Driving High Intensity LED Strings in DC to DC Applications

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Abstract   Improvements in high brightness LED technology offer enhanced energy efficient lighting solutions in a world where the cost of energy continues to rise along with increased demand. Unlike traditional lighting that has been in existence over the last 50-100 years, LEDs require new driver solutions that address the challenges of providing a constant regulated current to a load that can vary in voltage by +/-30% over process and temperature variation. This paper will focus on driving high brightness LEDs from low voltage DC and AC sources commonly used in lighting applications.

Solid State Lighting

Today, LEDs provide efficient, robust, and intense light sources. A conventional white LED consists of a blue LED coated with a yellow phosphor resulting in a secondary emission of light that approximates “white” light. The spectrum of an OSRAM White Golden Dragon is shown in Figure 1. Alternatively red, green and blue LEDs may be mixed to create white light. The arguments for adopting solid state lighting (SSL) are compelling. LEDs turn on instantly; even at -40 °C. Life expectancy of 50,000 hrs makes them attractive in locations where maintenance is difficult and costly. LEDs are fully dimmable, with no IR or UV components in the beam. The small point source facilitates simpler lens design, while their compact size allows easy integration into a variety of products. SSL may play a role in reducing global pollution. The International Energy Agency estimates that 1900 Mt of $C0_2$ was emitted for lighting in 2005. The figure represents 70% of light passenger car emissions. At an International Materials Forum in 2005, N. Stath illustrated the efficiency of a variety of light sources since 1879. Fluorescent light sources show efficacies between 80-100 Lumens/Watt; mercury and CFL sources between 40-60 Lumens/Watt; incandescent and halogen light sources between 10-20 Lumens/Watt. Recent announcements by LED manufacturers (Cree, Nichia) mention demonstrated efficacy between 130-150 Lumens/Watt exceeding that available from fluorescent and metal halide sources. While efficacy continues to increase, costs per lumen continue to improve at a rapid pace, driven by technology and manufacturing advances.

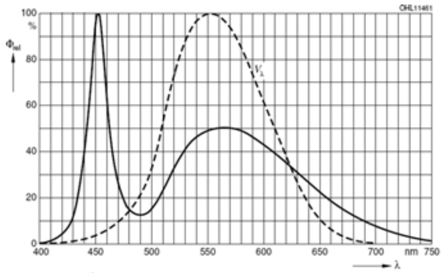

Figure 1: LED Spectral response compared to Photometric Eye Sensitivity

LED Characteristics

Due to the steep V/I curve of the LED and to achieve optimum performance, it is critical to drive LEDs with a constant current to achieve the specified brightness and color. For high brightness power LEDs the current ranges from 150 – 1500 mA, 350 mA being a common value. Manufacturer’s data for several product families is shown in Table 1. From the data, the minimum and maximum voltage for a generic LED was created. The output voltage swing for 3 to 6 generic LED strings is included at the end of the table for reference. It is apparent that +/- 30% variations can be expected in normal operation.

Table 1.White LED Forward Voltage Comparison

Vendor (Model)	**Current (A)**	**V_{min} (V) @ T_{Jmax} (°C)**	**V_{max} (V) @ 25 °C**
Cree (XR-E)	0.35	2.36	3.90
	0.70	2.81	4.35
Luxeon (K2)	0.35	2.54	4.23
	0.70	2.72	4.41
	1.00	2.78	4.95
Osram (Golden)	0.35	2.30	3.80
Osram (Platinum)	0.70	2.41	4.30
“Generic LED”	0.35	2.30	4.23
	0.70	2.41	4.95
3 LEDs	0.35	6.90	12.69
	0.70	7.22	14.85
4 LEDs	0.35	9.20	16.92
	0.70	9.62	19.80
5 LEDs	0.35	11.50	21.15
	0.70	12.03	24.75
6 LEDs	0.35	13.80	25.38
	0.7	14.43	29.70

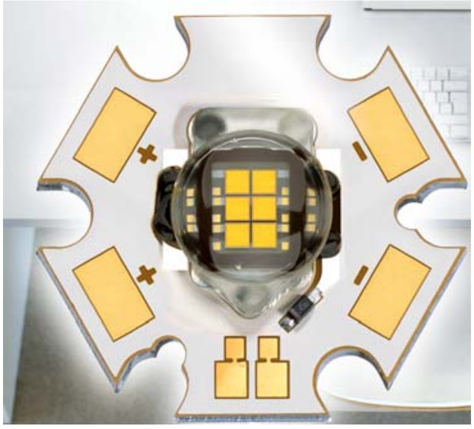

Figure 2: OSRAM OSTAR™

Driver Definition

There are numerous ways that LEDs may be combined in series or series/parallel strings. A typical interior automotive lighting application might require 200 lumens. Depending on LED selection, this requires a series string of 3 to 6 LEDs. Figure 2 shows a multi LED device package. Hence to drive any LED combination that may be envisaged, an efficient, high density, cost effective constant current converter with both a wide input (8 V to 19 V) and a wide output (6.9 V to 30 V) range is required. A pure buck or a pure boost switching regulator topology is not sufficiently flexible. What is proposed for the LED driver is a current regulated, non inverting buck/boost converter. A high side current sensing scheme is preferable since for automotive applications the LED string cathode is connected to chassis ground. Also, to maximize converter performance, a sensing scheme having a low loss (e.g. 200 mV) is required. The schematic of the LED driver is illustrated in Figure 3.

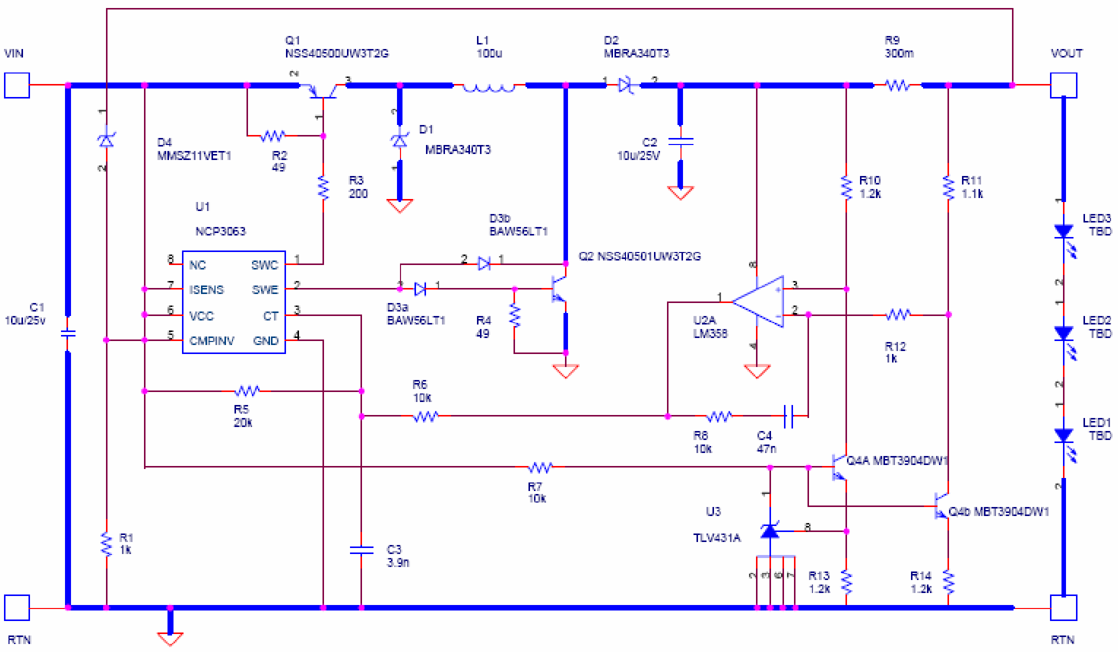

Figure 3: Schematic of Buck Boost Converter showing low drop high side current sensing.

Theory of Operation

The simplified power stage is shown in Figure 4 for clarity. To minimize power dissipation in the power circuit, low ripple current is required. So the converter is run in continuous current mode (CCM). For this analysis, all power components are assumed ideal. Switches Q1, Q2 turn on for time D*Ts (D duty cycle, Ts switching period) charging inductor L1 from input V_{in}. When Q1 and Q2 turn off, diodes D1, D2 deliver the inductor energy to the output $V_{out.}$ For the inductor flux (V*µs) to remain in equilibrium each switching cycle, the V*µs product across the inductor during each switch interval must balance.

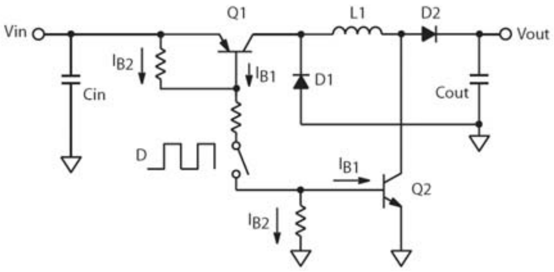

Figure 4: Power Stage showing BJT base drives

$$V_{in} \cdot D \cdot T_S = V_{out} \cdot (1 - D) \cdot T_S \tag{1}$$

Rearranging equation 1 the voltage gain of buck boost is given by:

$$V_{out} = V_{in} \cdot \frac{D}{(1 - D)} \tag{2}$$

Varying the duty cycle will vary the output such that when D is below 0.5, the converter is in buck mode, when D is above 0.5, the converter is in boost mode and when D equals 0.5, the voltage gain V_{out}/V_{in} is unity.

The ripple current in the inductor is given by expression

$$\Delta I_{L1} = \frac{V_{in} \cdot D \cdot T_S}{L1} \tag{3}$$

Assuming V_{in} = 12 V and $D*T_S$ = 0.5*5 µs, a value for L1 of 68 µH in equation 3 will maintain +/-30% ripple current in a 700 mA application maintaining CCM operation.
MOSFETs or BJTs can be selected as the primary switches Q1/Q2. NSS40500UW3T2G and NSS40501UW3T2G from ON Semiconductor's e²PowerEdge family of BJTs were chosen for cost/performance criteria. They feature ultra low saturation voltage and high current gain capability (Figure 5).

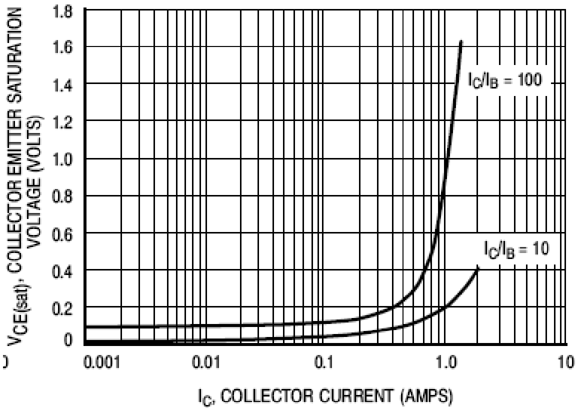

Figure 5: Collector Emitter Saturation Voltage versus Collector Current

Turn on, turn off, saturation voltage and storage time of a BJT are controlled by the magnitudes of turn on I_{B1} and turn off I_{B2} base currents. The drive currents are identified in Figure 4. The values of the base drive resistors R2, R3 and R4 in the schematic may be adjusted to optimize performance. The efficiency of the converter can be improved if the storage time of Q2 is less than Q1. The reasons for this will be discussed later. Q2's storage time can be reduced if it is held out of saturation by the addition of D3a/b shown in Figure 3. Once Q2 is near saturation, additional base current flows through diode D3a and into the collector junction. This diversion of base current IB1 reduces the stored charge in the base region and allows a faster turn off. Typical T_S of 1.5 µs is reduced to a few hundred nanoseconds.

The controller used to demonstrate the buck boost topology is ON Semiconductor's NCP3063. A functional block diagram is shown in the Figure 6.

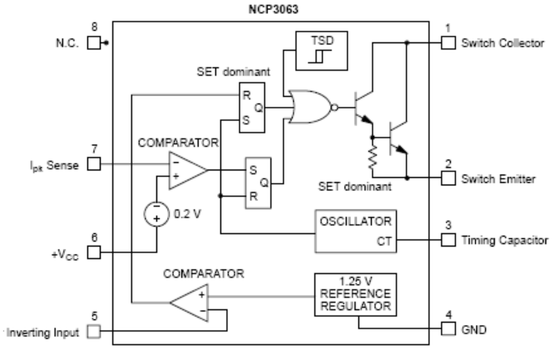

Figure 6: Block Diagram of NCP3063

This device consists of a 1.25 V reference, comparator, oscillator, an active current limit circuit, a driver and a high current output switch. In its traditional operating mode, the NCP3063 is a hysteretic, dc - dc converter that uses a gated oscillator to regulate the output voltage. Voltage feedback from the output is sensed at pin 5, and gates the oscillator on/off to regulate the output. The oscillator frequency and off-time of the output switch are programmed by the value selected for the timing capacitor, CT. CT is charged and discharged by a 1 to 6 ratio internal current source and sink, generating a ramp at pin 3. The ramp is controlled by two comparators whose levels are set 500 mV apart. In normal operation, D is fixed at 6/7 or 0.86. The “gated oscillator” mode is used to protect the LED string if a LED fails ‘open”. A zener diode between V_{out} and pin 5 will clamp the output at a voltage $V_Z + 1.25$ V.

The NCP3063 can also operate as a conventional PWM controller, by injecting current into the CT pin. The control current may be developed either from the input source, providing voltage feedforward (via R5) or from the output current sensing circuit (via R6). In both cases the slope of the oscillator ramp changes causing D to vary. In Figure 3, the current sense resistor R9 is placed in series with V_{out}, to satisfy the high side sensing requirement. The bandgap reference U3, together with dual NPN transistors Q4a,b and R13, R14 create two equal current sinks. If U3 is a 1.25 V bandgap and R13, R14 equal 1.24 kΩ (1%) two 1 mA current sinks are formed. Resistors R10, R11 level shift the current sense signal IOUT*R9 to satisfy the input requirements of U2. To create a 210 mV reference for the current loop, the expression 1 mA * (R10-R11) = 210 mV must be satisfied. Hence R10 is selected to be 210 Ω larger in absolute value than R11. Current regulation is set by the equation I_{out} * R9 = 210 mV. If R9 is 0.6 Ω, the programmed current is set for 350 mA. The difference between the 210 mV set point and the current sense is amplified by U2 to create an error voltage. This error voltage and R6 drives a programmed current into the CT pin to regulate the LED current.

Because the converter is switching at 200 kHz, MLCC capacitors in SMT packages can provide cost effective filtering. Low value MLCC capacitors (10 µF) have very small ESR (2 mΩ) and ESL (100 nH) values. When used in single or parallel combinations they form a “perfect” capacitor. Ripple voltage is due only to charging and discharging the capacitor by the inductor. Two 10 µF, 1210 capacitors are employed across the input and output of the driver. The ripple voltage across the input capacitor = $D*T_s*\Delta I$ (L1) / Cin. The ripple voltage developed across the output capacitor is given by $(1-D)*T_s*\Delta I$ (L1) / Cout.

Converter Waveforms

The voltage waveforms at both the input (upper trace) and output (lower trace) of the inductor L1 were measured while the difference waveform (middle trace) gives the voltage across the inductor. Figure 7 shows the converter operating in buck mode, while Figure 8 illustrates boost operation.

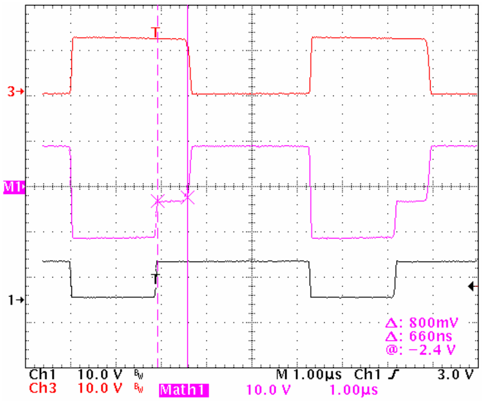

Figure 7: Buck Mode from 12 V_{in} to 8 V_{out}

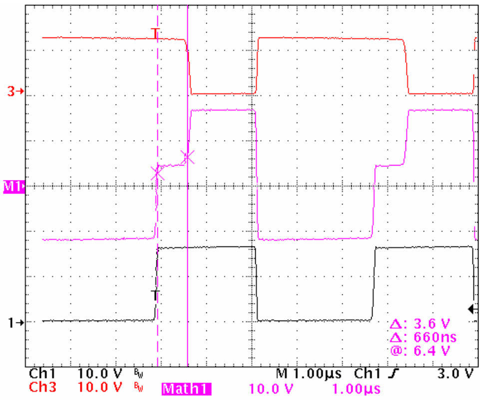

Figure 8: Boost Mode from 12 V_{in} to 16 V_{out}

It is evident from Figures 7 and 8 that the inductor waveforms differ from a classic buck boost. The voltage across the inductor is clamped at $(V_{out}–V_{in})$ for the duration of the storage delay interval T_D. During this interval Q2 is off and Q1 is on for its storage time. During this period, power is delivered to the output via Q1 and not by D1. Efficiency improvement is observed as the $V_{CE(sat)}$ of the PNP device (100 mV) is less that the voltage drop across the Schottky diode D1 (300 mV). If the time delay intervals were reversed and Q1 turned off first, power would cycle through the inductor L1, switch Q2 and diode D1. No power would be delivered to the load until Q2 turned off. The efficiency of the converter is shown in figure 9 and varied between 75 and 80%. The data was taken with V_{in} at 12 V while the output was varied between 11 V and 26 V at 700 mA constant current load.

The V*µs balance expression given in equation 1 is modified as follows.

$$V_{in} \cdot D \cdot T_S \pm \left(V_{out} - V_{in}\right) \cdot T_D = V_{out}\left(1 - D - T_D\right) \cdot T_S$$

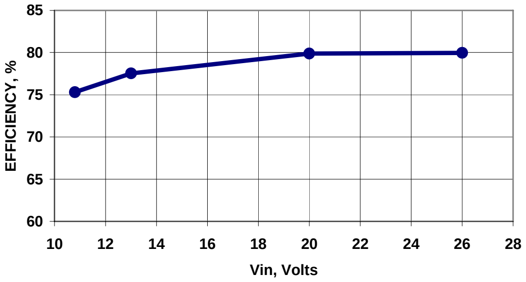

Figure 9: Measurements of Converter Efficiency

Conclusions

ON Semiconductor's latest monolithic NCP3063 controller and family of e2PowerEdge ultra low saturation bipolar transistors are combined to create a non inverting buck boost topology optimized to drive strings of LED's at a constant current. A high side, low drop, current sensing scheme has been implemented, targeted for automotive and other high efficiency applications. The output from the current sense is used to vary the slope of the oscillator ramp and achieve duty cycle modulation, independent of the gated oscillator function provided by the IC. The classic transfer function of the buck boost converter is modified by the storage time interval between the NPN and PNP bipolar switches.

References

N. Stath, "Nano Technology drives LED Advancements" International Materials Forum 2005