Driving WLED as Backlight for Small and Medium Size LCD Display

Sang-Woo Lee and Michael Wang

Abstract

This topic evaluates charge-pump and inductive boost topologies for several critical factors in backlighting with white-light-emitting diodes (WLEDs) in mobile applications. First, pros and cons of each method and guidelines for selecting the right one are introduced. Next, ways to improve the efficiency of WLED drivers are analyzed with respect to mode transition voltage, output impedance, current-sink threshold voltage, and typical sources of circuit losses. Finally, analog, digital, and pulse-width-modulation (PWM) dimming methods for optimal brightness control are compared.

I. Introduction

There are two major driver circuits used for backlighting with WLEDs in mobile designs. One uses a charge pump without an external inductor; the other uses an inductive boost converter. Each solution has pros and cons, and the choice depends on the type of application, the total solution size and cost, and efficiency requirements. System efficiency to prolong battery operation time for either solution is a critical factor in most cases. A single-cell Li-ion battery is the input source for most mobile applications, and Fig. 1 shows how its capacity relates to its voltage level. As shown in Fig. 1, the battery voltages from 3.6 to 4.0 V correspond to about 90% of the battery's capacity. Therefore, battery voltage range is critical to system efficiency.

II. Charge-Pump Topology

Fig. 2 shows a typical phone application of the TPS60250 that uses a charge-pump topology to drive up to 7 individually regulated WLED current paths. The example shown has 5 WLEDs in the main display and 2 WLEDs in the sub display. The TPS60250 provides 64 dimming steps and a maximum current of 25 mA for each WLED current path. The circuit employs only 4 capacitors (input, output, and 2 charge-pump flying capacitors) and maximizes power efficiency with dual charge-pump modes, X1 and X1.5. The TPS60250 always starts operation in the X1 mode in which the output voltage, V_{OUT}, is near the input voltage.

$$V_{OUT} = V_{IN} - I_{LED} \bullet R_{X1}, \qquad (1)$$

where I_{LED} is the total WLED current and R_{X1} is the X1-mode output impedance of the charge-pump stage.

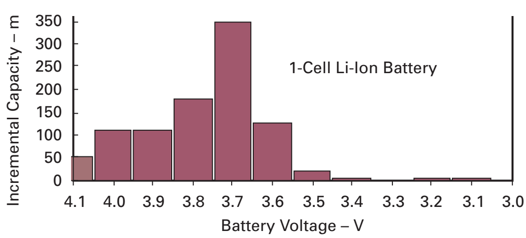


Fig. 1. Current capacity depends on battery voltage level.

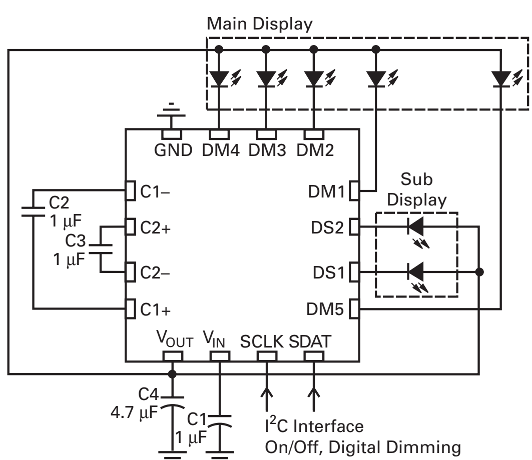


Fig. 2. Typical application circuit for the TPS60250 WLED display driver.

As the battery voltage drops and any of the WLED current paths approaches a preset low-current threshold, the TPS60250 automatically switches to the X1.5 mode, which boosts the output up to about 1.5 times the input voltage.

$$V_{OUT} = 1.5 \cdot V_{IN} - I_{LED} \cdot R_{X1.5}, \qquad (2)$$

where $R_{X1.5}$ is the X1.5-mode output impedance of the charge-pump stage. This mode-switching operation assures improved overall efficiency and improved illumination control over the full range of the battery input voltage.

Fig. 3 shows a simplified circuit for the charge-pump operation of the X1.5 mode. This mode has two operation phases, the charge phase and the discharge phase. During the charge phase, S11, S12 and S13 are closed, and the two flying capacitors, C_{F1} and C_{F2}, are charged in series from the input voltage. With $C_{F1} = C_{F2}$, the maximum voltage of each flying capacitor will reach half of the input voltage at this time. During the discharge phase, S21, S22, S23 and S24 are closed, and the two flying capacitors in parallel are discharged into the output capacitor, which can theoretically charge to a level 1.5 times the input voltage. As with any charge pump, the X1.5 mode generates considerably more ripple at the output than the X1 mode.

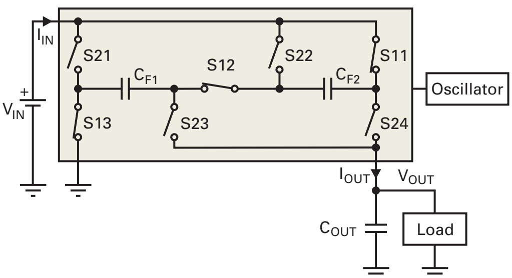


Fig. 3. Fractional conversion (X1.5-mode operation).

The TPS60250/1 functional block diagram in Fig. 4 shows the constant-current sinks that can drive 7 individual WLED current paths, and an I^2C interface for controlling on/off and dimming. The I^2C interface is becoming more popular for controlling WLED drivers to meet the market requirements for brightness or dimming control in fine steps, individual current-path programming, enable/disable, etc.

The I^2C interface also allows the WLED main display channels (DM1 through DM5) to be controlled independently of the sub channels (DS1 and DS2). Each WLED channel has a 25-mA maximum rating with 64 dimming steps. The DM5 channel can function as a main driver, but it

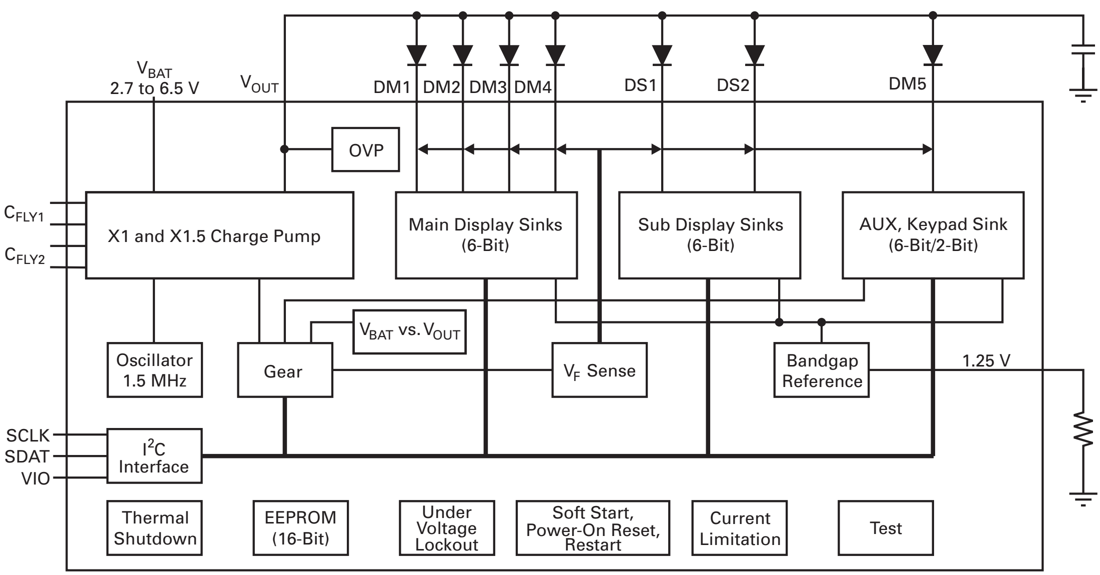


Fig. 4. The functional block diagram of the TPS60250/1.

can also function as an auxiliary driver for a torch or keypad backlight with an 80-mA maximum rating and 4 dimming levels (100%, 70%, 40%, and 20%).

LCD makers have new panels with a very low-current transparency rating, so the system efficiency under light-load conditions (100-µA LED current) is very critical. These new panels need as little as 100 µA to identify the information on the display, whereas conventional panels need 3 to 5 mA. With a growing demand for displays to be on all the time, these new panels require a highly efficient WLED driver under light-load conditions.

To support the new low-current panels, the TPS60250 driver can also provide between 100 µA and 1.5 mA in 16 dimming steps of 100 µA each. Fig. 5 shows the dimming control range for sub, main, and auxiliary display banks.

Fig. 6 shows the efficiency curve of the TPS60250/1 under light-load conditions. This driver has a typical operating current of 55 µA with a 100-µA WLED load and will stay in the X1 mode due to the low forward-voltage drop (V_F is about 2.6 V with a 100-µA WLED current). The total efficiency under light-load conditions is

$$\eta_{Light} = \frac{I_O V_F}{V_{IN}(I_O + I_{OP})}, \tag{3}$$

where I_O is the WLED output load current, V_F is the forward-voltage drop of WLED, V_{IN} is the input voltage, and I_{OP} is the operating current of the WLED driver.

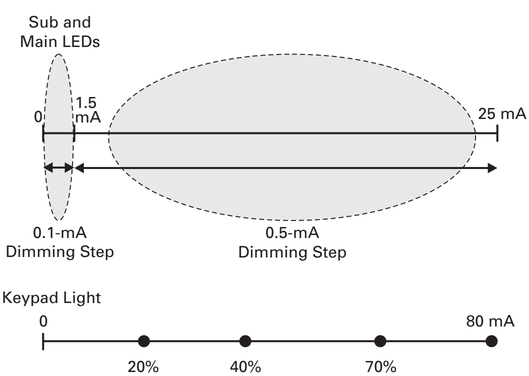


Fig. 5. Dimming steps for sub and main display banks.

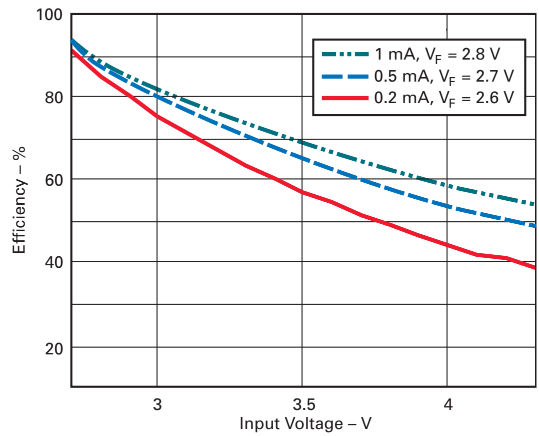


Fig. 6. The efficiency of the TPS60250/1 under light-load conditions.

A unique feature of the TPS60250 is that it provides independent control of the two sub-display current paths via the I^2C interface. This feature allows 15- to 25-mA LED indicators to be added for *Bluetooth*® and other functions without adding another driver.

III. Inductive Boost Topology

Since WLED forward voltage is about 3.3 V, it is clear that powering WLED backlighting directly from a single-cell Li-ion battery would present several problems. Given that all WLEDs in a device would have to be individually powered in parallel, the added voltage drop of switches would prevent proper WLED operation when the battery voltage approached the 3-V cutoff point. With requirements to backlight a main display and a sub display with multiple LEDs, power an LED flash, and drive other indicators, a supply voltage greater than the battery voltage is a necessity. For example, a main display may need up to 4 WLEDs connected in series for consistent illumination and simple control. The typical voltage required by the WLED string is 4 • 3.3 V = 13.2 V. WLED drivers using inductive boost topology are the ideal solution in many portable applications.

The boost converter is a popular nonisolated power-stage topology sometimes called a step-up power stage. The inductive boost topology can be used when the output voltage is always higher than the input voltage, is the same polarity as the input, and is not isolated from the input. The input current for a boost power stage is relatively continuous because of the inductor's smoothing action. The output current for a boost power stage is discontinuous or pulsating because the output diode conducts during only a portion of the switching cycle. The discharging output capacitor supplies the load current for the rest of the switching cycle.

Fig. 7 shows a simplified schematic of the boost power stage with a drive circuit included. Power switch Q1 is an n-channel MOSFET, the output diode is D1, R_C is the capacitor's equivalent series resistance (ESR), and R_L is the inductor's DC resistance. Resistor R represents the load seen by the power-supply output.

During normal operation, Q1 is repeatedly switched on and off, and the switching interval is governed by the control circuit. When Q1 is on, the inductor current linearly increases and stores energy, while the output capacitor provides power to the load. When Q1 is off, the energy stored in the inductor is transferred to the load through D1. This switching action creates a train of pulses at the junction of Q1, D1, and L. The output capacitor filters the pulses to produce a DC output voltage.

Fig. 8 shows the typical application circuit of the TPS61150 as a boost-based WLED-driver solution. To provide uniform display brightness, the WLEDs for each display bank are connected in series.

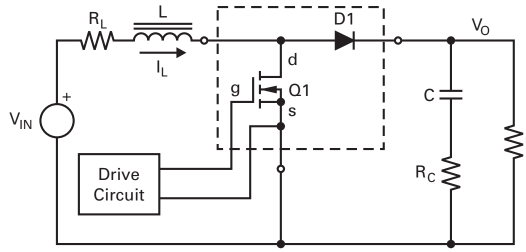


Fig. 7. Simplified schematic of boost power stage.

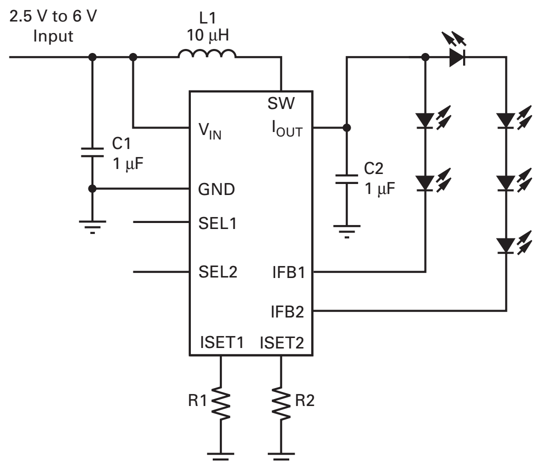


Fig. 8. Typical application circuit of the TPS61150.

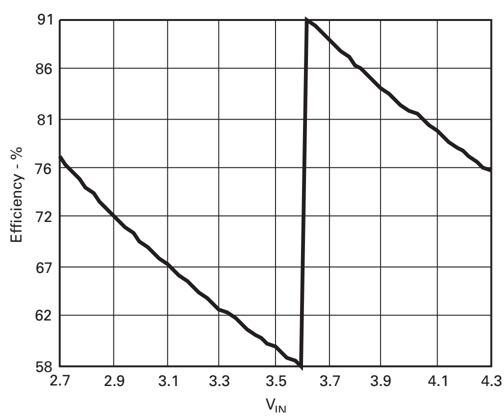


Fig. 9. Typical system efficiency for a bank of 4 WLEDs driven with 15-mA of current.

IV. Efficiency Analysis

A. Charge-Pump Efficiency

The system efficiency of the charge-pump driver depends on input voltage, output impedance, WLED forward-voltage drop (V_F), and the mode-transition threshold voltage of the current-sink stage. Most of the power loss in the WLED backlight system with a charge-pump driver is attributed to the internal power switch ($R_{DS(on)}$), solder bonding, and metal resistance. These factors directly contribute to the output impedance of the charge-pump power stage.

Fig. 9 shows the system efficiency of the TPS60250 over the full input-voltage range with a typical WLED application (4 WLEDs • 15 mA = 60 mA total, with V_F = 3.3 V). The TPS60250 driver achieves 90% maximum efficiency and 82% average efficiency (P_{LED}/P_{BATT}) over the normal voltage range of a single-cell Li-ion battery. The input-voltage level ($V_{IN.UP}$) at which the driver mode changes from X1 to X1.5 is

$$V_{IN.UP} = V_F + V_{TH} + I_{LED} \bullet R_{X1}, \tag{4}$$

where V_F is the WLED forward-voltage drop, V_{TH} is the mode-change threshold voltage that begins the mode change, I_{LED} is the total WLED current, and R_{X1} is the output impedance of the charge pump in X1 mode.

As shown in Fig. 9, the input-voltage range from 3.6 to 4.0 V allows the TPS60250 to achieve very high system efficiency in the X1 mode. Therefore, as Equation (4) demonstrates, lower V_{TH} and R_{X1} values are very important to keep the driver in X1 mode as long as possible. The TPS60250 typically has a V_{TH} voltage of 0.12 V, which is quite low compared to other devices on the market. Fig. 10 shows how V_{TH} can affect the point where mode change occurs, which in turn can affect efficiency. The dashed plot shows how another device with a V_{TH} of 0.4 V can limit the maximum efficiency to 84% and the average efficiency to about 64%. The TPS60250 (solid plot) has an average efficiency improvement of 10% in the 3.3- to 4.1-V input-voltage range (area B) due to the 0.28-V difference in V_{TH}. The efficiency variations in areas A and C are attributed mostly to the differences in device operating current and output impedance of the charge-pump stage in X1 and X1.5 modes.

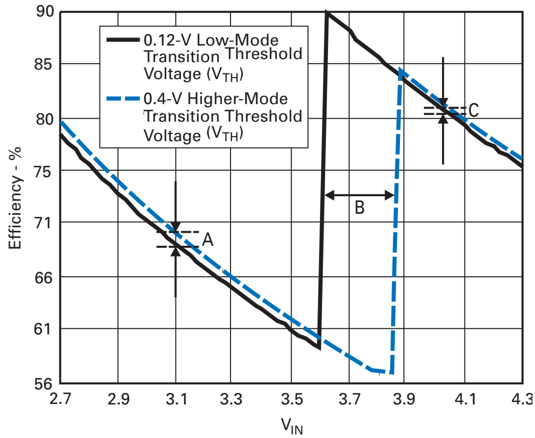


Fig. 10. Efficiency comparison of the TPS60250 and a competitor.

B. Inductive-Boost-Driver Efficiency

Fig. 11 shows the block diagram of the TPS61150 dual-output WLED boost driver.

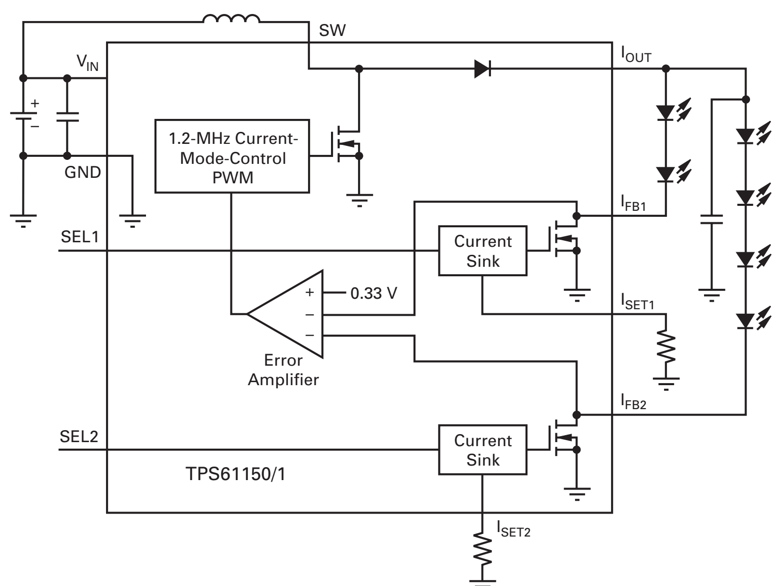


Fig. 11. Functional block diagram of the TPS61150.

Primary internal features of this driver that contribute to high efficiency are the low turn-on resistances of the power and current-sink switches, and the low forward-voltage drop (V_F) of the power diode. Careful selection of the power inductor and output capacitor can improve efficiency.

The inductor affects steady-state operation, transient behavior, and loop stability, all of which make it the most important component in the circuit. The three specifications important to the performance of the inductor are inductor value, DC resistance, and saturation current. The inductor's inductance value determines its ripple current, I_P, as given by Equation (5).

$$I_P = \frac{1}{L\left(\frac{1}{V_{OUT} + V_F - V_{IN}} + \frac{1}{V_{IN}}\right) \cdot f_S}, \qquad (5)$$

where L is the inductor value, V_{OUT} is the boost output voltage, V_F is the power-diode forward-voltage drop, and f_S is the switching frequency. V_{OUT} is typically the total forward drop across the WLEDs plus 0.33 V. A good compromise between power loss and inductor size is to set peak-to-peak ripple current at 30 to 40% of the DC current. A 10-µH inductor is recommended for the TPS61150/1.

The maximum output current, $I_{OUT(max)}$, can be determined with Equation (6).

$$I_{OUT(max)} = \frac{V_{IN}\left(I_{Limit} - \frac{I_P}{2}\right) \cdot \eta}{V_{OUT}}, \qquad (6)$$

where I_{Limit} is the overcurrent limit and η is the efficiency. The output-current limit is usually not a concern because the current-sink ports, FB1 and FB2, are each limited to a maximum of 35 mA.

The maximum expected load current for I_{OUT} and the minimum expected V_{IN} can be used to calculate the inductor's DC current as

$$I_{L\_DC} = \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot \eta} \qquad (7)$$

In switching power-supply power stages, the function of the output capacitor is to store energy to maintain a constant voltage. The output capacitor for a boost power stage is selected to limit output-voltage ripple to the level required by the application. The series impedance of the capacitor and the power-stage output current contribute to output-voltage ripple. The three elements of the capacitor that contribute to its impedance (and output-voltage ripple) are equivalent series resistance (ESR), equivalent series inductance (ESL), and capacitance (C). This ripple voltage is the sum of the ripple caused by the capacitor's capacitance and its ESR. Assuming that a capacitor has zero ESR, the minimum capacitance needed for a given ripple can be calculated with Equation (8).

$$C_{OUT} = \frac{(V_{OUT} - V_{IN}) \cdot I_{OUT}}{V_{OUT} \cdot f_S \cdot V_{Ripple}}, \qquad (8)$$

where V_{Ripple} is the peak-to-peak output ripple. For example, if V_{IN} = 3.6 V, V_{OUT} = 20 V, I_{OUT} = 30 mA, and f_S = 1.2 MHz, limiting ripple to 0.1% (20 mV) would require a 1.0-µF capacitor. Ceramic capacitors are usually the best choice relative to size, cost, and availability.

The additional output-ripple component caused by ESR is calculated as

$$V_{Ripple\_ESR} = I_{OUT} \cdot R_{ESR}. \qquad (9)$$

Since ceramic capacitors have low ESR, V_{Ripple_ESR} can usually be neglected, but ESR must be considered if tantalum or electrolytic capacitors are used. During a load transient, the output capacitor has to supply additional current until the boost circuit can restore the output-voltage level. A larger capacitor helps to maintain loop stability and to reduce output-voltage overshoot and undershoot during a load transient. Factors like applied DC voltage, aging, and frequency response may require a ceramic capacitor's parameters to be derated. For example, large-form-factor (size 1206) capacitors have self-resonant frequencies in the TPS61150's switching-frequency range, so the effective capacitance is significantly lower. Therefore, it may be beneficial to use small capacitors in parallel rather than one large capacitor.

In switching power-supply power stages, the power switch is used to control the energy flow from the input power source to the output. The inductor stores the energy while the switch is on and transfers it to the output when the switch is off. To avoid excessive switching power dissipation, the power switch should have very fast state changes. The power MOSFET can switch on and off much faster and more efficiently than the bipolar transistor, which makes the MOSFET the preferred device in most boost-converter designs . The total power dissipation across the power switch is given by Equation 10.

$$P_D = \left(\frac{I_O}{1-D}\right)^2 \bullet R_{DS(on)} \bullet D + \frac{1}{2} \bullet V_O \bullet \frac{I_O}{1-D} \bullet (t_{on} + t_{off}) \bullet f_S + Q_{Gate} \bullet V_{GS} \bullet f_S, \quad (10)$$

where t_{on} and t_{off} are the MOSFET turn-on and turn-off switching times, and Q_{Gate} is the MOSFET gate-to-source capacitance.

When the power switch turns off, the output-power diode provides a current path from the inductor to the output capacitor and load. Characteristics to consider when selecting the best diode include: fast switching, breakdown voltage, current rating, low forward-voltage drop to minimize power dissipation, and appropriate packaging. Unless the application justifies the expense and complexity of a synchronous diode, the best solution for low-voltage outputs is usually a Schottky diode. The diode's breakdown voltage must be greater than the maximum output voltage, and some margin should be added for transients and spikes. The current rating should be at least two times the maximum power-stage output current. Diode power losses are mainly due to the forward-conduction voltage drop. The power dissipated by the diode can be calculated as the product of the forward voltage and the output load current. The switching losses that occur at the transitions from conducting to nonconducting states are very small compared to conduction losses and are usually ignored. The power dissipated by the power diode is given by Equation 11.

$$P_D(\text{Diode}) = V_D \bullet I_O(1-D), \quad (11)$$

where V_D is the forward-voltage drop of the output diode, and D is the duty cycle.

Fig. 12 shows the efficiency performance of the TPS61150 relative to output WLED current for various input voltages.

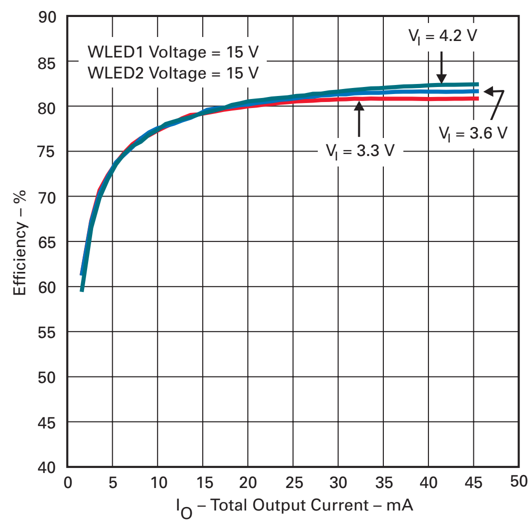


Fig. 12. TPS61150 power-conversion efficiency.

V. Pros and Cons of Charge Pumps and Inductive Boost Converters

Table 1 shows a general comparison between charge pumps and inductive boost converters. The biggest limitation of the charge-pump is the limited input-voltage range that makes the device inefficient when high voltage-conversion ratios are required. The charge-pump device has a much bigger die size and thus a higher core cost than the boost converter; but the charge pump has a smaller total solution size and thus a lower total cost because the boost converter needs an external inductor. Charge pumps are known for being noisy and inefficient with a high output-voltage ripple, but new design techniques and process technologies solve these problems for many applications.

Board layout is critical to the performance of both the charge-pump and boost-converter WLED drivers. A board-solution height of 0.8-mm was acceptable for most WLED drivers, but thinner solutions are required for mobile applications like cell phones. I will be an ongoing challenge for designers to place passive components close to active components to prevent sacrificing performance for small size.

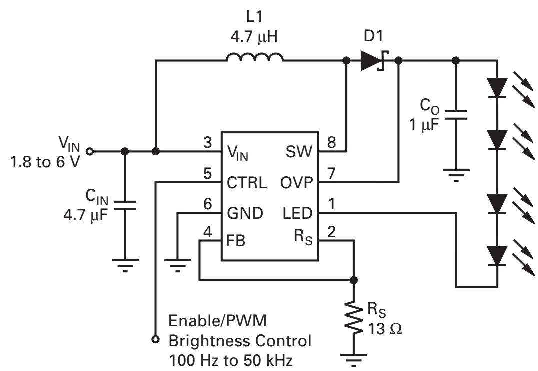
VI. Optimal Brightness Dimming

WLED backlighting in mobile-phone displays and other consumer electronics are now very common, so the need for brightness control is widespread. There are currently three major dimming technologies: pulse-width modulation (PWM), analog, and digital. Many available drivers can support one or more of these technologies.

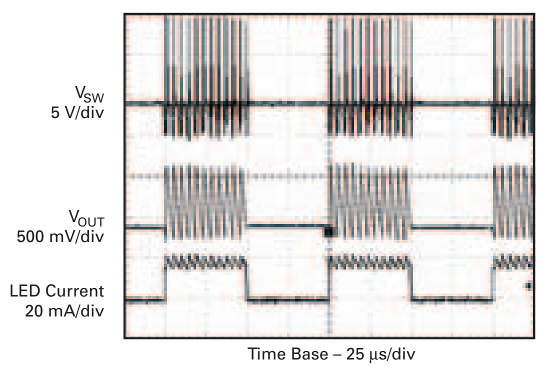
PWM dimming uses a simple digital PWM signal to repeatedly turn the WLED drivers on and off. Since the average current through the WLED is a function of the PWM signal's duty-cycle ratio, adjusting the pulse width makes the WLED appear dimmer. Figs. 13a and 13b show a typical application circuit with waveforms that supports dimming. The benefits of PWM dimming include the ability to provide quality illumination with a relatively simple circuit at high efficiency. For example, an I/O port can be used to generate a pulse signal of any duty cycle in a mobile-phone system, so the CTRL pin of the WLED driver can

Table 1. Charge Pump Versus Inductive Boost Converter

Charge Pump	Inductive Boost Converter
• High-power conversion efficiency over limited input-voltage range	• High-power conversion efficiency over wide input-voltage range
• Low quiescent current	• Low quiescent current
• Small size of total solution	• High voltage-conversion ratios possible
• Extremely low EMI	• Bigger total-solution size due to external inductor
• Low output-voltage ripple	• High EMI
• Low total-solution cost	• Higher total-solution cost
• Suitable for applications requiring low-output current	• Suitable for high-current applications



a. PWM dimming circuit.



b. PWM dimming waveforms.

Fig. 13. Dimming application for typical WLED driver. [1]

be connected to the I/O port of the system to achieve PWM dimming.

A disadvantage of PWM dimming is that it is more likely to produce audible (or microphonic) noise. Typically, power-switching WLED drivers like buck, boost, and charge-pump converters have switching frequencies of around 1 MHz. The audible noise is usually not a problem in basic applications, but PWM dimming can cause the inductor or output capacitor to produce audible noise when the dimming frequency is in the range of 200 Hz to 20 kHz.

Ceramic capacitors commonly used in cell phones can exhibit piezoelectric characteristics that may cause a capacitor to hum when a low-frequency dimming signal is used. When the PWM dimming signal turns off the WLED driver, the output capacitor discharges through the WLEDs and the current-sensing resistor, which can produce large ripple effects. To avoid audible noise during PWM dimming, WLED drivers should be designed to produce dimming frequencies beyond the audible range. Some companies are developing new ceramic capacitors that can reduce audible noise during PWM dimming.

Analog dimming is an option if the value of the equivalent current-sensing resistance for the WLED driver can be dynamically changed, which in turn would vary the current flowing through the WLED. Fig. 14 shows a typical analog-dimming circuit that routes the PWM signal through a low-pass RC filter, which clamps the voltage at the R_S pin to an averaged value of the PWM signal.

The biggest advantage of analog dimming is that it eliminates audio noises associated with dimming. With analog dimming, the WLED's forward-voltage drop decreases as LED current decreases, which lowers the WLED's energy consumption. In contrast to PWM dimming, the WLED driver is always working during analog dimming, and the driver's power-conversion efficiency falls significantly because of the drop in output current. Therefore, using analog dimming often increases the power consumption of the overall system.

Because analog dimming directly changes the WLED's current, it also changes the white-light quality. As shown in Fig. 15, WLED chromaticity can vary significantly with changing forward current. Reference [2] provides more information about parameters that affect WLED light quality.

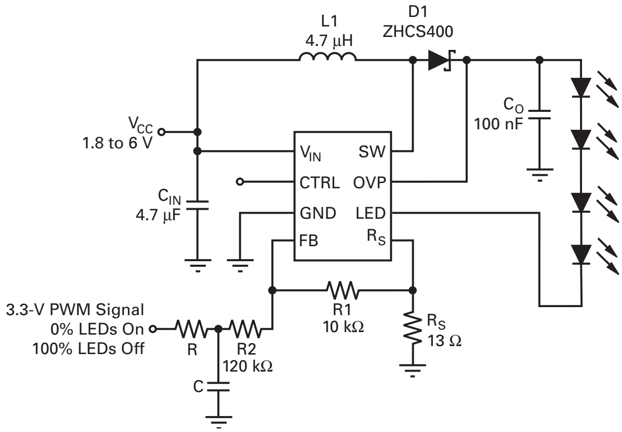


Fig. 14. Analog dimming with typical WLED driver.

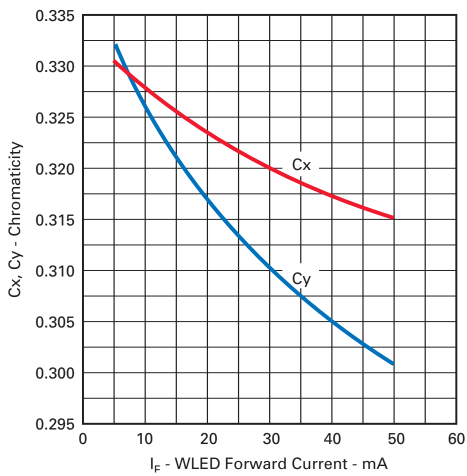


Fig. 15. Typical chromaticity drift of a WLED.

Topic 5

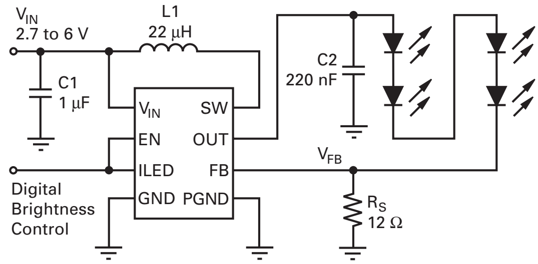
Some drivers support digital dimming, which requires them to have an application-specific digital interface such as SMBus, I^2C, or other single-line interface. The WLED's brightness can be controlled by simply sending timed pulses to the driver. For example, The TI TPS61060 driver shown in Fig. 16 can support digital dimming through the ILED pin. The driver has an internal DAC that clamps the reference voltage by a simple digital signal. Digital dimming can save processor power and battery life, and it does not require a digital signal all the time.

Table 2 provides a brief comparison of the three dimming technologies.

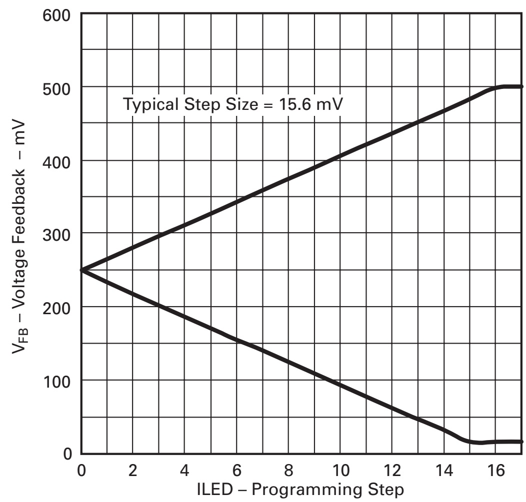
TABLE 2. COMPARISON OF THREE DIMMING SOLUTIONS

Characteristic	PWM	Analog	Digital
Noise	Yes	No	No
White-light quality	Good	Average	Average
Battery-power consumption	Low	Average	Average
Peripheral device requirements	Simple	Average	Simple

TI offers a variety of high-performance LED drivers to meet different challenges and applications. The TPS61150/1 shown in Fig. 17 is a dual WLED driver with regulated-current outputs suitable for LCD backlighting of sub and

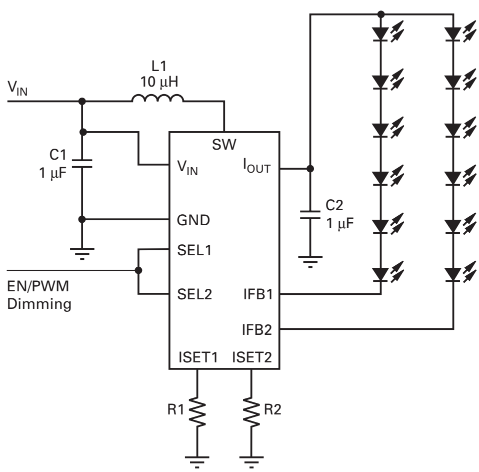


a. Application circuit.

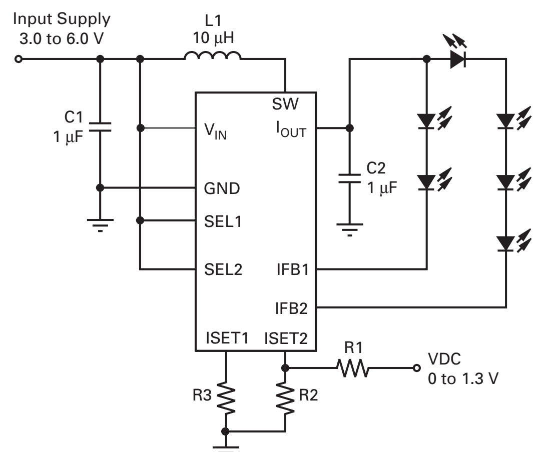


b. Feedback-voltage plot of digital dimming.

Fig. 16. TPS61060 digital-dimming application. [3]



a. 12 WLED drivers with PWM dimming.



b. Display and keypad application with analog dimming.

Fig. 17. TPS61150/1 application circuits. [4]

main cell-phone displays. The driver supports PWM or analog dimming, and the dual outputs can also be used to drive backlights for a display and a keypad. For large displays, the TPS61150/1 can drive up to 12 WLEDs in 2 parallel strings. It runs at a 1.2-MHz, fixed switching frequency and an integrated power diode to provide an extremely compact solution with high efficiency and has plenty of flexibility. The PWM-dimming function can operate at up to 30 kHz, which is beyond the audible range.

In contrast to ordinary drivers, the TPS61150/1 uses an active current-mirror circuit to regulate two independent output-current paths controlled by external resistors connected to the ISET1 and ISET2 pins. The I_O output current for each output can be calculated as follows.

$$I_O = \frac{V_{ISET}}{R_{SET}} \bullet K_{ISET}, \qquad (12)$$

where V_{ISET} is the ISET pin voltage, R_{SET} is the resistor value connected to the ISET pin, and K_{ISET} is the current multiplier (900 is typical).

To control brightness with the analog dimming method, a DC voltage is added to the ISET2 pin through the R1 resistor shown in Fig. 17b. For specific application parameters, see Reference [4].

VII. Conclusion

Several critical factors for designing a WLED backlight system in mobile devices have been covered. Regardless of the type, color, size, or power, all WLEDs work best when driven with constant current. WLED manufacturers specify device characteristics such as lumens, beam pattern, and color at a specified forward current (I_F) instead of forward voltage (V_F). When consistent illumination and chromaticity are critical, placing WLEDs in a series string ensures that the same current flows through each WLED. The inductive boost driver is an ideal solution for the higher drive voltages required by WLED series strings. For WLED applications requiring an output current of less than 1 A, the charge-pump driver is desirable for its high efficiency, brightness control, individual current-path on/off control, lower cost, and small solution size. However, the charge-pump driver has poor brightness matching in comparison with the inductive boost driver.

VIII. References

[1] TPS61042 Datasheet, TI Literature No. SLVS441C

[2] OSRAM LW E6SC Datasheet

[3] TPS61060 Datasheet, TI Literature No. SLVS538A

[4] TPS61150/1 Datasheet, TI Literature No. SLVS625A

[5] "High Efficiency Charge Pump for WLED Drivers," TPS60250/1 Datasheet, TI Literature No. SLVS769

[6] S.W. Lee, "A New and Flexible Control Method for Small Size LCD Backlighting using White LED with Highly Efficient Charge Pump Technique," PCIM Europe 2006, Nurnberg, Germany (May 30–June 1, 2006), pp.283–288.

[7] "Understanding Boost Power Stage in Switchmode Power Supplies," Application Report, TI Literature No. SLVA061

Topic 5