LED Backlight Driving Circuits and Dimming Method

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Abstract

In this paper, light-emitting-diode (LED) backlight driving circuits and dimming method for medium-sized and large liquid crystal displays (LCDs) are proposed. The double loop control method, the intelligent-phase-shifted PWM dimming method, the fast-switching current regulator, and the current matching techniques are proposed to improve not only the current regulation characteristics and the power efficiency but also the current matching characteristics and the transient response of the LED current. The brightness of the backlight using the proposed local dimming method was determined from the histogram of the local block to reduce the power consumption of the backlight without image distortion. The measured maximum power efficiency of the LED backlight driving circuit for medium-sized LCDs was 90%, and the simulation results showed an 88% maximum power efficiency of the LED backlight driving circuit for large LCDs. The maximum backlight power-saving ratio of the proposed dimming method was 41.7% in the simulation with a high-contrast image. The experiment and simulation results showed that the performance of LEDs as LCD backlight units (BLUs) improved with the proposed circuits and method.

Keywords: LED, backlight, boost converter, current regulator, dimming algorithm

1. Introduction

Light-emitting diodes (LEDs) are recently being used as backlights of liquid crystal displays (LCDs) because of their various advantages such as low power consumption, slimness, high image quality, improved dynamic contrast ratio, wide color gamut, and high reliability [1-3]. LED backlight driving circuits and control ASIC with the backlight dimming method, as shown in Fig. 1, are required to operate LEDs as LCD backlight units (BLUs) [4-11]. LED backlight driving circuits supply voltage and current to LEDs, which are determined by the panel size; and the control ASIC with the backlight dimming method changes the input image data into backlight dimming signals. The backlight dimming signals are transferred from the control ASIC to the LED backlight driving circuits to control the luminance of LEDs.

Many researches on LED backlight driving circuits have focused on regulating the current of LEDs to guarantee uniform LED light and improved power efficiency [4-7]. There are many methods of regulating the current of LEDs, such as with a current mirror, a current regulator, a linear current regulator, and a switch mode current regulator. The linear current regulator with the switch-mode pre-regulator is mainly used due to its high power efficiency. Improvements in the current matching characteristics and the transient response of the LED current are still required, however, although the current regulation characteristics and power efficiency are improved with the use of a linear current regulator with a switch-mode pre-regulator. The channel-to-channel and chip-to-chip current matching characteristics should be improved to prevent deterioration of the image quality, and the transient response of the LED current should be improved for a high dimming frequency and...
reduction of harmonic noise, which is audible to human ears [7].

Images are displayed in conventional LCDs by controlling the transparency of the liquid crystal with the constant-luminance backlight. Therefore, much backlight power is consumed even with dark images, and the contrast ratio is poor because light is not blocked completely at the lowest gray level. The dimming methods with LED BLUs are proposed to solve these problems [8-11]. The brightness of the backlight according to the input image is modulated adaptively with the dimming method. Consequently, power efficiency is improved due to the elimination of unnecessary power consumption, and the contrast ratio is improved because light is blocked completely at the lowest gray level. Image distortion occurs in the backlight brightness modulation process, though. Therefore, the dimming method, which improves the power efficiency and contrast ratio without image distortion, is required.

LED backlight driving circuits for medium-sized and large LCDs are proposed in this paper. LED backlight driving circuits are designed to improve not only the current regulation characteristics and the power efficiency but also the current matching characteristics and the transient response of the LED current. The double loop control method, the intelligent-phase-shifted PWM dimming method, the fast-switching current regulator, and the current matching techniques are proposed to achieve these requirements. In addition, the LED dimming method is proposed in this paper. The brightness of the backlight in the proposed dimming method is determined by the histogram of the local block to reduce the power consumption of the backlight without image distortion. The improvement of the performance of LEDs as LCD BLUs is verified by the experiment and simulation results.

2. LED backlight driving circuits

2.1 LED backlight driving circuit for medium-sized LCDs

The proposed LED backlight driving circuit for medium-sized LCDs is shown in Fig. 2. A power MOSFET, a boost converter, a current regulator with a PWM controller, and a control block are integrated in a chip. The double loop control method with the adaptive reference voltage generator is proposed to improve the power efficiency and the transient response. The regulating voltage of the boost converter is optimized, and the transient response of the LED current depends only on the transient response of the current regulator in the proposed double loop control method. Therefore, the driving voltage margin is eliminated, and low power consumption is achieved because the forward voltage variation of LEDs is automatically compensated for by the negative feedback loop in the proposed method. Furthermore, a high PWM dimming frequency is achieved due to the fast transient response characteristics of the proposed method.

The proposed double loop control method has two separate feedback loops. The first feedback loop is the reference voltage generation loop, which controls the output voltage of the boost converter. The adaptive reference voltage generator is proposed to generate the adaptive reference voltage and to control the frequency of this loop. The schematic of the adaptive reference voltage generator is

![Fig. 2. Block diagram of the proposed LED backlight driving circuit for medium-sized LCDs.](image)

![Fig. 3. Schematic of the proposed adaptive reference voltage generator.](image)
shown in Fig. 3. This circuit consists of two sub-blocks. One sub-block is the lowest voltage selector, and the other is the reference voltage generator. The inputs of the lowest voltage selector are the feedback channel voltages in the LED channels. Therefore, the lowest of these voltages is selected as the minimum channel voltage ($V_{CH,MIN}$) by the source and emitter followers. The second feedback loop is the boost converter output voltage regulation loop, which enhances the transient response of the boost converter. Therefore, high power efficiency and a high dimming frequency are simultaneously achieved with the proposed method.

In addition, the intelligent-phase-shifted PWM dimming method is proposed, as shown in Fig. 4, to remove the harmonic noise and the output voltage fluctuation that are generated when any channel is disabled for the multi-channel LED backlight. Since the previously reported phase-shifted backlight driving method has a fixed phase-shifted value between channels, there can be harmonic noise and output voltage fluctuation in a LED backlight when any channel is disabled via open or short LED detection [6]. The proposed method controls the phase difference between channels according to the number of the enabled channels. Therefore, the proposed method reduces the load current variation of the boost converter and the harmonic noise of the LED backlight.

2.2 LED backlight driving circuit for large LCDs

The proposed LED backlight driving circuit for large LCDs is shown in Fig. 5. A discrete power MOSFET, one boost converter IC, and two LED current regulation ICs were used. The boost converter IC was designed to make the output voltage 60 V, and each LED current regulation IC was designed to drive the 24 channels. The double loop control method and the intelligent-phase-shifted PWM dimming method, which are used in the LED backlight driving circuit for medium-sized LCDs, are used to improve the power efficiency and the transient response and to reduce the harmonic noise and output voltage fluctuation. In addition, the fast-switching current regulator is proposed to increase the dimming frequency, and two current matching techniques are proposed to improve the current matching characteristics.

The proposed fast-switching current regulator is shown in Fig. 6. M1 was used as a low-voltage NMOS switching element, and M2 was used as a high-voltage blocking switch and a PWM switching element. The current regulator switching speed was influenced only by the RC time constant at the M2 gate, because the M1 gate voltage maintains a constant voltage during the off-time of the PWM signal. Therefore, the rising time of about several nanoseconds and the high PWM dimming frequency were achieved.

Channel-to-channel mismatch is caused mainly by MOSFET mismatch, resistor mismatch, and offset mismatch of the amplifier in the current regulator. The offset
calibration technique is used to reduce the offset of the amplifier and to improve the channel-to-channel current matching characteristics in the proposed current regulator. The schematic of the proposed offset calibrated current regulator is shown in Fig. 7. This circuit consists of the voltage DAC, the digital control logic, and the amplifier itself. The offset voltage of the amplifier is calibrated by voltage DAC and control logic before the start of the normal operation of the current regulator.

A highly accurate current mirror, which is shown in Fig. 8, was used to improve the chip-to-chip current matching characteristics. The cascode current mirror, which is less sensitive to the channel length modulation effect, was used to reduce the difference between the bias currents, because chip-to-chip mismatch is caused mainly by the difference between the bias currents (I_SET) of the LED current regulation ICs. Therefore, only one external resistor (R_SET) is required to determine the LED current of several LED driver ICs.

3. LED backlight dimming method

The process of the proposed dimming method is shown in Fig. 9. First, the input image that is stored in the memory, and the characteristics data such as the histogram and the maximum luminance of the local block, are extracted. Second, the dimming rate of the LED string is determined using the histogram of the local block. Third, the pixel data of the input image are compensated for according to the backlight distribution. Finally, the mixture of the backlight and the compensated image is displayed on the panel.

The histogram of the local block was used to analyze the characteristics of the input image, as shown in Fig. 10, in the proposed local dimming method. The bright pixels greatly influence the image quality of the displayed image because the luminance of the displayed image cannot exceed the backlight luminance [8]. The backlight luminance is determined by the average luminance of the bright pixels that have higher luminance than the threshold value. The flowchart of the proposed brightness modulation is shown in Fig. 11. LB is the threshold value of the luminance of the bright pixels, TL is the sum of the luminance of the total pixels in the local block, α and β are coefficients, ML is the maximum luminance of the local block, n is the n-bit gray
scale, \( SL \) is the sum of the luminance values of the pixels that are over the \( i \)th gray level, \( NP(i) \) is the number of pixels at the \( i \)th gray level in the histogram, \( TNP \) is the total number of pixels that are over the \( i \)th gray level, and \( BL \) is the backlight luminance of the local block. The threshold value is changed according to the maximum luminance of the local block. A low maximum luminance means the input image has many low-gray-level pixels. The dimming rate of the LED string can be significantly reduced with low image distortion. The displayed image will be distorted easily at a high maximum luminance. Therefore, the threshold value is determined close to the maximum luminance of the local block to reduce the image distortion.

The luminance of the displayed image is reduced because the backlight luminance is reduced from the full luminance of the backlight. The pixel data of the input image should be changed according to the luminance of the backlight to compensate for the reduced luminance of the displayed image. The luminance of the displayed image is expressed as

\[
LD = BL \times CL / 2^n, \tag{1}
\]

wherein \( CL \) is the compensated-for luminance of the input image. The stretch method [9] is used to calculate \( CL \). \( CL \) is calculated by comparing the backlight luminance at each pixel and the maximum luminance of the local block of the input image in the stretch method.

4. Results and Discussion

4.1 LED backlight driving circuit for medium sized LCDs

The micrograph of the fabricated LED backlight driver circuit for medium-sized LCDs is shown in Fig. 12, and the technical summary of the proposed circuit is listed in the middle column in Table 1. The proposed circuit was fabricated using the 0.35 \( \mu \)m BCD process technology. The targeted boost converter output voltage was 24 V, and the proposed IC was designed to drive the six channels of the eight-series connected LEDs to drive medium-sized LCDs. The measured boost converter output voltage waveform and the phase-shifted current waveforms of two LED chan-

Fig. 11. Flowchart of the proposed brightness modulation.

Fig. 12. Micrograph of the fabricated LED backlight driver circuit for medium-sized LCDs.

Table 1. Technical summary of the proposed LED backlight driving circuits for medium-sized and large LCDs

<table>
<thead>
<tr>
<th>Item</th>
<th>LED backlight driving circuit for medium-sized LCDs</th>
<th>LED backlight driving circuit for large LCDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.35 ( \mu )m BCD technology</td>
<td>0.35 ( \mu )m BCD technology</td>
</tr>
<tr>
<td>Number of LED channels</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>Input voltage range (V)</td>
<td>5-24</td>
<td>5-30</td>
</tr>
<tr>
<td>Output voltage range (V)</td>
<td>12-48</td>
<td>40-60</td>
</tr>
<tr>
<td>LED current range (mA)</td>
<td>20-30</td>
<td>30-60</td>
</tr>
<tr>
<td>Maximum power efficiency (%)</td>
<td>90 (measurement)</td>
<td>88 (simulation)</td>
</tr>
</tbody>
</table>
nels among the six LED channels during the normal operation of the proposed circuit are shown in Fig. 13. In Fig. 13 (a), the measured boost output voltage and the PWM dimming duty cycle are 26.1 V and 10%, respectively. The measured boost output voltage and the PWM dimming duty cycle in Fig. 13 (b) are 26.7 V and 90%, respectively. The maximum power efficiency of 90% was obtained, and the rising time and the falling time of the LED current were 86 nsec and 7 nsec, as shown in Fig. 13 (c) and (d), respectively. A prototype of the proposed circuit is shown in Fig. 14. The PWM dimming duty cycles in Fig. 14 (a) and (b) are 10% and 90%, respectively. The difference in the LED backlight between the 10% PWM dimming duty cycle and the 90% PWM dimming duty cycle is verified as shown in Fig. 14.

4.2 LED backlight driving circuit for large LCDs

The proposed LED backlight driving circuit for large LCDs was simulated using the 0.35 μm BCD process technology, and the technical summary of the proposed circuit is listed in the right column in Table 1. The targeted boost converter output voltage was 60 V, and each current regulator IC was designed to drive 24 channels of the series-connected LEDs. Fig. 15 shows the simulated boost converter output voltage waveform and the simulated current waveforms of four of out of 48 LED channels during the normal operation of the proposed circuit. In Fig. 15, the simulated boost converter output voltage is 59.98 V, and the rising time and the falling time are 7 nsec and 6 nsec, respectively. A fast rising time and a high dimming frequency were achieved with the fast-switching current regulator, and the maximum power efficiency of 88% was obtained from the simulation results. Fig. 16 shows the simulated waveforms of the phase-shifted PWM dimming signals.
during the normal operation of the LED backlight driver circuit for large LCDs. The phase-shifted PWM signals of the 24 LED channels are verified as shown in Fig. 16.

4.3 LED backlight dimming method

Fig. 17 shows the simulation images of IMF [10], BDG [11], and the proposed local dimming method. The two images, one of a night scene and the other of the sky, were used to test the influence of the luminance; a landscape image was used to test high-contrast images; and a still life image was used to test the influence of the color characteristic. The sample images had a 1,080x1,920 resolution and an eight-bit gray scale. The backlight divides into 6x12 local blocks. The backlight power-saving ratio is shown in Table 2. The distribution functions of the image distortion are shown in Fig. 18. In the IMF method, 54.4%, 2.3%, 43.7%, and 50.9% backlight power was saved in low-luminance, high-luminance, high-contrast, and colorful images, respectively. The power consumption of the backlight was significantly reduced, but the image quality was bad, as shown in Fig. 18. In the BDG method, 37.0%, 8.2%,

<table>
<thead>
<tr>
<th>Dimming Method</th>
<th>Low-luminance Image (Night Scene)</th>
<th>High-luminance Image (Sky)</th>
<th>High-contrast-ratio Image (Landscape)</th>
<th>Colorful Image (Still Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Image</td>
<td><img src="image1" alt="Night Scene" /></td>
<td><img src="image2" alt="Sky" /></td>
<td><img src="image3" alt="Landscape" /></td>
<td><img src="image4" alt="Still Life" /></td>
</tr>
<tr>
<td>IMF [10]</td>
<td><img src="image5" alt="Night Scene" /></td>
<td><img src="image6" alt="Sky" /></td>
<td><img src="image7" alt="Landscape" /></td>
<td><img src="image8" alt="Still Life" /></td>
</tr>
<tr>
<td>BDG [11]</td>
<td><img src="image9" alt="Night Scene" /></td>
<td><img src="image10" alt="Sky" /></td>
<td><img src="image11" alt="Landscape" /></td>
<td><img src="image12" alt="Still Life" /></td>
</tr>
<tr>
<td>Proposed Method</td>
<td><img src="image13" alt="Night Scene" /></td>
<td><img src="image14" alt="Sky" /></td>
<td><img src="image15" alt="Landscape" /></td>
<td><img src="image16" alt="Still Life" /></td>
</tr>
</tbody>
</table>

Fig. 17. Simulation results for a low-luminance image (night scene), a high-luminance image (sky), a high-contrast ratio image (landscape), and a colorful image (still life).
26.6%, and 30.0% backlight power was saved in low-luminance, high-luminance, high-contrast, and colorful images, respectively. The backlight power-saving ratio was small, and the image quality depended on the input images. In the proposed method, 20.3%, 9.5%, 41.7%, and 36.7% backlight power was saved in low-luminance, high-luminance, high-contrast, and colorful images, respectively. The proposed method simultaneously achieved lower or equivalent power consumption and lower image distortion than the other methods.

Table 2. Comparison of backlight power-saving ratios

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<tbody>
<tr>
<td>Low luminance (night scene)</td>
<td>54.4%</td>
<td>37.0%</td>
<td>20.3%</td>
</tr>
<tr>
<td>High luminance (sky)</td>
<td>2.3%</td>
<td>8.2%</td>
<td>9.5%</td>
</tr>
<tr>
<td>High contrast (landscape)</td>
<td>43.7%</td>
<td>26.6%</td>
<td>41.7%</td>
</tr>
<tr>
<td>Colorful (still life)</td>
<td>50.9%</td>
<td>30.0%</td>
<td>36.7%</td>
</tr>
</tbody>
</table>

Fig. 18. Distribution functions of image distortion for a low-luminance image (night scene), a high-luminance image (sky), a high-contrast-ratio image (landscape), and a colorful image (still life).
5. Conclusion

LED backlight driving circuits and dimming methods for medium-sized and large LCDs are proposed for low power, low cost, and high image quality. The double loop control method, the intelligent-phase-shifted PWM dimming method, the fast-switching current regulator, and the current matching techniques are proposed to drive LEDs as LCD BLUs for medium-sized and large LCDs. The current regulation characteristics, the power efficiency, the transient characteristics, the noise characteristics, and the current matching characteristics were improved by the proposed methods and circuits. The brightness of the backlight was determined using the histogram of the local block to reduce the power consumption of the backlight without image distortion. The experiment and simulation results showed that the LED current was successfully controlled by the proposed methods for the LED backlight driving circuits, and that low power consumption was achieved with an improvement in the image quality by the proposed dimming method.

References


[Parts of this work were presented in Proceedings of IMID 2010.]