LM27952,LM27965

Optimizing Efficiency in White LED Backlight Applications

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No. 113

Optimizing Efficiency in White LED Backlight Applications

— *By Dario Nurzad, Applications Engineer*

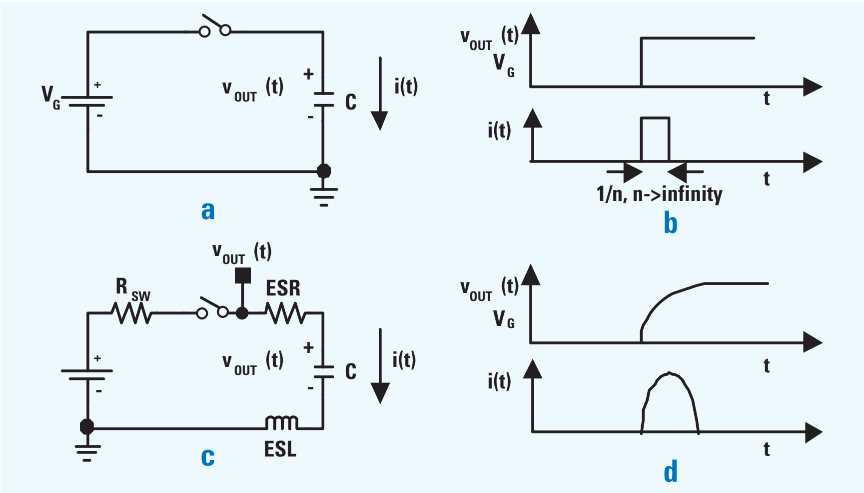

Figure 1. Charging a Capacitor From a Voltage Source (Both the ideal [a, b] and real [c, d] cases are shown)

White LEDs are typically driven with a constant DC current source to maintain constant luminosity. In portable applications with a single-cell Li-Ion source, the sum of the voltage drop across the white LED and the current source can be lower or higher than the battery voltage. This means that a white LED requires the battery voltage to be occasionally boosted. The best way to accomplish this is to use a step-up DC-DC converter. This method significantly optimizes efficiency at the expense of cost and PCB area. An alternative method of boosting the battery voltage is to use a charge pump, also called a switched capacitor converter. Here we will analyze in more detail the principle of operation of such a device.

Basic Principles of Charge Pumps

A capacitor is a component that stores electrical charge or energy for release at some predetermined rate and time. If an ideal capacitor is charged with an ideal voltage source V_G *(Figure 1a)* the charge storage occurs instantly

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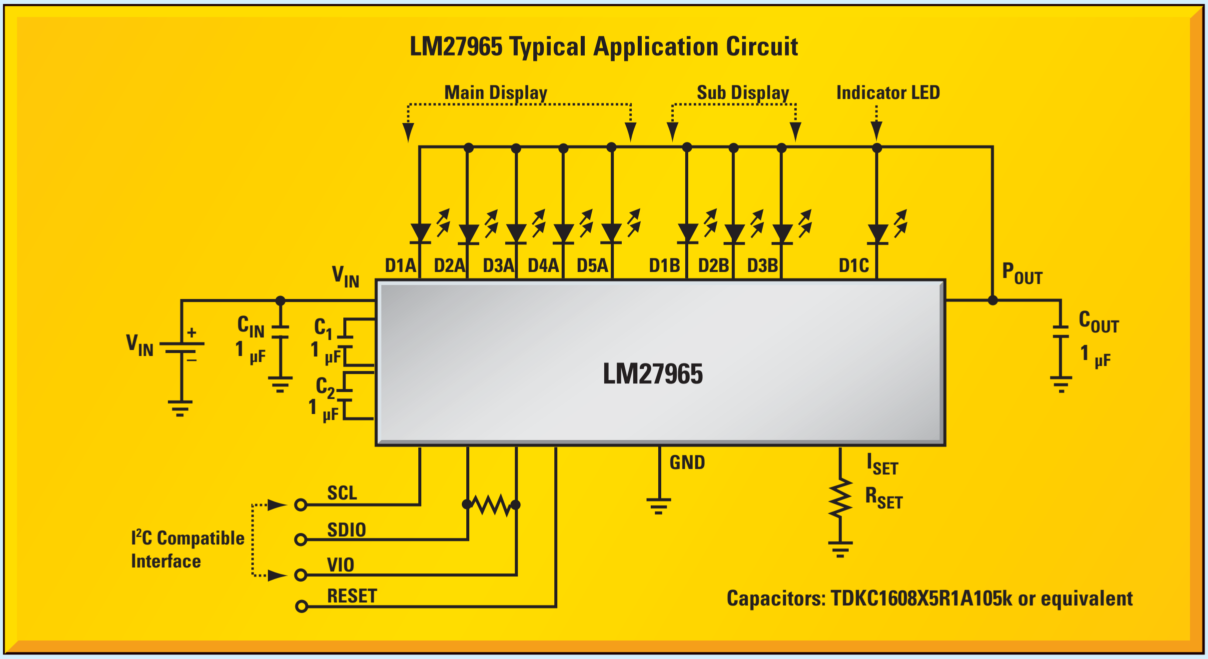
White LED Driver System with I²C Compatible Brightness Control

Inductorless LM27965 Drives Up to 9 LEDs at 91% Efficiency



Features

- 91% peak LED drive efficiency
- No inductor required: 25 mm² total solution size
- 0.3% typ. current matching
- Drives LEDs with up to 30 mA per LED
- Adaptive 1x to 3/2x charge pump
- I²C compatible brightness control interface
- Extended Li-Ion input: 2.7V to 5.5V
- Available in LLP-24 packaging AVAILABLE LEAD-FREE

Ideal for use in mobile phone display and keypad lighting, PDA backlighting, and general LED lighting

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corresponding to a Dirac impulse function for the current *(Figure 1b)*. The total stored charge is given by: $Q = CV_G$.

Real capacitors have Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL). Neither affects the ability of the capacitor to store energy; however, they have a large effect on the overall efficiency of the switched capacitor voltage converter. An equivalent circuit for the charge of an actual capacitor is shown in ***Figure 1c,*** where R_{SW} is the resistance of the switch. The charging current path will have a series inductance, which can be reduced with proper component layout.

As soon as the circuit is energized, transient conditions of an exponential nature occur until a steady-state condition is reached. The capacitor parasitics limit the peak charge current and increase the charge transfer time *(Figure 1d)*. Therefore, the capacitor charge build-up cannot occur instantly, meaning that the initial voltage variation across the capacitor is equal to zero. Charge pumps use this property of capacitors as shown in ***Figure 2a***.

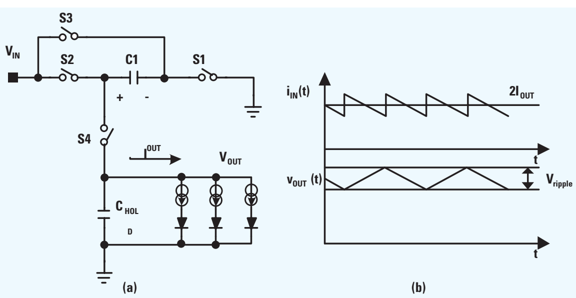


Figure 2. Charge Pump Circuit (a) with Relevant Waveforms (b)

The voltage conversion is achieved in two phases. During the first phase, switches S_1 and S_2 are closed, whereas switches S_3 and S_4 are open and are charged to the input voltage:

$$V_{C1+} - V_{C1-} = V_{C1+} = V_{IN}$$

During the second phase, switches S_3 and S_4 are closed, whereas switches S_1 and S_2 are open. Because the voltage drop across the capacitor cannot change instantly, the output voltage jumps to twice the value of the input voltage:

$$V_{C1+} - V_{C1-} = V_{OUT} - V_{IN} = V_{IN} \rightarrow V_{OUT} = 2V_{IN}$$

Voltage doubling can be accomplished using this technique. The duty cycle of the switching signal is usually 50%; which generally yields the optimal charge transfer efficiency. Let us examine in more detail the charge transfer procedure and how the switched capacitor converter parasitics influence its operation.

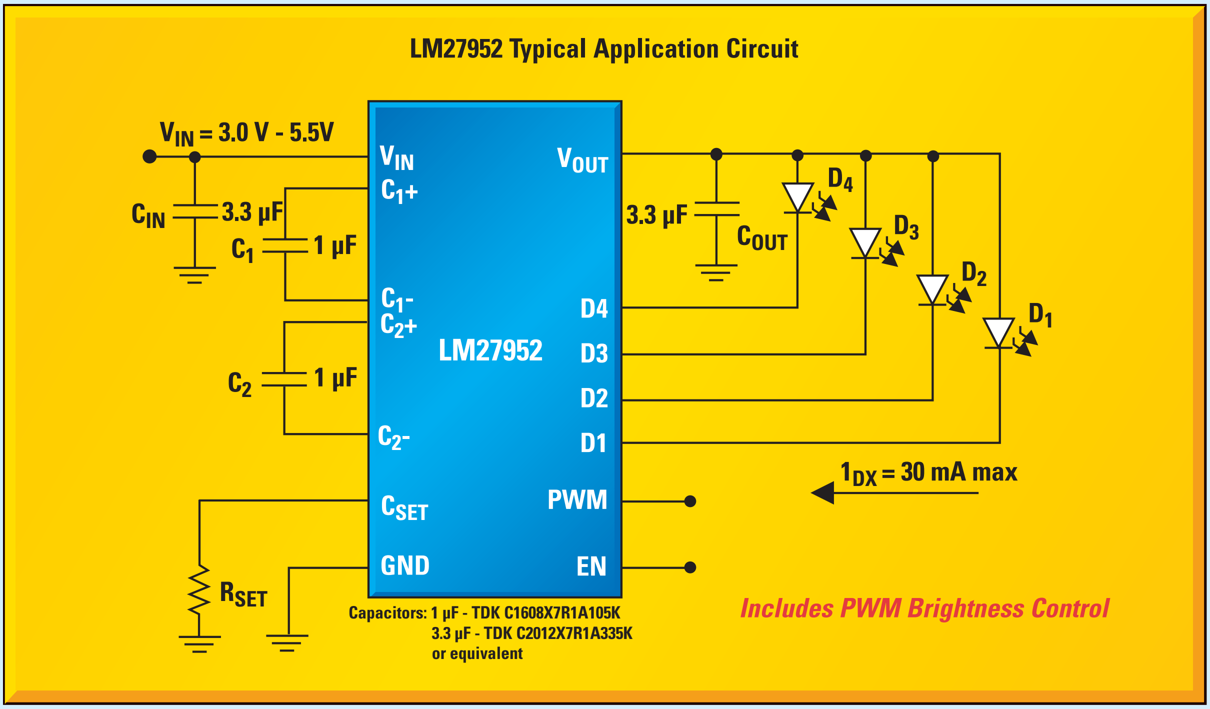
The steady-state current and voltage waveforms for a switched capacitor voltage doubler are shown in ***Figure 2b***. Due to power conservation, the average input current is twice the output current. During the first phase, a charging current flows into C_1. The initial value of this charging current depends upon the initial voltage across C_1, the ESR of C_1, and the resistance of the switches. The charging current then decays exponentially as C_1 is charged. The charging time constant is several times greater than the switching period. Smaller time constants will cause the peak currents to increase. During this time the output capacitor C_{HOLD} supplies the load current discharging linearly by an amount equal to:

$$\Delta V_{OUT} = \frac{I_{OUT}}{2fC_{HOLD}}$$

During the second phase when C_1+ is connected to the output, a discharge current (whose magnitude is the same as the previous charging current,) flows through C_1 to the load. In this phase, the step change in the output capacitor current is approximately $2I_{OUT}$. Although this current step should create an output voltage step equal to $2I_{OUT}ESR_{C\_HOLD}$, the use of low-ESR ceramic capacitors renders this step change negligible. At this point, C_{HOLD} charges

White LED Adaptive 1.5X/1X Switched Capacitor Current Driver

LM27952 Drives Up to 4 LEDs with Up to 30 mA Each



LM27952 Features

- Regulated current sources with 0.2% (typ.) matching
- 3/2x, 1x gain transition based on LED V_F
- Peak efficiency over 85%
- Input voltage range: 3.0V to 5.5V
- Fixed 750 kHz switching frequency
- <1 µA shutdown current
- Available in LLP-14 packaging

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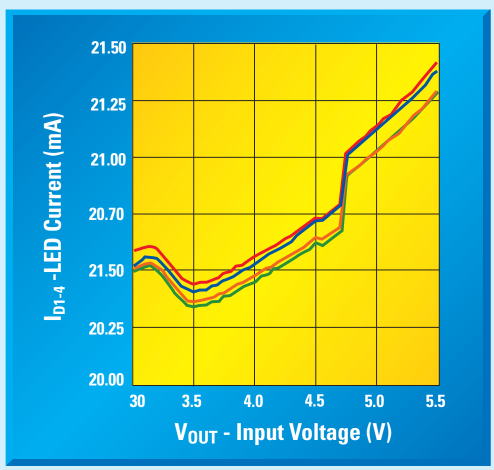

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linearly by an amount equal to: $\Delta V_{OUT} = \frac{I_{OUT}}{2fC_{HOLD}}$

When C_1 is connected back between the input and ground, C_{HOLD} discharges linearly by an amount equal to:

$$\Delta V_{OUT} = \frac{I_{OUT}}{2fC_{HOLD}}$$

The total peak-to-peak output ripple voltage is given by:

$$V_{RIPPLE} \cong \frac{I_{OUT}}{2fC_{HOLD}}$$

Higher switching frequencies allow smaller output capacitors for the same amount of ripple.

Parasitics of the charge pump cause the output voltage to fall as the load current increases. As a matter of fact, there is always an RMS current of $2I_{OUT}$ flowing through C_1 and two switches $(2R_{SW})$ resulting in a power dissipation of:

$$P_{SW} = (2I_{OUT})^2 (2R_{SW} + ESR_{C1}) = I^2_{OUT} (8R_{SW} + 4ESR_{C1})$$

In addition to these purely resistive losses, an RMS current of I_{OUT} flows through the equivalent resistance of the switching capacitor C_1:

$$P_{C1} = I^2_{OUT} R_{C1} = I^2_{OUT} \frac{1}{fC_1}$$

The RMS current flowing through C_{HOLD} is equal to I_{OUT}, resulting in a power dissipation of:

$$P_{ESR\_HOLD} = I^2_{OUT} ESR_{C\_HOLD}$$

All of the losses can be grouped in an equivalent output resistance:

$$R_{OUT} = 8R_{SW} + 4ESR_{C1} + \frac{1}{fC_1} + ESR_{C\_HOLD}$$

Thus the output voltage of the charge pump can be modeled as follows: $V_{OUT} = 2V_{IN} - I_{OUT}R_{OUT}$

In general, because of the low ESR of ceramic capacitors and the high switching frequency, the output ripple and output voltage drop depends on the switch resistances. Utilizing more switches and capacitors enables additional voltage conversions.

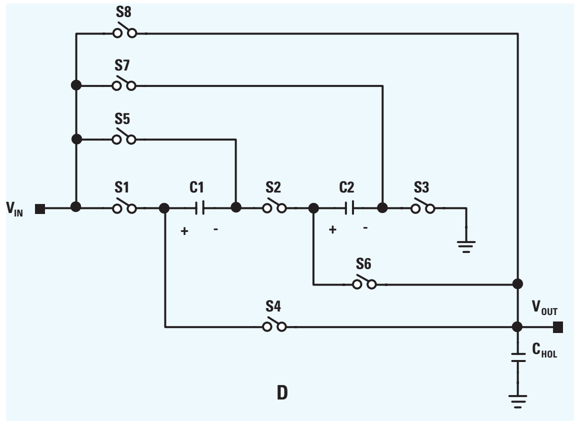


Figure 3. Switched Capacitor Circuit with 1x and 1.5x Gains

Figure 3 demonstrates this property using capacitors.

Once more, the voltage conversion is achieved in two phases. During the first phase switches S1 to S3 are closed, whereas switches S4 to S8 are open. Therefore C_1 and C_2 are stacked and—assuming C_1 equal to C_2— charged to half the input voltage:

$$V_{C1+} - V_{C1-} = V_{C2+} - V_{C2-} = \frac{V_{IN}}{2}$$

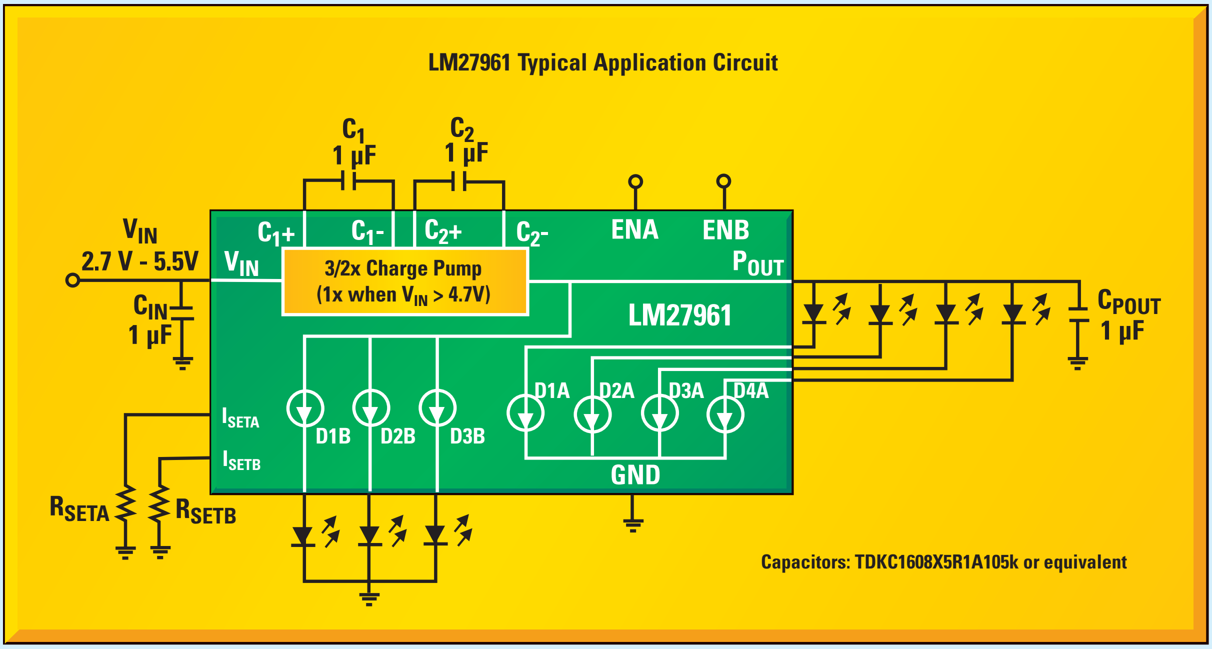
The output load current is provided by the output capacitor C_{HOLD}. As this capacitor discharges and the output voltage falls below the desired output voltage, the second phase is activated to boost the output voltage above this value. During the second phase, C_1 and C_2 are in parallel, tied between V_{IN} and V_{OUT}. Switches S4 to S7 are closed, whereas switches S1 to S3 and S8 are open. Because the voltage drop across the capacitor can not change instantly, the output voltage jumps to 1.5X the value of the input voltage:

$$V_{C1+} - V_{C1-} = V_{C2+} - V_{C2-} = V_{OUT} - V_{IN} = \frac{V_{IN}}{2} \Rightarrow V_{OUT} = \frac{3}{2} V_{IN}$$

The voltage boost operation is accomplished this way: A voltage conversion with a gain of 1x is achieved by closing switch S8 and leaving switches S1 to S7 open.

Dual-Display White LED Driver with 3/2x Switched Capacitor Boost

Inductorless LM27961 Only Uses Tiny Ceramic Capacitors to Provide Superior Performance



LM27961 Features

- Drives 4 individual common-anode LEDs with up to 20 mA each for a main display backlight
- Drives 3 individual common-cathode LEDs with up to 20 mA each for a sub-display backlight
- Independent resistor-programmable current setting
- Excellent current and brightness matching
- Extended Li-Ion input: 2.7V to 5.5V
- PWM brightness control: 100 Hz to 1 kHz
- Available in micro SMD packaging

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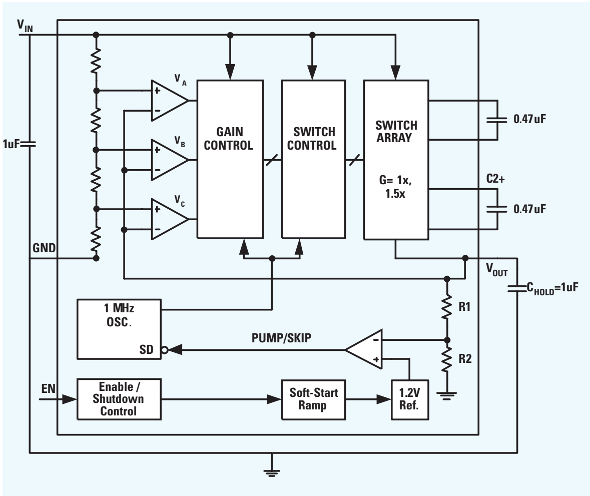

Figure 4. Switched Capacitor Regulator Block Diagram

Pulse Frequency Modulation (PFM) Scheme

A simplified Pulse Frequency Modulated (PFM) regulation scheme, which utilizes multiple gains, is depicted in ***Figure 4.*** The down-scaled output voltage is compared by the PUMP/SKIP comparator to a 1.2V voltage reference. The PUMP/SKIP comparator is ramped up linearly on start up to provide the soft-start function. When the output voltage is above the desired limit the device does not switch, consuming minimal supply current. During this idle state the output load current is provided by the output capacitor. As this capacitor discharges and the output voltage falls below the desired output voltage, the charge pump is activated until the output voltage is above this value again.

The primary advantage of the PFM regulation architecture is evident at light loads. Typically the load is provided with energy by the output capacitor. The supply current is very low, as the output capacitor only needs to be re-charged occasionally by enabling the charge pump.

In general, regulated charge pumps do not maintain a high efficiency over a wide input range. Because the input-to-output current ratio is scaled according to the basic voltage conversion, any output voltage magnitude less than the input-voltage-times-the-charge-pump-gain will result in additional power dissipation within the converter and efficiency will be degraded proportionally:

$$\eta_{IDEAL} = \frac{V_{OUT}\, I_{OUT}}{V_{IN}\, I_{IN}} = \frac{V_{OUT}\, I_{OUT}}{V_{IN}\, G I_{OUT}} = \frac{V_{OUT}}{V_{IN}\, G}$$

$$\eta_{IDEAL} \rightarrow 1 \Leftrightarrow V_{OUT} = G V_{IN}$$

The ability of the converter to change gains according to the input/output ratio allows for optimal efficiency over the entire input voltage range. Ideally, the gain should vary linearly. In reality, given a certain number of capacitors and switches, only a finite number of gain configurations are possible.

Referring to ***Figure 4*** the input voltage is scaled and fed into the non-inverting nodes of three comparators. All inverting nodes of the comparators are connected to the output voltage. Based on the input-to-output voltage ratio the outputs of the comparators provide the gain control circuitry with a three-bit word, which is used to select the minimum gain G, able to achieve the desired voltage conversion. In white LED applications, however, the selection of the proper gain G is not only based on the input and output voltages.

Conclusion

There are certain advantages in using switched capacitor rather than inductor-based switching techniques. An obvious advantage of switched capacitor converters is the elimination of the inductor and the related magnetic design issues. They usually have relatively low noise and minimal radiated EMI. Additionally, the applications circuits are simple and only a few small capacitors are needed.

Because there is no inductor, the final PCB component height is generally smaller than a comparable switching converter. ■

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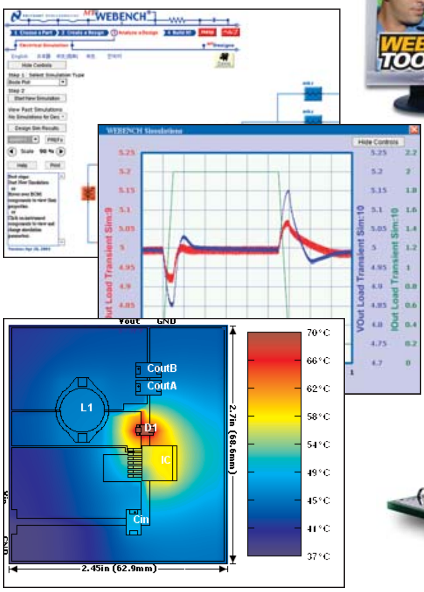

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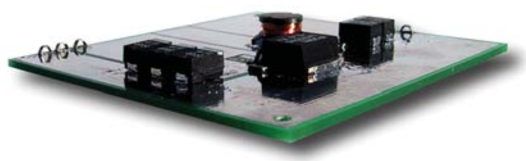

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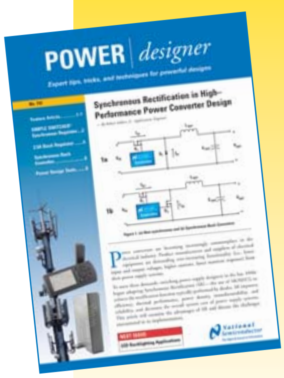

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