

Multistring LED Backlight Driving System for LCD Panels With Color Sequential Display and Area Control

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Abstract—In this paper, a multistring light-emitting diode (LED) backlight driving system for liquid crystal display (LCD) panels with color sequential display (CSD) and area control is proposed. In large-scale LCD panels, multistring LED backlights are required to provide sufficient back lighting. The most popular structure to achieve multistring current regulation is a current mirror. However, it cannot be applied to high-power LED (>100 mA) driving, and the number of LEDs in each string is highly limited. In the driving system, a multioutput flyback converter associated with a novel control IC is proposed to tightly regulate LED driving currents and to readily achieve CSD and area control. The proposed driving system for a 32-in LCD panel has been built, from which experimental measurements have verified that the proposed driving system has the following features: low power consumption, high power conversion efficiency, stable driving currents, and high reliability.

Index Terms—Area control, color sequential display (CSD), light-emitting diode (LED), liquid crystal display (LCD).

I. INTRODUCTION

LIGHT-EMITTING diodes (LEDs) are about to gradually substitute cold cathode fluorescent lamps as backlights [1]–[3]. In large-scale LCD panels, multistring LED backlights are required to provide sufficient back lighting. In addition, two novel display techniques, multiflashing color sequential display (MFCSD) and area control, can be achieved when multistring LED backlights are adopted. In [4], the advantages of a single-string LED backlight driving system for LCD panels with CSD have been presented. However, a single-string LED driver cannot be applied to multistring LED backlights. In this paper, a multistring LED backlight driving system for LCD panels with CSD and area control is proposed.

CSD can be implemented by two methods, of which one is one-flashing CSD (OFCSD), and the other is MFCSD [5]. With OFCSD, a frame is decomposed into red–green–blue (RGB) subframes, which are sequentially displayed at short time intervals so as the human eye cannot perceive the timing latency. By adopting OFCSD, power consumption can be significantly

reduced due to removal of their color filters [6], [7]. However, LED backlights and their driving circuit should be overdesigned since their peak power is much higher than their average due to extremely short LED turn-on times. MFCSD was proposed to alleviate this limitation. With the MFCSD, a backlight panel is partitioned into several horizontal areas, and they take turns emitting light. Thus, LEDs with a lower current rating can be adopted, or the number of LEDs can be reduced.

In addition, an area control is introduced to further reduce power consumption and increase the dark–bright contrast ratio. With a conventional display technique, the brightness of an LCD panel is only controlled by twisting the conduction angles of liquid crystals. On the other hand, with the area control, the panel is partitioned into several areas, and the backlight brightness of each area can be individually controlled. With this approach, the contrast ratio of LCD panels can be improved to around 8 000 000:1, and the power consumption can be reduced by 10%.

The most popular structure of the existing LED driver ICs is a current mirror. LED strings are directly connected to the ICs, and the current mirrors in the ICs regulate LED driving current. In addition, burst-mode dimming can be achieved by controlling the duty ratio of the current mirrors. However, there exist some limitations.

- 1) The efficiency of the current mirrors drops with a driving current increase; thus, the existing driver ICs are only suitable for low-power LED applications.
- 2) The number of LEDs in each string is highly limited since the driving voltage almost directly imposes on the driver ICs.
- 3) If there are too many LEDs in short circuit, the driver ICs must block a high voltage, which will result in a thermal problem.

In this paper, a novel control IC is proposed to alleviate the limitations. In the proposed driving circuit, there is an external active switch in series with each LED string, and the control IC will achieve burst-mode dimming, current regulation, and protection features.

In the paper, the operation of the proposed driving system is described in Section II. In Section III, the design and practical consideration is addressed. Experimental results are presented in Section IV, and conclusions are given in Section V.

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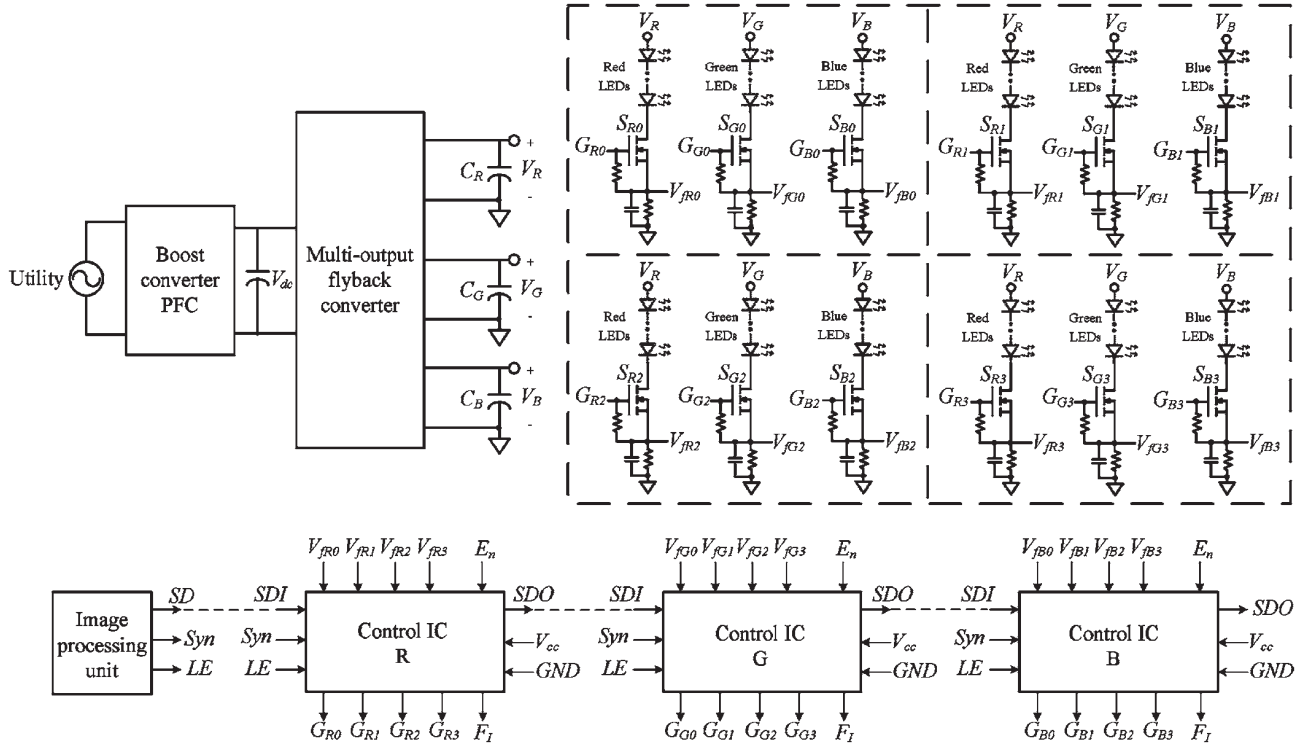


Fig. 1. Block diagram of the proposed LED backlight driving system with CSD and area control.

II. OPERATION OF PROPOSED SYSTEM

The proposed multistring LED backlight driving system, as shown in Fig. 1, consists of a boost converter for power factor correction (PFC), a multioutput flyback converter, RGB LED arrays with switches (S_{R0} , S_{G0} , etc.), and the proposed control IC. In this section, the emphasis is on the operation of the driving system and the proposed control IC, which are briefly explained as follows.

A. Driving System

As shown in Fig. 1, the panel is partitioned into four areas, and their brightness can be individually controlled. The proposed system adopts a burst-mode dimming approach, and its conceptual LED driving current waveforms are shown in Fig. 2, in which f_{BM} is the frame rate of the LCD, I_{R0} is the current flowing through S_{R0} , I_{G1} is the current flowing through S_{G1} , and so forth. In Fig. 2(a), LEDs with different colors are sequentially turned on to achieve OFCSD, and the on-time intervals of LEDs with the same color can be individually controlled to achieve an area control. In Fig. 2(b), $N_0 \sim N_3$ are the first time intervals for scanning the panel in area 0 ~ area 3, $N_0 + 1 \sim N_3 + 1$ are the second time intervals for scanning the same area, and so forth. With the MFCSD, the backlight in each area can be turned on after the panel in the corresponding areas is scanned. Thus, the turn-on time can be extended, and the peak power can be significantly reduced.

To individually drive RGB LED arrays, a multioutput converter has to be adopted, such as a flyback, forward, push-pull, half-bridge, or full-bridge converter. In those converters, there is an LC filter at the output side, except for the flyback con-

verter. With the LC filter, the output voltages will rise under a no-load condition, and it will induce current spikes through LED strings during switch turn-on transition. Without the LC filter, the output voltages can be maintained under the no-load condition because they are limited by the turn ratio among the output windings. Thus, the voltage-rising and current-spike problems can be alleviated by adopting a multioutput flyback converter. An LCD panel with CSD requires its RGB backlight driver to alternatively operate under the no-load condition. To achieve CSD, a multioutput flyback converter is a better choice. A forward converter and a flyback converter are simulated to verify the discussion. Fig. 3 shows the simulated output voltage and current waveforms, illustrating that the cross regulation of a flyback converter is better than that of a forward converter. Thus, a multioutput flyback converter is adopted in the proposed backlight driving system.

As shown in Fig. 1, the PFC stage accommodates a universal line input, shapes its input current, and regulates dc-link voltage V_{dc} to be around 400 V. The multioutput flyback converter fulfills a step-down conversion and governs the driving voltages of LED arrays. In the multioutput flyback converter, the leakage inductance of the primary winding of the transformer will induce voltage spikes across the active switch at its turn-off transition, whereas those of the three output windings will induce voltage spikes across the output diodes at their turn-off transition. The spikes will reduce power conversion efficiency and impose a higher component stress. With an active-clamp circuit, the energy trapped in the leakage inductance of the primary winding can be recycled, and the voltage spikes across the active switch can be suppressed [8]–[17]. Moreover, the leakage inductance of the primary winding acts as the resonant

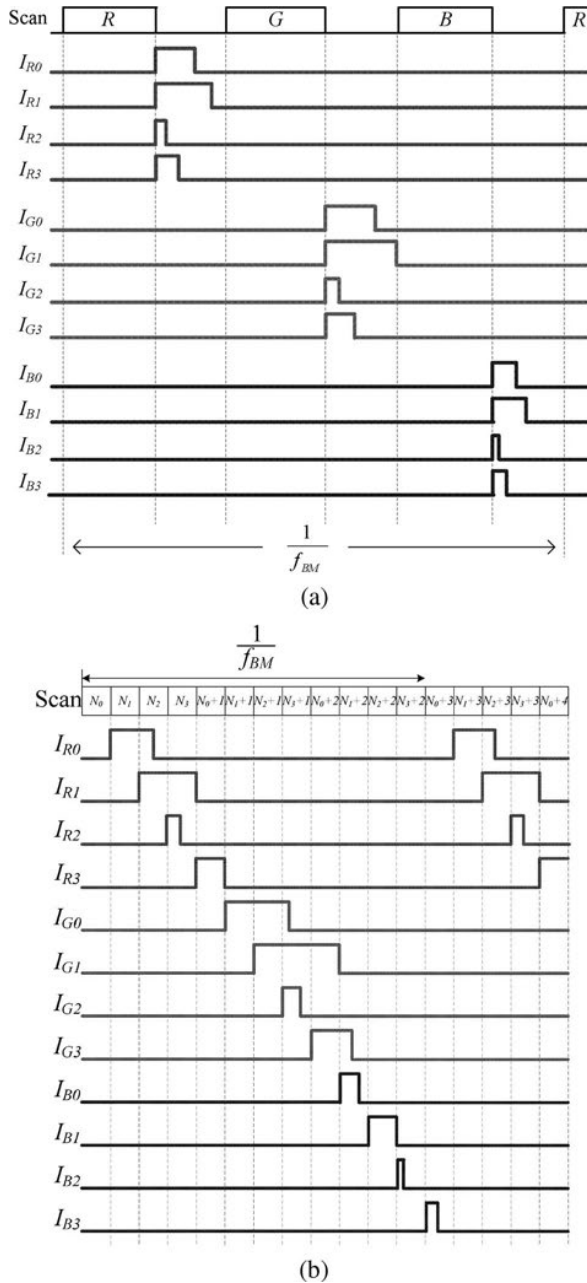


Fig. 2. Conceptual LED driving current waveforms for LCD with area control and (a) OFCSD and (b) MFCSD.

inductor in the active-clamp circuit, so it is not necessary to minimize the leakage inductance at the primary winding. However, it still needs to minimize the leakage inductance at the secondary windings to reduce voltage ringing. In this paper, an active-clamp circuit is adopted to suppress voltage spikes on the active switches and improve power conversion efficiency.

The active-clamp circuit, as shown in Fig. 4, is composed of an auxiliary switch S_2 , a resonant inductor L_r , and a clamping capacitor C_{clamp} . Switches S_1 and S_2 are driven in an asymmetrical complementary manner with a dead time to achieve a zero-voltage-switching (ZVS) feature. When S_1 is turned on and S_2 is turned off, the input current flows through

L_r , L_m , and S_1 . When S_1 is turned off, L_m is discharged through transformer T_1 and output diodes D_R , D_G , and D_B to the load. Meanwhile, L_r resonates with C_{r1} and C_{r2} to release its trapped energy. When the voltage across C_{r2} drops to zero, the body diode of S_2 is forced to conduct, and then, the energy trapped in L_r is recycled to C_{clamp} . After a quarter of the resonant period of L_r and C_{clamp} , capacitor C_{clamp} begins to release its stored energy through S_2 , T_1 , and the output diodes to the load. With this operation, the energy trapped in the leakage inductance of T_1 is recycled, and voltage spikes imposed on S_1 are suppressed. In addition, the body diodes of the active switches are forced to conduct before their corresponding switches are turned on. Hence, ZVS features for both primary and auxiliary switches are achieved.

B. Current Regulation and Area Control IC

To achieve CSD, area control, and constant-current driving, a control IC is proposed to receive the signals from the image processing unit and provide the gate driving signals for the switches (S_{R0} , S_{G0} , etc.). Fig. 5 shows its functional block diagram, and it mainly includes error amplifiers (EAs), comparators (Coms), D flip-flops, transmission gates, a buffer register (BR), and a working register (WR). The BR is a 4-b series-input parallel-output shift register. Fig. 6 shows a set of conceptual timing diagrams of the proposed IC, from which it can be seen that the BR receives the serial data input (SDI) and a synchronization (Syn) signal from the image processing unit and correspondingly shifts. The WR receives the control signals from the BR and the latch (LE) signal from the image processing unit and then controls the transmission gates. With this approach, the duty ratio of the switches (S_{R0} , S_{G0} , etc.) can be individually controlled, and CSD and area control can be achieved.

The other major feature of the proposed control IC is multi-LED-string current regulation. LED arrays should be driven by constant current to emit constant light intensity and avoid thermal runaway. The variable resistance of the active switches (S_{R0} , S_{G0} , etc.) are utilized to regulate the LED driving current, whereas the power converter provides constant-voltage sources V_R , V_G , and V_B . The switches are operated at their saturation regions under normal conditions. When a single LED is in short circuit, the current will go beyond its current rating so that through a negative feedback, the gate voltage will be reduced to drive its corresponding switch to a saturation region. Thus, multi-LED-string current regulation can be achieved. However, if there are too many LEDs in a string in short circuit, the switch must block a higher voltage. Since the switch is operated in the saturation region, an operating current flowing through the switch will result in a thermal problem. If the switch is burned out and is in short circuit, its associated LED string might be damaged. Hence, it is necessary to protect the switches. When one of the feedback voltages is higher than the threshold voltage V_p , the output voltage of its corresponding comparator will go to a high level, causing the inverting output of its corresponding D flip-flop to drop to a low level. Thus, the output of the AND gate also drops to a low level, and the transmission gate is turned off. The channel is therefore shut down, and the failure

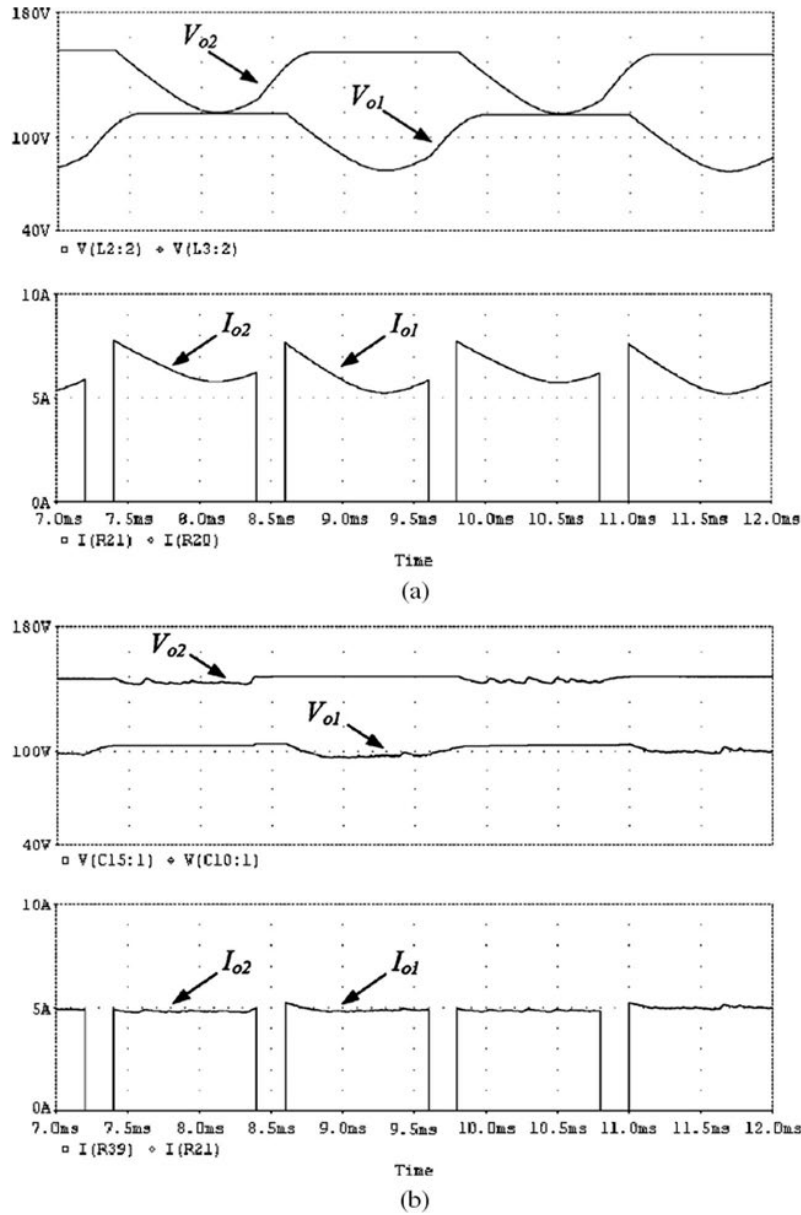


Fig. 3. Simulated output voltage and current waveforms of (a) a forward converter and (b) a flyback converter.

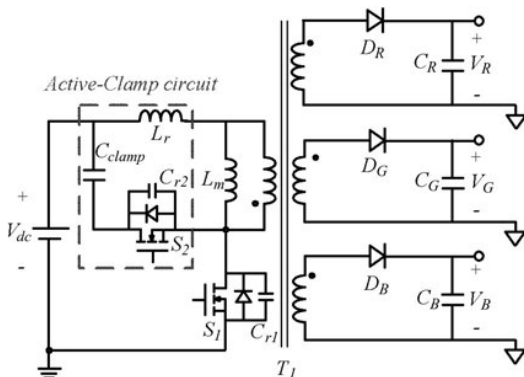


Fig. 4. Multioutput flyback converter with an active-clamp circuit.

indication signal (F_I) will not be pulled low until the supply voltage V_{cc} is reset. With this approach, switch protection can be achieved, and the reliability of the system can be improved.

In addition, the proposed IC is expandable by connecting the serial data output (SDO) pin to the SDI pin of its next IC when the number of areas is larger than the number of channels in the control IC, and it is suitable for various kinds of LED backlights, such as white LED, RGB LED, and sequential color LED backlights.

III. DESIGN AND PRACTICAL CONSIDERATION

In a practical circuit design, determining component values, designing current regulation circuits, and realizing thermal

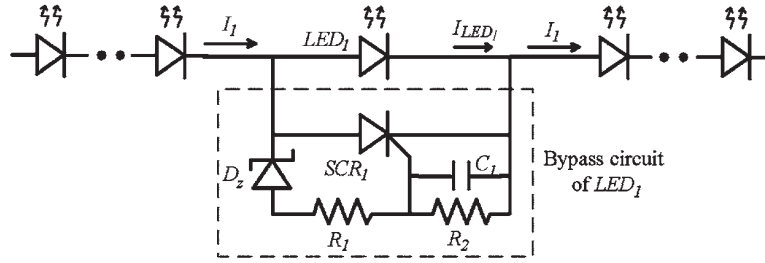


Fig. 8. LED bypass circuit.

red, green, and blue LED arrays, respectively. Substituting the specifications into (4) yields the curves showing the relationship between P_d and R for different numbers of areas (N), and they are illustrated in Fig. 7. Considering the power dissipation and SNR, $3\text{-}\Omega$ sensing resistors are adopted; thus, P_d is lower than 0.3 W when the panel is partitioned into six areas.

During turn-off intervals of the switches ($S_{R0}, S_{R1}, \dots$, etc.), the output voltage of the EA is almost equal to V_{cc} since the feedback voltage is zero. It will induce current spikes at the next turn-on transition when the switches are operated in saturation regions. To alleviate this problem of current spikes, the supply voltage of the EA is synchronously controlled with the corresponding transmission gate. With this approach, the output voltage of the EA is zero when its corresponding switch is turned off, whereas it will rise when its corresponding switch is turned on. Thus, current spikes can be avoided, and system reliability can be improved.

C. Thermal Protection Circuit for Switches

LED failure conditions can be divided into two types, open circuit and short circuit. A bypass circuit was proposed in [4], which is redrawn and shown in Fig. 8. It offers an alternative current path during a single LED failing to conduct current, and it can prevent a whole LED string from becoming an open circuit. Under normal conditions, the voltage across D_z does not reach its breakdown voltage, so the current flows through LED_1 . If LED_1 fails to conduct current, the voltage across D_z will increase and finally reaches its breakdown voltage. At the beginning, current I_1 will flow through D_z , R_1 , and R_2 and charge C_1 . Once the voltage of C_1 is high enough to trigger SCR_1 , current I_1 will flow through SCR_1 and prevent the LED array from becoming an open circuit. When a single LED is in short circuit, the gate voltages of the switch, as shown in Fig. 9, will be controlled, so the switch will operate at the saturation region and regulate the driving current. Hence, the proposed system can regulate the LED driving current even when LEDs failed in either open- or short-circuit condition. However, if too many LEDs (> 3 LEDs) are in short circuit, the switches must block higher voltages while also allowing the LED current to flow through, which will result in thermal problems. For this reason, a thermal protection circuit, shown in Fig. 9, has been adopted to protect the switches. In the figure, the resistance of the negative temperature coefficient (NTC) resistor varies with the temperature. When the temperature goes beyond its rating, Zener diode ZD_{R0} will break down, and SCR_{R0} will

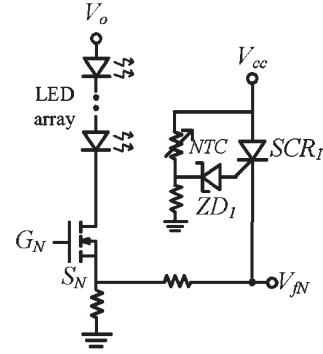


Fig. 9. Thermal protection circuit for a current regulation switch.

be triggered, pulling V_{fR0} to V_{cc} , which is higher than the threshold voltage V_p . The corresponding switch is therefore shut down, and the failure indication signal F_I is pulled up. Thus, the switches can be protected, and the reliability of the system can be significantly improved.

IV. EXPERIMENTAL RESULTS

A multistring LED backlight driving system for a 32-in LCD panel with CSD and area control, as shown in Fig. 10, was implemented to verify the theoretical analysis. The backlight is partitioned into six areas, and each of them includes only one LED string composed of 40 RGB three-in-one LEDs. The system has been designed according to the following specifications:

- dc-link voltage : 400 V_{DC} ;
- LED driving currents: 275 mA ;
- switching frequency: 50 kHz ;
- burst-mode dimming frequency: 60 Hz .

The components of the power stage were designed as follows:

- S_1 and S_2 : FS7KM-16A;
- C_R , C_G , and C_B : $220\text{ }\mu\text{F}$;
- T_1 core: EI-33;
- D_R , D_G , and D_B : HFA08TP120;
- N_P : N_R : N_G : $N_B = 32 : 19 : 30 : 29$;
- LED arrays: Edison EDERTB-1LC6 $\times$ 240;
- $S_{R0}, S_{G0}, \dots, S_{B5}$: IRL510;
- C_{clamp} : 330 nF ;
- L_r : $50\text{ }\mu\text{H}$.

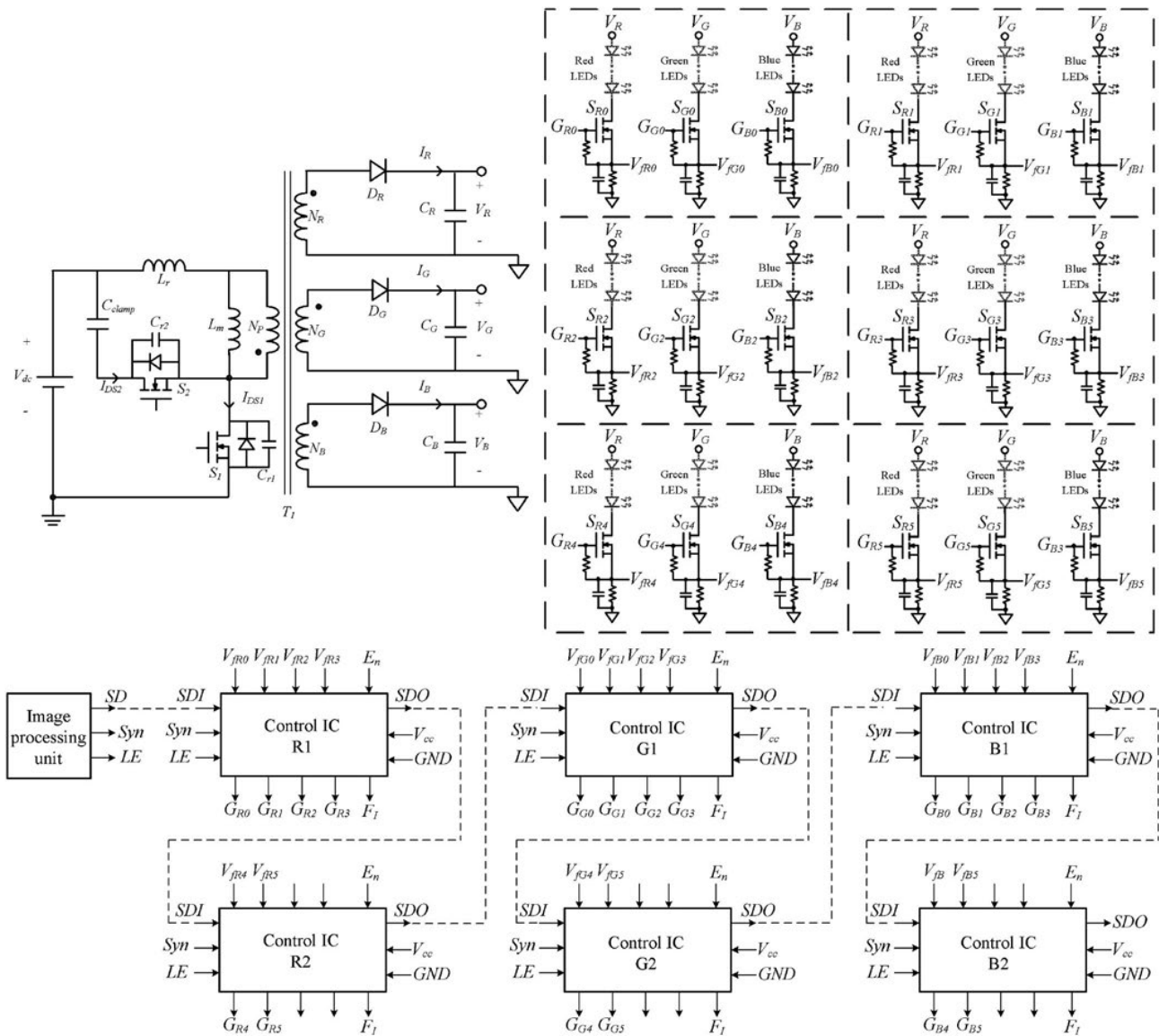
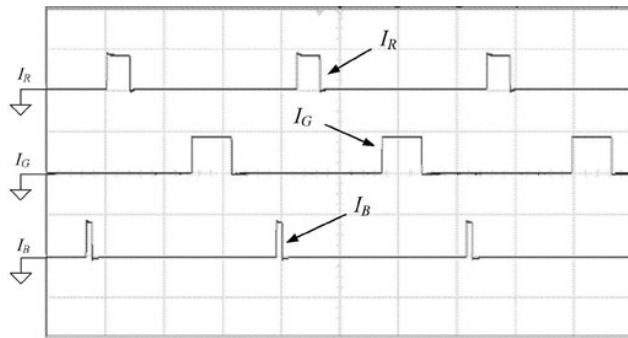
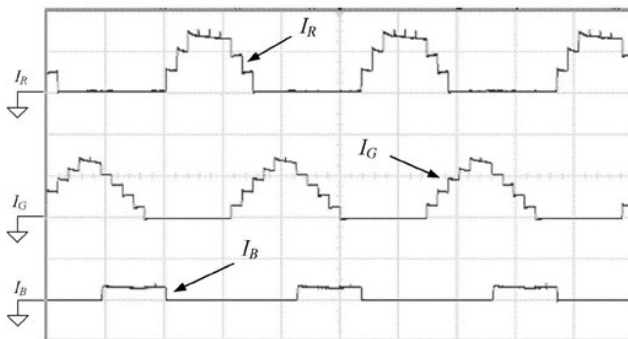
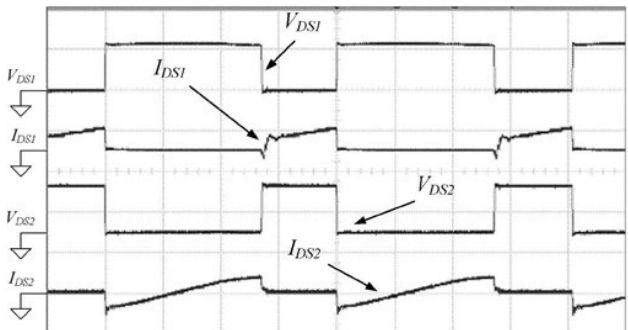


Fig. 10. Proposed LED backlight driving system with CSD and area control.

Fig. 11 shows measured waveforms of LED driving currents to illustrate that the CSD techniques can be achieved. Fig. 12 shows measured waveforms of drain-source voltage and current to illustrate that ZVS features of both primary and auxiliary switches can be achieved and the voltage spikes can be suppressed. Fig. 13 shows voltage waveforms of SDI, W_0 , W_1 , and W_2 to illustrate that the area control can be achieved by utilizing the SDI signal. The curves showing the driving current of each LED string are illustrated in Fig. 14, and it can be seen that the current variation is lower than 1.8% of the rated driving current, and the LED-string current regulation can be achieved. Fig. 15 shows current and voltage waveforms during switch S_{R0} shut-down transition, from which it can be observed that thyristor voltage V_{SCR} drops to around 1.5 V, which is its forward voltage, and LED driving current I_{R0} drops to zero. It illustrates that a protection for switches can be realized, and system reliability can be improved.

Table I shows the power consumption on several kinds of 32-in LCD backlight with 500 cd/m². The power consumption on LED backlight for LCDs with CSD is less than 60 W, but its peak power is as high as 250 W when OFCSD is adopted. By adopting MFCSD, its peak power can be reduced to around 120 W, and the cost can be, therefore, significantly reduced. By adopting an area control, the power consumption on sequential color LED backlight can be further reduced to 53.8 W. Fig. 16 shows efficiency measurements of the proposed system, from which it can be seen that the maximum efficiency can reach as high as around 94%. The color gamut measured by color analyzer KONICA MINOLTA CA-210 is 118% of NTSC, as shown in Fig. 17, in which the inner solid triangle represents 100% of NTSC, and the outer triangle with white solid line represents the color gamut of the panel with LED backlight. Hence, the proposed system is relatively feasible for a 32-in LCD TV, which has been verified by the experimental results.

(a) (I_R , I_G and I_B : 2 A/div, Time: 5 ms/div)(b) (I_R , I_G and I_B : 500 mA/div, Time: 5 ms/div)Fig. 11. Measured waveforms of LED driving current I_R , I_G , and I_B illustrating that the (a) OFCSD and (b) MFCSD techniques can be achieved.(V_{DS1} and V_{DS2} : 500 V/div, I_{DS1} and I_{DS2} : 5 A/div, Time: 5 μs/div).Fig. 12. Measured waveforms of drain-source voltages V_{DS1} and V_{DS2} and current I_{DS1} and I_{DS2} illustrating that ZVS features of both primary and auxiliary switches can be achieved and voltage spikes can be suppressed.

V. CONCLUSION

In this paper, a multistring LED backlight driving system for LCD panels with CSD and area control has been proposed. By adopting CSD, power consumption can be significantly reduced due to removal of its color filter. When adopting MFCSD, the peak power of LED backlight and its driving circuit can be reduced by 50%. Additionally, by adopting an area control, power consumption can be further reduced by 10%, and the dark-bright contrast ratio can be improved up to 8 000 000:1.

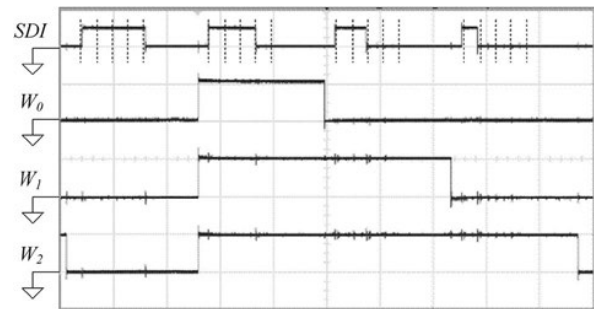
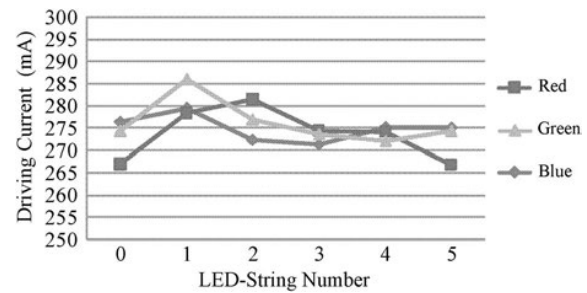
(SDI: 10 V/div, W_0 , W_1 , and W_2 : 5 V/div, Time: 10 μs/div)Fig. 13. Measured waveforms of signals SDI, W_0 , W_1 , and W_2 illustrating that the area control can be achieved.

Fig. 14. Plots of measured driving currents of the six LED strings in each color.

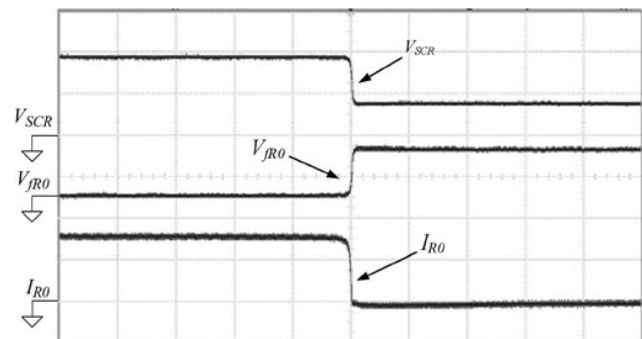
(V_{SCR} and V_{fR0} : 2 V/div, I_{R0} : 200 mA/div, Time: 50 μs/div)Fig. 15. Measured waveforms of voltage V_{SCR} , V_{fR0} and current I_{R0} illustrating the transition at S_{R0} shutdown.

TABLE I
LIST OF POWER CONSUMPTION ON 32-in LCD
BACKLIGHTS WITH 500 cd/m²

	CCFL	LED	LED with CSD	LED with CSD and area control
Power consumption (W)	96	161.5	59.8	53.8

In the proposed driving system, the power conversion efficiency has been improved by adopting an active-clamp circuit, and multi-LED-string current regulation has been achieved by utilizing the proposed control IC. Moreover, protection for switches has been realized, and system reliability has been

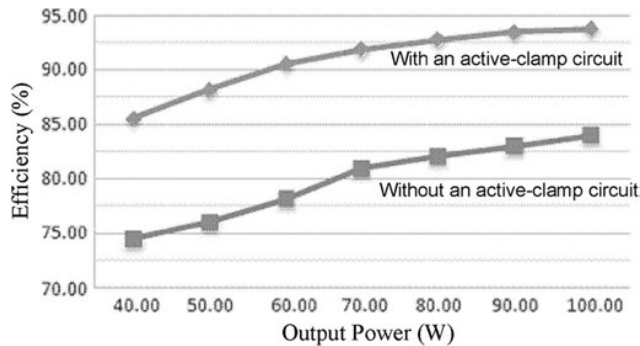


Fig. 16. Efficiency plot of the proposed driving system versus output power.

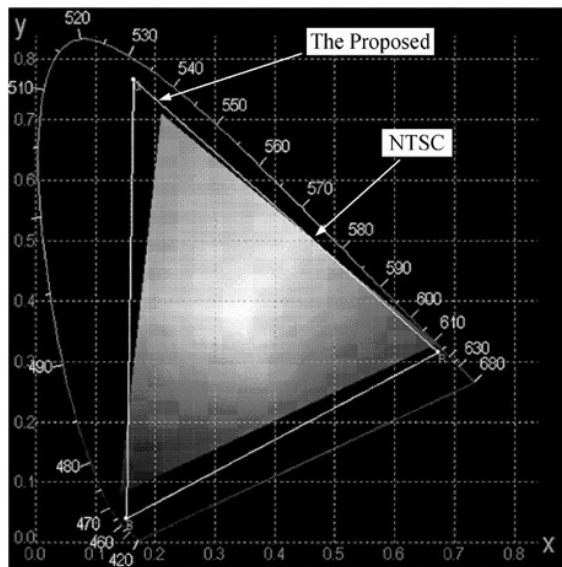


Fig. 17. Measured color gamut from the LCD panel with LED backlight in comparison to NTSC in CIE chart 1931.

therefore improved. In other words, the proposed driving system has the following features: low power consumption, high contrast ratio, high power conversion efficiency, stable driving currents, and high reliability.

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