µF (peak-to-peak ripple = 30% max) was found to be adequate for most applications up to 100 mA output current.

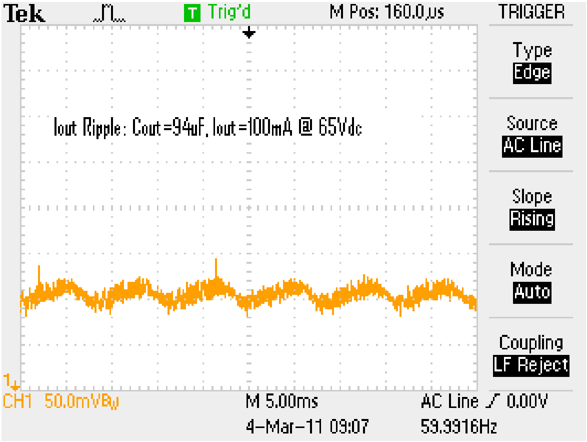


**Figure 6. Output Current Ripple with Cout = 94 μF and LED Load = 100 mA (Vf = 65 Vdc)**

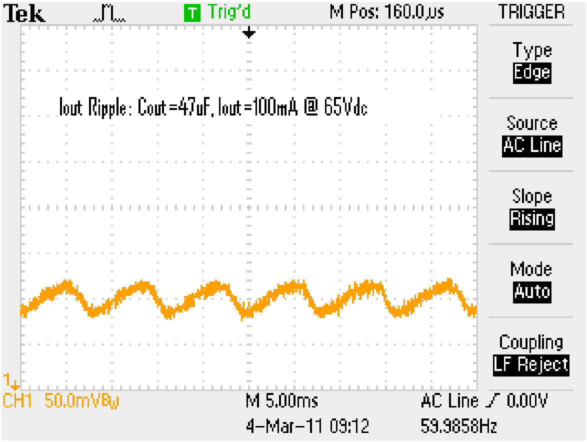


**Figure 7. Output Current Ripple with $C_{out}$ = 47 μF and LED Load = 100 mA**

### Inductor Selection

The buck-boost inductor was selected for continuous conduction mode (CCM) operation so as to minimize the peak-to-average current ratio in the converter and make maximum use of the current capability of the NCP1014's internal MOSFET. In addition, it was desired to use an off-the-shelf available inductor so as to avoid the expense of custom made inductors. As such, a commercially available inductor from Wurth Electronik with a nominal inductance of 3.3 mH and a dc resistance of about 4 Ω was selected and appeared adequate for the application. It should be noted that a custom made inductor with lower dc resistance would improve the overall efficiency; however, the cost would also probably increase. The minimum required inductance for CCM operation can be determined as follows:

The minimum lower tolerance on the MOSFET current limit level in the NCP1014 is 400 mA. For CCM operation let's figure on the inductor magnetizing current being no more than 50% of this amount, or 200 mA. Assuming a minimum nominal ac input of 90 Vac, this translates to 120 Vdc peak. Now, since we are not using a bulk input capacitance that can charge to peak, the average value of the input is 60 Vdc. Assuming a typical output voltage Vf (in this example) of 60 V and the fact that the transfer function for a CCM buck-boost is $V_{in}/V_{out} = D/(1-D)$ where D is the duty ratio, we can solve for D to determine the average on-time of the MOSFET at low ac input:

$$D/(1-D) = V_{in}/V_{out} = 60\text{ V}/60\text{ V} = 1,$$

so solving for D we get D = 0.5.

So, for a 100 kHz switching frequency the average on-time will be 5 μs. From this we can now calculate a minimum inductance value:

$$L = V_{pk} \times dt/dI = 120 \times 5\ \mu\text{s}/0.2\text{ A} = 3000\ \mu\text{H}$$

where $V_{pk}$ is the peak voltage across the inductor at low line and dI is the maximum selected peak-to-peak value of the choke magnetizing current. Since 3.3 mH is a common value, this was selected.

### Triac Dimming

Triac dimming is possible with this buck-boost circuit as long as the triac holding current is low enough for stable operation at the lowest desired dimming current. One advantage of this circuit implementation that helps stability during dimming is the fact that the NCP1014 utilizes current mode control. This control approach does deteriorate the power factor somewhat since it attempts to instantaneously control the 120 Hz output ripple by adjusting the duty ratio, however, this effect also tends to shape the line current as a trapezoidal waveform. With a trapezoidal current waveform, the trailing edge at the end of a line cycle is still relatively high as opposed to the sinusoidal "tail-off" typical of a normal sine wave. The fact that the current remains high at the end of the half-cycle current pulse helps to maintain the triac holding current for the very short conduction angles necessary for low level dimming. Figures 8 and 9 show the 120 Vac input line current (yellow) and voltage (blue) during dimming for conduction angles of 100° and 22° respectively.

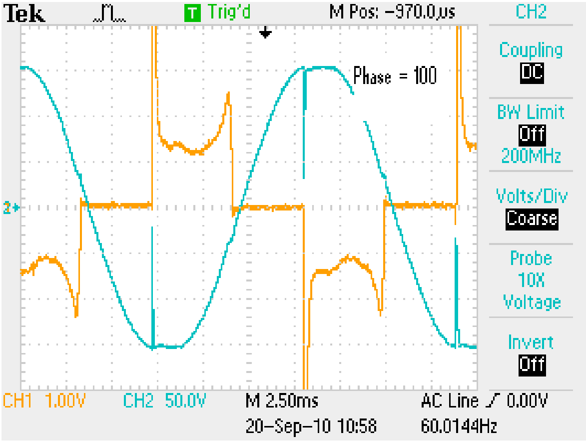


**Figure 8. Line Current and Voltage − Triac Conduction Angle of 100°**

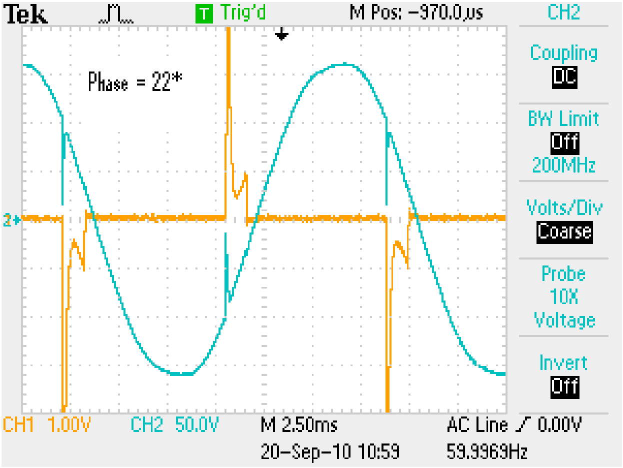


**Figure 9. Line Current and Voltage − Conduction Angle of 22°**

Referring to the schematic in Figure 1, the input current limiting resistor R1 and the damping network of R4 and C3 help to nullify the capacitive loading effects that the converter presents to the triac at its initial turn-on. The inhibit circuit composed of Q1 and Q2 monitors the line voltage and inhibits U1 via the feedback pin when the line voltage is below approximately 15 V during triac dimming. Diode D6 prevents discharge of the frequency compensation capacitor C7 during the triac zero conduction periods. This circuitry enhances the stability and performance of the converter when triac dimming is utilized. For applications where dimming is not required, the components of the inhibit circuit can be omitted and D6 replaced with a zero ohm resistor. Depending on the triac dimmer circuit characteristics, it may be necessary to adjust the resistance of the output pre-load resistor R16 to set the minimum desired dimness at minimum triac phase angle.

Figure 10 shows the converter output current versus line phase angle for the 120 Vac Leviton Sureslide and Rotary triac line dimmers (65 mA max, 60 Vf LED load).

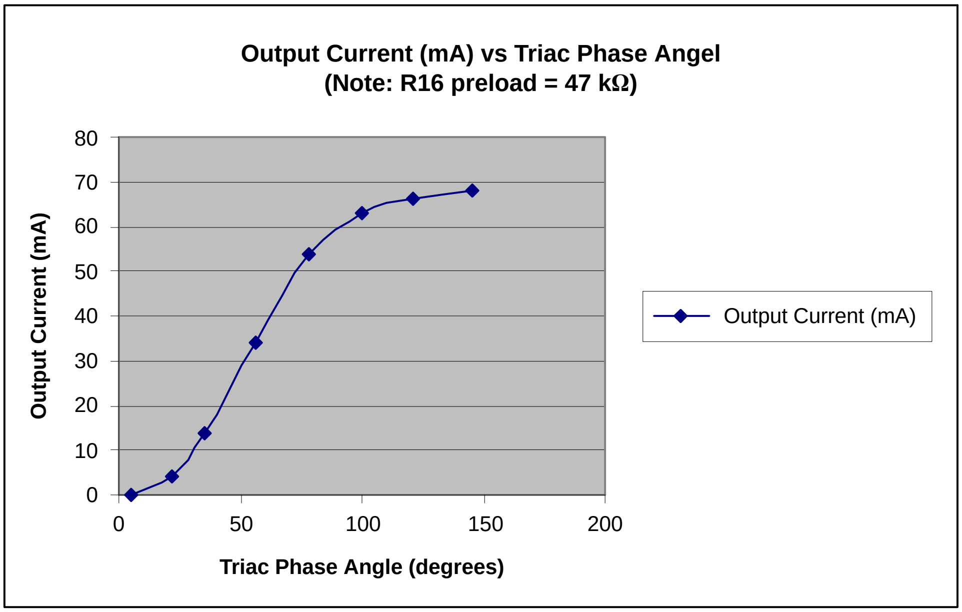


**Figure 10. Converter Output Current versus Triac Phase Angle**

## REFERENCES

[1] NCP1014 Data Sheet: http://www.onsemi.com/pub_link/Collateral/NCP1010−D.PDF

[2] NCP1014 Application Notes: http://www.onsemi.com/PowerSolutions/supportDoc.do?type=AppNotes&rpn=NCP1014

[3] NCP1014 Design Notes: http://www.onsemi.com/PowerSolutions/supportDoc.do?type=Design Notes&rpn=NCP1014

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