Meeting new challenges

With the right design approach, power supplies can easily achieve higher power factor levels, as Bernie Weir and Frazier Pruett explain

As standard incandescent bulbs are phased out, the options that offer meaningful energy savings are compact fluorescent (CFL) and LED. Helical CFL bulbs were invented in 1976 and are now mature in terms of lumen efficacy (lumens/W) as well as lifetime which can be 6-12 times longer than incandescent depending on how it is operated. In fact, recently much of the focus for CFL manufacturers has been getting the form factor to be compatible with existing incandescent bulb shapes. Conversely, "white" LEDs (actually phosphor converted blue LEDs) are still advancing with higher lumens per packaged LED as well as increased efficacy and improved colour point control announcements on a regular basis. As a result, the best LED bulbs can now offer lifetimes at least 25 times that of a standard incandescent with efficacy that exceeds the performance level of CFL bulbs. As a mature technology, CFL energy saving have reached a plateau and their advantages as well as drawbacks - slow warm up and mercury content remain understood.

What may not be understood is that while incandescent bulbs appear like resistive loads to the AC mains and have near perfect (~1) power factor (PF), the electronic ballast inside a residential CFL is highly capacitive and has a typical PF of 0.5-0.6. This means that while the homeowner only pays for delivered watts, the electric utility must actually generate the proportional volt-amps so a 13 W CFL bulb with a PF of 0.5 represents a 26 volt-amp load, which is slightly less than 50% of the volt-amps of 60 W incandescent. This low power factor is similar to cell phone chargers but with the right design approach, power supplies can easily achieve higher power factor levels. When the Energy Saving Trust was preparing guidelines for LED lamps and luminaires, they recognised this limitation for mains powered LED bulbs and established a minimum power factor of 0.7 with a long term objective of > 0.9. For LED luminaires over 15 W, they set the minimum power factor at 0.9. This presents new challenges in designing the drive electronics.

LEDs can be modelled as a voltage source with a low series resistance so a regulated current drive is ideal. In fact, LED manufacturers specify the optical properties of their LEDs at prescribed constant current levels. This constant current constraint is actually a simpler power conversion control requirement than that used for gas discharge tubes which must be "struck" for the mercury vapour in the tube to be ignited. To achieve a specific lumen level, multiple LEDs are connected in a string to increase the light output while ensuring that the current through each LED is identical. The LED drive electronics primary task is to convert the AC mains into a controlled current source operating over the range of LED forward voltages which can vary across temperature and process. In this point, the basic design of a cell phone charger is similar to a simple LED driver as they both are designed to regulate a constant current.

This is where the cell phone charger and the optimised LED driver diverge on completely different paths. Recall that incandescent bulbs are purposefully designed for one specific line voltage. Applying the same principle for LED bulbs introduces a huge degree of freedom for the power supply designers as they no longer need to consider a universal design that must work globally and operate from 90 – 264 Vac. In addition the power supply within the bulb does not need to be electrically isolated from the load as it is all integrated inside a single housing. Granted care must still be taken in the mechanical design of the housing to ensure that the mains voltage is not inadvertently present on the metal heat sink housing under a fault condition. Taking that into account, it is no longer necessary to use an isolated flyback topology as the only power conversion architecture option when designing an integral LED bulb driver.

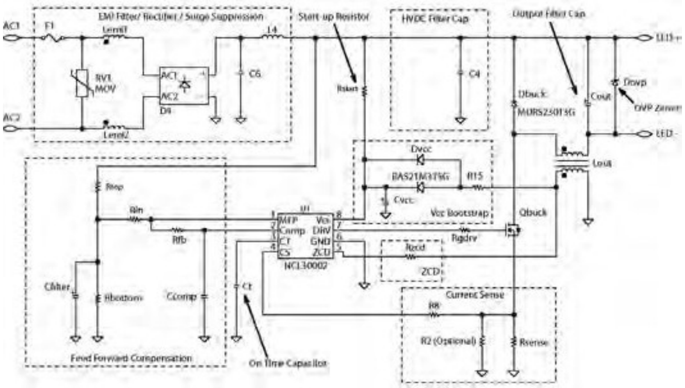

Figure 1: *Power factor buck application schematic*

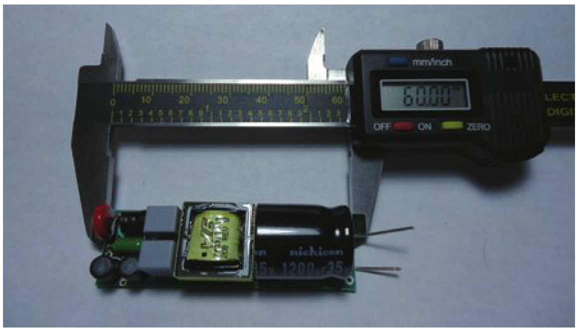

Figure 2: *Example 18 W NCL3002 LED Driver Board*

Bear in mind, the bulb application presents unique constraints that need to be added to the design equation. Inside the integral bulb there is very little space so a compact size is paramount. Secondly because the shape of the bulb must fit within the incandescent form factor, the thermal capacity of the housing to remove heat from the LEDs and drive electronics sets an upper ceiling on power dissipation so the efficiency of the driver must be very high to not place an artificial limit on the light generation capability of the bulb. Lastly there is the high power factor requirement where the Energy Saving Trust has established a long term objective of ≥ 0.9 for integral LED bulbs. While the UK targets are more aggressive than most countries, this requirement is already in place in South Korea where the minimum PF requirement is 0.9 for bulbs with input power over 5 W.

The most common topology for achieving high power factor is the boost and for high power commercial lighting applications a boost converter is inserted prior to the main power conversion stage. This two stage topology results in extra conversion losses as well as an increased number of components but is a widely acceptable solution for high power applications. Unfortunately this approach does not scale down for low power bulb applications so other topologies need to be considered. A buck topology can be optimised for good power factor within specific boundaries. Recall for high power factor the input current is coincident with the line and increases proportionally as the rectified line voltage increases. The drawback of the buck is that no current flows until Vin is greater than Vout, this is why it is important that compared to the line voltage, the LED string voltage must be relatively low. This is not a problem for low power bulbs as in most cases the number of LEDs in series is relatively low. For example, 10 LEDs in series is ~

31 V which is < 10% of the peak voltage of a rectified 240 Vac input.

One topology for high PF boost converters is fixed on time control where the switching cycle restarts when the current through the inductor reaches zero. To control the power delivery, feedback is used to adjust the on time. The same principle can be adapted to implement a buck topology and can be improved with a twist. One characteristic of the fixed on time is that the current through the inductor and switch rise in proportion to the line, this results in near perfect power factor with the trade-off that the peak current can be very high at the top of the switching cycle. In the bulb case, ideal power factor is not required so if the peak current is limited during a portion of the switching cycle, power factors of greater than 0.9 can be achieved with reduced losses in the switch and inductor which helps to achieve higher conversion efficiency and limit the size of the inductor. This creates a typical line current waveform which doesn't look very sinusoidal. However this waveform can have a PF > 0.9 even with the trade-off of increased distortion. To implement this hybrid fixed on time/peak current topology the NCL30002 controller from ON Semiconductor has been developed and Figure 1 illustrates the basic application schematic.

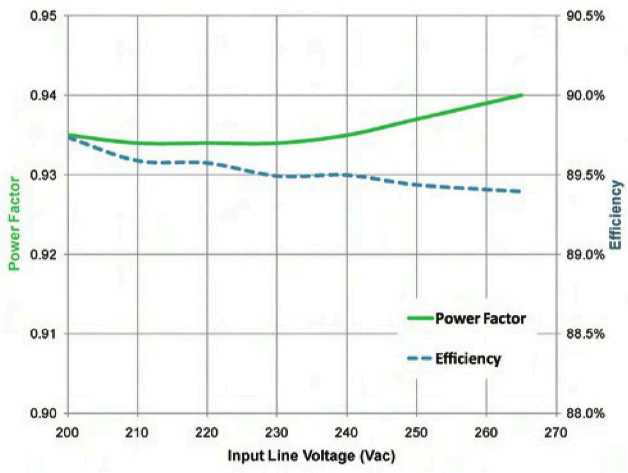

Figure 3: *Hi-PF buck performance with 18.8 W output (25 V@750 mA)*

The first point in reviewing the schematic is that the LEDs are referenced to the high voltage rail while the power switch is referenced to ground. This is referred to as a reverse or "inverted" buck and simplifies the architecture since the peak current through the inductor and LEDs can be sensed directly and to drive the FET, a level shifter is not required. After the controller starts switching, the driver is biased from an auxiliary winding on the inductor, this actually has two functions as it is also used to sense when the current through the inductor drops to zero indicating a new switching cycle should start. A precise 485 mV (± 2% typical) is used to accurately regulate the peak current through the switch. After Vin exceeds LED load Vf, fixed on time control is used to regulate the power to the LEDs until the peak current limit is reached which is detected by Rsense. To control the delivered power if the AC line varies from nominal, line feed forward compensation is used vary the on time. During the design procedure, the amount of time that the controller is operating in fixed on time versus peak current regulation can be varied to trade-off current regulation accuracy, overall efficiency, PF, and inductor size.

An example design was implemented for an 18 W nominal output power driver suitable to be incorporated inside an LED replacement for a 75 W A-lamp based on driving 8 LEDs in series at 750 mA with nominal output ripple of < ± 30%. Figure 2 is a picture of this board which had a width of 18 mm and a length of 60 mm. Typical efficiency was 89.5% and measured power factor was 0.935 at 240 Vac as seen in Figure 3.

As illustrated with an optimised architecture, it is possible to solve the challenging puzzle of achieving high power in a compact form factor while meeting the Energy Saving Trust long term objective of > 0.9 for integral LED bulbs. Efficiency can be further improved over >90% at the same power level with higher forward voltage LED strings at lower drive current. As a controller based architecture, the basic design approach can be scaled downward for lower power applications by changing the MOSFET and reducing the size of the inductor. This is critical since LED efficacy will continue to advance for the foreseeable future as manufacturers increase lumen output per LED, requiring fewer LEDs for the same lumen output and thus pushing down the energy consumption while at the same time reducing the cost of integral bulbs and increasing their market acceptance.

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