White LED Power Supply Design Techniques

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Abstract

With the emerge of color displays in the portable market like cellular phones, PDAs and Pocket PCs a white backlight or sidelight is required for a homogeneous illumination of the LCD colors. The white LED seems to be a good choice for backlight since it requires less power and space compared to the commonly used CCFL (Cold Cathode Fluorescent Light) backlight. The typical forward voltage of a white LED is in the range of 3V to 5V. Since the best choice to power white LEDs is a constant current source and the input voltage range of a Li-Ion battery is below or equal to the LED forward voltage a new power supply solution is required.
The main power supply requirements are high efficiency, small solution size and the possibility of adjusting the LED brightness. Acceptable EMI performance becomes an additional focus for portable systems with wireless capabilities. The boost converter is a very attractive solution when high efficiency is a key criteria for the selection of the power supply. Another popular solution is the use of a charge pump converter. Both solutions to drive white LEDs are discussed and how they relate to the main power supply requirements. Another important design consideration is the control method to adjust the LED brightness that will affect the overall converter efficiency and any possible chromaticity shifts of the white LED. A simple solution will be presented using a PWM signal to control the brightness. An additional advantage of this solution is the higher efficiency compared to other standard solutions.

The Task

When a power supply for a white LEDs is selected the main requirements for a portable system is efficiency, overall solution size, solution cost and last but not least EMI (electro magnetic interference). Depending on the portable system these requirements are rated differently amongst one another. Efficiency usually comes out as the number one or two key design parameter and needs to be considered when selecting a power supply. In figure 1 the basic circuit of a white LED power supply is shown.

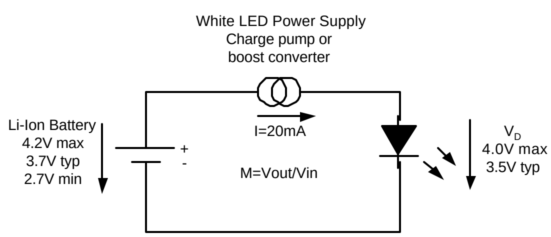

Figure 1: A good efficiency requires a variable conversion gain M

The Li-Ion battery has a voltage range between 2.7V to 4.2V. The power supply has the task to provide a constant current with a typical forward voltage of 3.5V for a white LED.

Boost converter achieves higher efficiency comparedto a charge pump solution

In general two power supply topologies exist to drive white LEDs, which is the charge pump or switched capacitor solution and the boost converter. Both solutions are able to provide a higher output then input voltage. The main difference between the two is the conversion gain M=Vout/Vin that directly affects the efficiency. The charge pump solution usually has a fixed conversion gain. A simple charge pump with a fixed conversion gain of 2 will always develop a voltage much higher than the

LED forward voltage and is shown in formula (1). This will result in an efficiency of just 47% as shown in formula (2).

(1) $V_{chrgpump} = V_{Bat} \cdot M = 3.7V \cdot 2 = 7.4V$

(2) $h = \dfrac{V_{LED}}{V_{chrgpump}} = \dfrac{3.5V}{7.4V} = 47\%$

$V_{chrgpump}$ is the voltage internally developed in the charge pump IC and V_{Bat} is the typical battery voltage of a Li-Ion battery. The charge pump needs to provide a constant current with an output voltage equal to the LED forward voltage of typical 3.5V. The charge pump with a fixed conversion gain of 2 develops always a much higher voltage internally (1), which will cause an internal voltage drop reducing the overall system efficiency (2). More advanced charge pump solutions address this drawback with solutions allowing to switch between two conversion gains of 1.5 and 1. This allows the operation at efficiency levels between 90% and 95% when the battery voltage is just above the LED voltage enabling the use of a conversion gain of 1. The improvements are shown in formula (3) and (4).

(3) $V_{chrgpump} = V_{Bat} \cdot M = 3.7V \cdot 1.0 = 3.7V$

(4) $h = \dfrac{V_{LED}}{V_{chrgpump}} = \dfrac{3.5V}{3.7V} = 95\%$

As soon as the battery voltage decrease further the charge pump needs to switch to gain 1.5 causing a drop in efficiency down to the 60% to 70% range as shown in the examples (5) and (6).

(5) $V_{chrgpump} = V_{Bat} \cdot M = 3.4V \cdot 1.5 = 5.1V$

(6) $h = \dfrac{V_{LED}}{V_{chrgpump}} = \dfrac{3.5V}{5.1V} = 68\%$

Figure 2 shows the theoretical and practical efficiency curve for a charge pump solution with different conversion gains M.

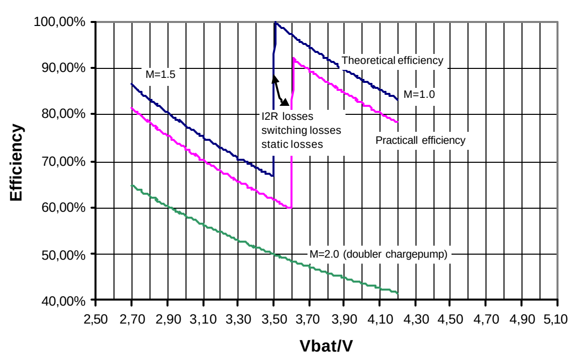

Figure 2: Efficiency variation of a charge pump solutions

The pure voltage doubler charge pump with a conversion gain of 2.0 has a fairly low efficiency down to 40% and is not really attractive for portable devices. A charge pump with a combined conversion gain of 1.0 and 1.5 shows far better results. The remaining problem with such a charge pump is the switchover point from a gain M=1.0 to M=1.5 because the efficiency will drop down to the 60% range. The overall efficiency is reduced when the efficiency drop (switchover) occurs at a point where the battery operates for most of its time. Therefore high efficiency can be achieved when the switchover happens at low battery voltages close to 3.5V. However the switchover point depends on the LED forward voltage, LED current, I2R losses of the charge pump and the voltage drop required by the current sense circuit. These parameter will move the switchover point to higher battery voltages.

Therefore such a charge pump has to be evaluated very carefully in the specific system to achieve high efficiency numbers.
The calculated efficiency numbers show the best theoretical case for charge pump solutions. In reality additional losses will occur depending on the current control method, which can have a quite significant impact on the efficiency. In addition to that I2R losses, switching losses and static losses in the device will further reduce the efficiency of the charge pump solution.
These drawbacks can be addressed using an inductive boost converter, which has a variable conversion gain M as shown with formula (7) and figure 3.

(7) $$M_{boost} = \frac{1}{1-D}$$

The boost converter duty cycle D can vary between 0% and practical around 85% as shown in figure 3.

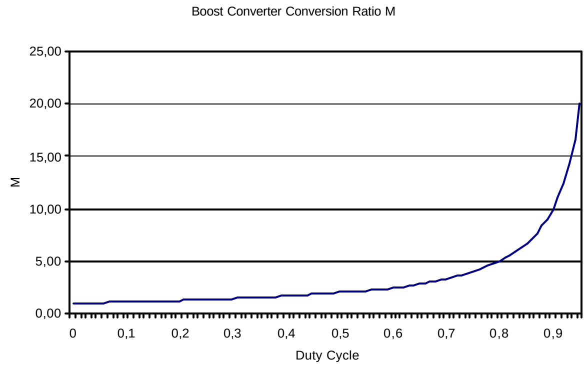

Figure 3: Variable conversion gains M of the boost converter

A variable conversion gain allows developing a voltage just matching the LED forward voltage avoiding internal voltage drops and efficiencies up to 85% can be achieved.

Standard boost converter solution driving 4 white LEDs

The boost converter in figure 4 is configured as a current source driving 4 white LEDs. The device regulates the voltage across the sense resistor Rs to 1.233V giving a defined LED current.

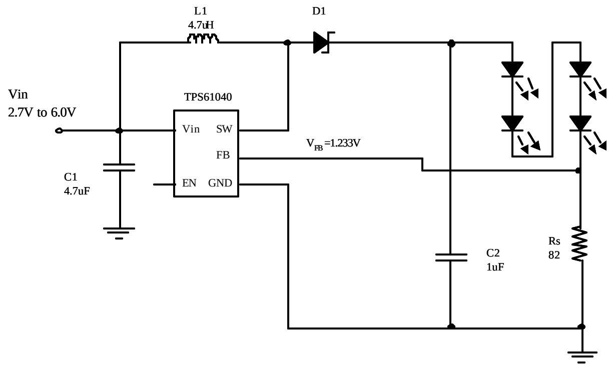

Figure 4: Boost converter configured as current source

The boost converter used in this configuration will have a voltage drop across the current sense resistor of 1.233V. The power dissipated in the sense resistor reduces the efficiency of such a solution. Therefore the voltage drop to sense and regulate the LED current needs to be reduced. In addition to that a possibility to adjust the LED current and LED brightness is required for many applications. Both requirements are implemented in the circuit of figure 5.

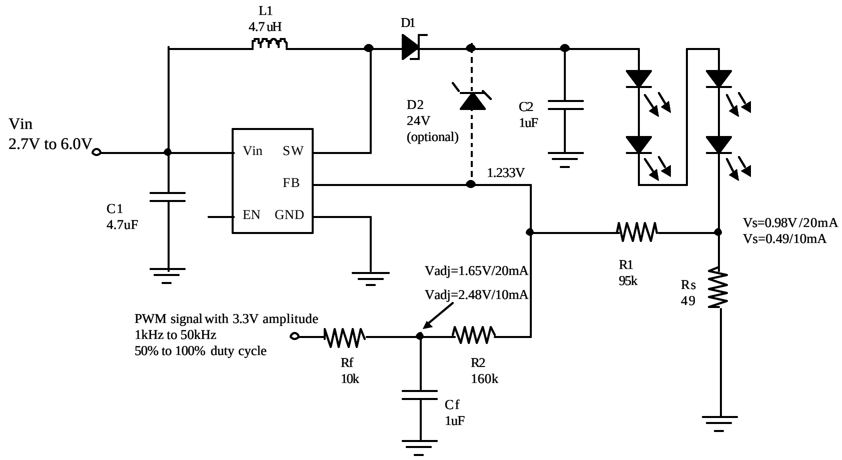

Figure 5: Increasing the efficiency by lowering the current sense voltage

In Figure 5 an optional zener diode is added to the circuit to clamp the output voltage in case one LED is disconnected or high impedance. A PWM signal with an amplitude of 3.3V is applied to the feedback circuit of the converter. A low pass filter Rf and Cf is used to filter the DC part of the PWM signal and establishes an analog voltage (Vadj) at R2. By changing the duty cycle of the applied PWM signal the analog voltage will increase or decrease thus modulating the feedback voltage of the converter, which increases or decreases the LED current of the converter. By applying an analog voltage at R2 larger than the feedback voltage (1.233V) of the converter results in a lower sense voltage across the sense resistor. For a 20mA LED current the sense voltage is reduced form previously 1.233V down to 0.98V and even down to 0.49V for 10mA LED current.
When using a PWM signal with a 3.3V amplitude the duty cycle range to control the LED brightness has to be adjusted from 50% to 100% to have an analog voltage always higher than the feedback voltage of 1.233V. At 50% duty cycle the analog voltage will be 1.65V giving a sense voltage of 0.98V with 20mA. Limiting the duty cycle range from 70% to 100% and so on can further reduce the sense voltage. The resulting efficiency curve is shown in figure 6.

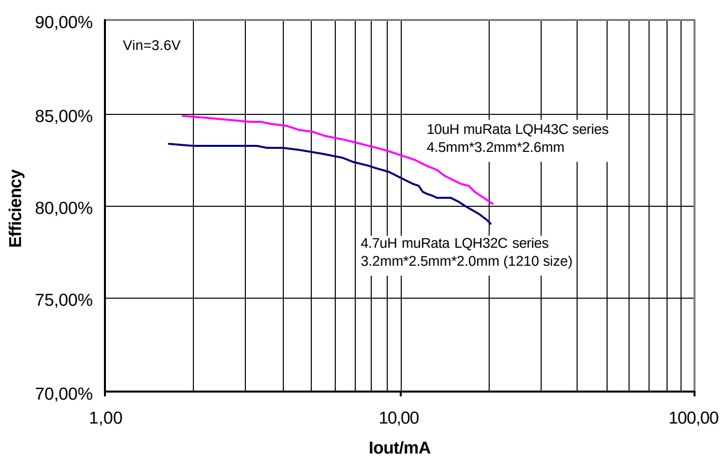

Figure 6: Higher efficiency by lowering the current sense voltage

The efficiency depends on the chosen inductor as well. In this case a small inductor coming in a 1210 size can achieve efficiencies up to 83% making the total solution size comparable with a charge pump solution requiring two flying capacitors in 0603 size.

Figure 7 shows the LED current as a linear function of the PWM duty cycle controlling the LED brightness.

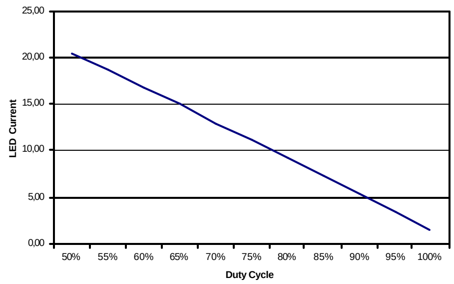

Figure 7: Simple LED current control by applying PWM signal

The discussed solution showed the configuration of a standard boost converter to drive white LEDs and a possibility to increase the efficiency by limiting the PWM duty cycle range and choosing a different current control feedback network. As a next logical step a solution having all these features integrated will be discussed.

Dedicated LED driver reduces external component count

A device having the previously detailed features integrated is shown in figure 8. The LED current can be controlled by directly applying a PWM signal to the CTRL pin.

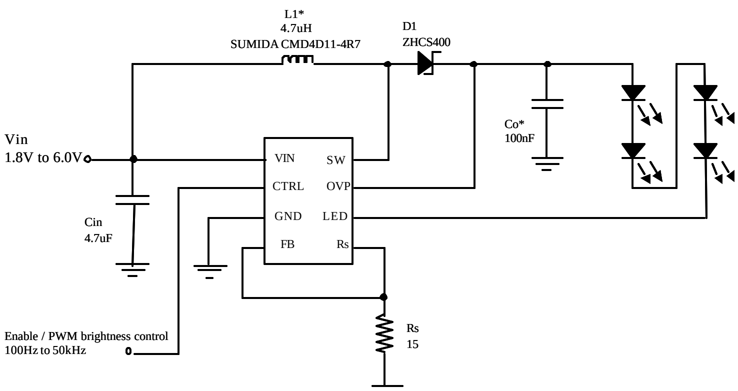

Figure 8: White LED constant current driver IC

The current sense voltage is reduced to 250mV and the overvoltage protection is integrated into the device which comes in a small 3mm*3mm QFN package. The efficiency curves are shown in figure 9 and 10.

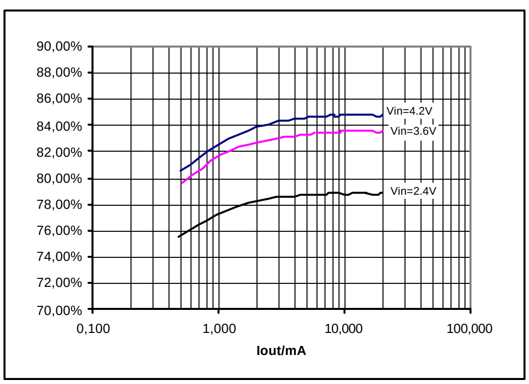

Figure 9: Efficiency vs Load current

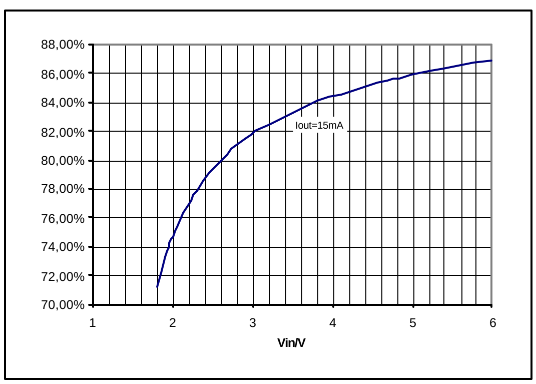

Figure 10: High efficiency over battery input voltage range

Figure 10 shows that over the entire battery voltage range of a Li-Ion battery from 2.7V to 4.2V a efficiency above 80% can be achieved. In this case an inductor with just 1.2mm height was used (Sumida CMD4D11-4R7, 3.5mm*5.3mm*1.2mm).
The efficiency curve in figure 10 shows that a boost converter can achieve a higher efficiency compared to a charge pump solution in the majority of cases. However, when using a boost converter or charge pump in a wireless application EMI needs to be considered as well.

Keeping the EMI under control

Whatever solution is considered a charge pump or a boost converter special care is required to minimize EMI since both solutions are switching converter operating at switching frequencies up to 1MHz having fast rise and fall times. When using a charge pump solution no inductor is required and therefore no magnetic field can cause EMI issues. However the flying capacitors of a charge pump solution are constantly charged and discharged by opening and closing switches at high frequencies. This causes current spikes with very fast rise times, which can interfere with other circuits. Therefore the flying capacitors need to be connected a close as possible to the IC with very short traces to minimize radiation. A low ESR input capacitor must be used to minimize the high current spikes occurring especially at the input.
When using a boost converter a shielded inductor will have a more limited magnetic field and therefore a better EMI performance. The switching frequency of the converter should be chosen to minimize any interference with the wireless portion of the system. The PCB layout will have a major impact on EMI and especially the traces carrying switching or AC currents must be kept as small as possible to minimize radiation as shown in figure 11.

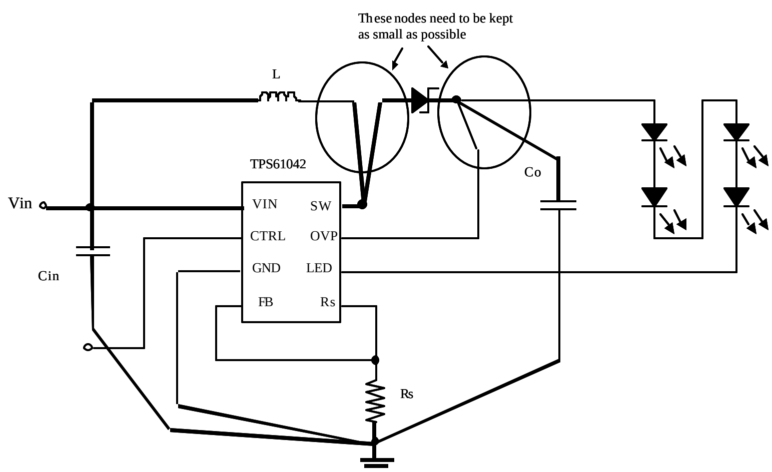

Figure 11: Nodes and traces carrying switching currents should be kept small

Traces in bold should be routed first and a star ground or ground plane must be used to minimize the noise. The input and output capacitor should be a low ESR ceramic capacitor to minimize the input and output voltage ripple.

Conclusion

In the majority of cases the boost converter shows a superior efficiency compared to the charge pump. Using a boost converter with an inductor as small as a 1210 case reduces the advantage of the charge pump in terms of total solution size. At least, efficiency needs to be rated versus total solution size. In terms of EMI the boost converter needs more design effort and knowledge that must be considered as well.
Overall a charge pump will be a good solution for some systems especially when the device has a flexible conversion gain of 1.0 to 1.5. Such a solution will achieve the best efficiency when the transition between the conversion gain of 1.0 and 1.5 happens just slightly above the LED forward voltage. When selecting a boost converter or a charge pump solution for each case the key requirements

for the portable system have to be considered. If efficiency is the key requirement the boost converter will be the more favorable solution.

References

[1] Texas Instruments Datasheet: TPS61040 Low Power DC/DC Boost Converter in SOT23 package
[2] Texas Instruments Datasheet: TPS61042 Constant Current LED Driver

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