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A novel single-inductor eight-channel light-emitting diode driver for low power display backlight applications

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Abstract: A novel decoder-based single-inductor eight-channel light-emitting diode (LED) driver circuit for low power display backlight applications has been proposed. Uniform brightness in the display provides better picture clarity, which can be achieved by providing uniform DC currents to all channels in the backlight arrangement. Existing systems use individual current regulators for each channel, which fails to provide uniform current to individual channels. Instead, uniform current is provided to all eight channels in the proposed system as the same current is distributed to all channels using time-multiplexing by a 3 $\times$ 8 decoder and a 3-bit binary up-counter. A digital pulse width modulator is used in the existing system, which has unwanted switching activities and electromagnetic interference (EMI). Unwanted switching activities and EMI are completely eliminated in the proposed system by applying a novel switching technique. The proposed LED driver is designed and implemented using the 180-nm CMOS process. Each channel is designed to conduct 300 mA of current through it when the supply is 12 V. The proposed LED driver consumes total power of 8.746 W at 27 $^\circ$C while the peak power efficiency is 96.26%. The minimum current balancing error of the proposed LED driver is 0.019%, whereas it is 0.12% for the existing system. The existing method exhibits an average current balancing error of 2.04% whereas the proposed technique exhibits 1.33% as the average current balancing error, which is 34.82% less than the existing system.

Key words: Backlight, current balancing error, light-emitting diode driver, single-inductor multiple-output

1. Introduction

In recent years, light-emitting diode (LED) displays have gained more popularity because of their vital role in high-definition (HD) televisions, laptops, and smart phones. Due to their higher lumen per watt, better lifespan, fast response time, wider color capacity, and better suitable for green energy, LEDs are being used in display backlighting applications instead of compact fluorescent lights [1–4]. When the display size is larger, multiple-channel LED drivers are used to supply uniform currents to all channels to achieve the best picture clarity. The brightness of the LED string depends on the current flows through them; hence, it is mandatory to supply uniform current through all channels in the display backlight arrangement. Multichannel LED drivers are used to achieve uniform current in all channels [5–7]. A single-inductor eight-channel DC-DC boost converter is designed to supply a total current of 300 mA in the proposed system, which is circulated to all channels based on the time-division multiplexing access method. This provides uniform distribution of current to all eight channels so that uniform brightness is achieved in the proposed system. The conventional individual current regulator-based LED driver is depicted in Figure 1. The channel current in each channel is controlled by the

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dedicated individual current regulator of each channel in the conventional LED driver. The individual current regulator in each channel fails to supply uniform current in all channels because of temperature and process variations. This causes more current balancing error and the current distribution in the existing conventional LED driver with individual current regulator is not uniform. Hence, the clarity of the picture is affected by the existing LED drivers. In the conventional individual current regulator-based LED driver, the turn-on voltage of the LED is more sensitive to the process. The resistors connected in each channel are more sensitive to temperature. Hence, the current in each channel is not uniform and moreover the variations cause more voltage fluctuations in the existing LED driver, which in turn consumes more power. Hence, the power efficiency is degraded in conventional LED drivers.

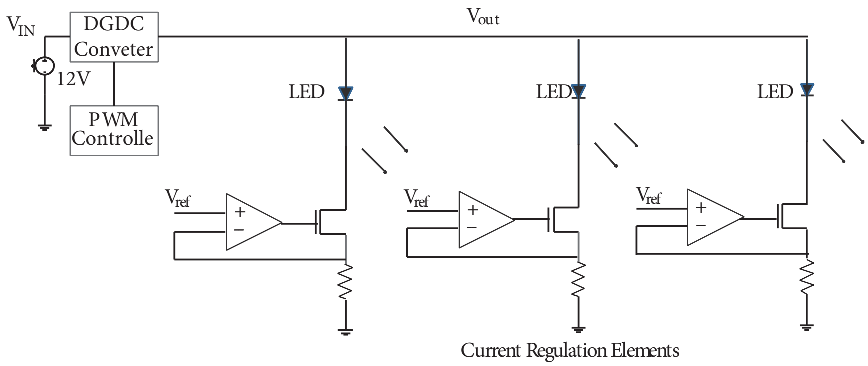

Figure 1. Conventional LED driver with individual current regulator [3].

Uniform current distribution is mandatory to achieve uniform brightness and better clarity of picture in the latest display panels for HD televisions, laptops, and smart phones. Hence, the single-inductor multiple-output (SIMO) DC-DC boost converter plays a vital role in the latest large display backlight applications to provide better picture clarity with uniform brightness. Since the SIMO boost converter topology distributes the uniform current to all channels based on the time-division multiplexing method, the total current balancing error is very small and the voltage fluctuation is also eliminated. This paper proceeds as follows. Section 2 identifies similar works on display backlighting. Section 3 discusses the proposed technique and the simulation results are analyzed in Section 4. The conclusion of the paper is presented in Section 5.

2. Related works

Various types of SIMO topology-based boost converters are used to achieve uniform current distribution to all channels [8–13]. An extended source-based direct LED display backlighting technique was used to provide uniform current [14]. An auto-zeroed integrator-based accurate current control technique was implemented to provide uniform current with better power efficiency [15]. A dual mode current control with dimming control and current balancing was designed and used for display backlighting applications [16]. A feedback reversing technique with extended resources for uniform illumination for directly lit backlighting was tested [17]. An improved uniform dimming with fast response time for an eight-channel LED driver was designed and analyzed for backlighting [6]. A single time-shared control loop-based SIMO dimmable LED driver with uniform current distribution was discussed [4]. A digitally controlled boost LED driver for low power display backlighting was exhibited [18]. The use of DC/DC drivers in an active power distribution management application for electric vehicles was illustrated [19]. Frequency modulation (FM) technique-based EMI reduction was proposed [20].

A SIMO-based LED driver using a current balancing technique is shown in Figure 2. The SIMO boost converter-based LED driver drives three channels with individual channel current of 300 mA and supply voltage of 12 V. As soon as the LED driver is switched ON, the inductor in the boost converter is charged. During the ON time of the square wave, current is allowed to flow, which is driving the gate terminal of transistor S_M. During the OFF time of the gate driving, transistor S_M is in cut-off state and the total current through the inductor is supplied to the first channel through transistor S_1. The same thing is repeated to the second and third channels by S_2 and S_3, respectively. This SIMO-based boost converter is designed to work in continuous conduction mode and it supplies the total current to all three channels one by one in one switching period. The SIMO boost converter presented in [8] has a timing diagram as shown in Figure 3. In each switching period of the boost converter, one additional unwanted switching is present in the existing LED driver. The unwanted switching is repeated every 10.66 μs since the switching frequency of the existing LED driver is 93.75 kHz. The unwanted switching activities are circled in red color. For example, if the existing LED driver is operated for 1 h, it causes about 3.38×10^8 unwanted switching activities. The unwanted switching sequence in the existing LED driver dissipates one $CV^2 f\alpha$ J of energy per switching cycle. For 1 h of operation, it dissipates $3.38 \times 10^8 \times C \times V^2 \times f \times \alpha$ J of energy. Here C represents the load capacitance, V represents the supply voltage, f represents the frequency of operation, and α represents the switching activity. This unwanted additional switching in each switching period causes an enormous amount of dynamic power dissipation in the existing LED driver, which in turn will heat the system and a thermal runaway situation may occur. The unwanted additional switching sequences are completely eliminated by a novel switching technique in the proposed low-power LED driver for display back light applications.

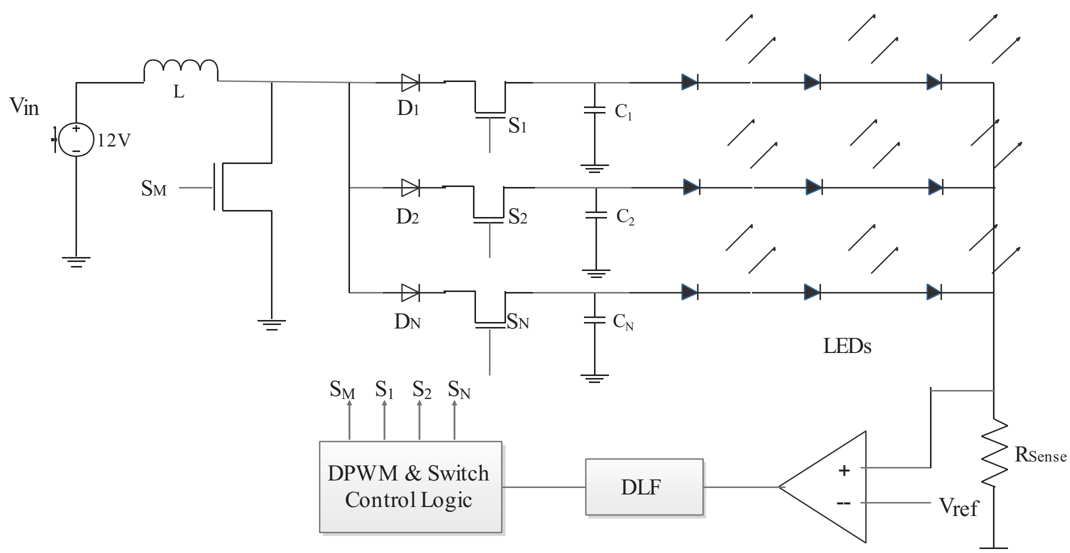

Figure 2. SIMO boost converter topology [8].

3. Proposed work

A single-inductor eight-channel low-power LED driver for portable display backlight applications is proposed in this paper. A SIMO DC-DC boost converter is used in this work. Figure 4 exhibits the timing diagram of the proposed design. The timing diagram exhibits the switching transitions of the power transistor of boost converter T_{BC} and all control transistors of all eight channels from T_1 to T_8. Time multiplexing-based uniform current distribution to all eight channels is implemented in the proposed work. While the switching transistor

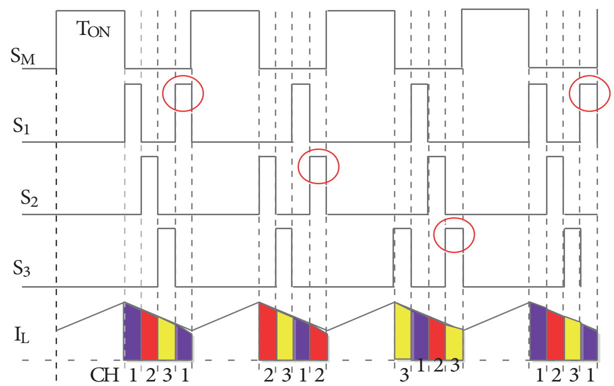

Figure 3. Timing diagram of time division multiplexed control [8].

of boost converter T_{BC} is in the ON state, the inductor is charged to the maximum current of 300 mA. During the OFF state of transistor T_{BC}, this total current is distributed to all eight channels one by one in a time-multiplexing manner. Since the currents in all channels are almost equal, the proposed system has minimum current balancing error and uniform brightness is achieved in the display panel, which in turn provides better picture clarity. The proposed boost converter uses 93.75 kHz as its switching frequency for comparing the performance metrics of the proposed LED driver with the existing LED driver. The time period of one cycle is 10.66 μs. Hence, switching transistor T_{BC} is ON for 5.33 μs and OFF for 5.33 μs. During the ON time of 5.33 μs, the inductor is charged and it delivers a total current of 300 mA to the channels. During the 5.33 μs of OFF time of switching transistor T_{BC}, the current delivered by the inductor is uniformly distributed to all eight channels based on time-multiplexing. The total current of 300 mA is provided to each channel for 0.3 μs. Transition or changeover time of 0.1 μs is provided between each channel in a cycle. A guard time of 1.1 μs is provided before starting the switching sequences of the channels and 1.1 μs is allocated after completing current distribution to all eight channels. This eliminates the unwanted glitches in the proposed LED driver, whereas in the existing LED driver [8], the current is distributed to consecutive channels by switching OFF transistor S_1 of the first channel and switching ON transistor S_2 of the second channel simultaneously. This simultaneous ON and OFF transition of the control transistors of the channels causes glitches in the existing LED driver, which in turn consumes more power, and the distributed currents will not be uniform. The changeover time between the channels in the proposed system avoids simultaneous transitions and hence the unwanted glitches are completely eliminated. The control sequence for the control transistors of the channels were generated by a complex DPWM and digital loop filter [8]. This consumes a large area and enormous dynamic power because of unwanted switching transitions occurring in each cycle. Moreover, PWM causes EMI and unwanted noise and other side effects for the existing LED driver.

The switching transistors in the proposed LED driver are controlled by the switching pattern generated by a 3 $\times$ 8 decoder, which is driven by a 3-bit binary up-counter. The power transistor of the single-inductor eight-channel boost converter is switched at the same frequency [8] to compare the performance metrics of the proposed design. Output lines of the 3-bit binary up-counter are connected to the input terminals of the 3 $\times$ 8 decoder. The output lines of the 3 $\times$ 8 decoder are connected to the gate terminals of the control transistors of each channel. The schematic diagram of the proposed glitch and EMI-free low-power LED driver is shown in Figure 5. The 3-bit binary up-counter generates the required 3-bit binary combinations from '000' to '111', which in turn drives the 3 $\times$ 8 decoder.

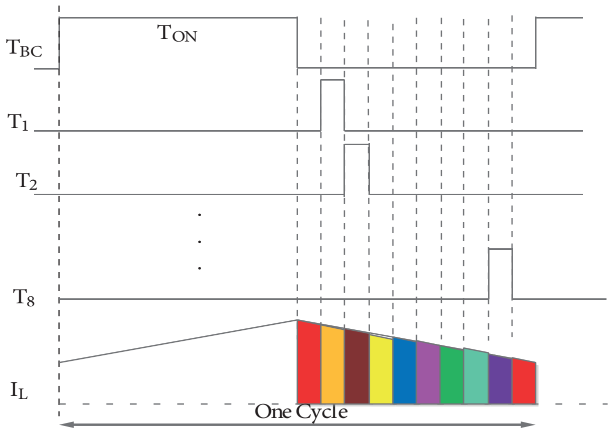

Figure 4. Timing diagram of the proposed LED driver.

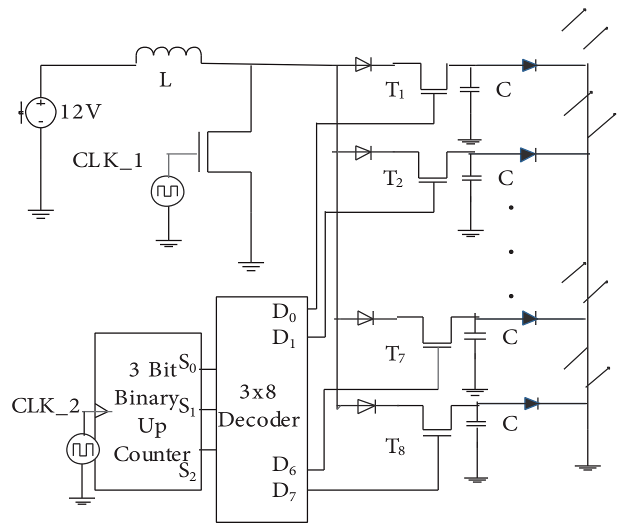

Figure 5. Schematic diagram of the proposed low-power LED driver.

The clock frequency of the 3-bit binary up-counter is set to 1.5 MHz, which is 16 times faster than the switching frequency of power transistor T_{BC} in the boost converter. This generates the required switching pattern. The status of each channel in a cycle is represented in Table 1. In the first clock of the 3-bit counter, the first channel of the LED driver is switched ON by applying binary '1' to the gate of nMOS transistor T_1. Similarly, in the consecutive clock cycles of the counter, the remaining channels are switched sequentially by transistors T_2–T_8. The average currents in all eight channels will have a relation as follows: $I_{LED1} > I_{LED2} > I_{LED3} > I_{LED4} > I_{LED5} > I_{LED6} > I_{LED7} > I_{LED8}$, since the channels of the LED driver are switched ON only during the decaying transient of the inductor current. Hence, the first channel will get the maximum current and the last channel will get the minimum current.

Table 1. Status of the individual channels of the proposed LED driver.

Clock	Present state	Next state	Status of individual channel							
			Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7	Ch8
1	000	001	**ON**	OFF	OFF	OFF	OFF	OFF	OFF	OFF
2	001	010	OFF	**ON**	OFF	OFF	OFF	OFF	OFF	OFF
3	010	011	OFF	OFF	**ON**	OFF	OFF	OFF	OFF	OFF
4	011	100	OFF	OFF	OFF	**ON**	OFF	OFF	OFF	OFF
5	100	101	OFF	OFF	OFF	OFF	**ON**	OFF	OFF	OFF
6	101	110	OFF	OFF	OFF	OFF	OFF	**ON**	OFF	OFF
7	110	111	OFF	OFF	OFF	OFF	OFF	OFF	**ON**	OFF
8	111	000	OFF	OFF	OFF	OFF	OFF	OFF	OFF	**ON**

Each channel is switched only one time in a cycle, which avoids the unwanted additional switching, whereas in the existing LED driver [8] an additional unwanted switching occurs in each switching cycle of the boost converter, which dissipates additional dynamic power as heat. The existing LED driver consumes total power of 12.4 W, whereas the proposed low-power LED driver consumes total power of 8.746 W since the glitches and the additional switching activities are completely eliminated. Hence, the proposed low-power LED driver outperforms the existing LED driver.

4. Results and discussion

The proposed single-inductor eight-channel low-power LED driver is designed and implemented in the 180-nm CMOS process. Simulation parameters used in this proposed work are listed in Table 2. The proposed LED driver is simulated using the Cadence Virtuoso Analog Design Environment (ADE) platform with Spectre as the simulator. Transient analysis and DC analysis are performed at the temperature of 27 °C to validate the proposed design. The inductor current of the SIMO LED driver is shown in Figure 6. The average inductor current is 302.57 mA. Inductor current reaches a stable state after 100 μs. The inductor is charged every 5.33 μs and similarly discharged every 5.33 μs since the frequency of operation of the boost converter is 93.75 kHz with a time period of 10.66 μs. The design value of the inductor is 1 mH and the supply voltage is 12 V. Figure 7 exhibits switching pulses of the boost converter and the individual channels. During OFF times of the switching pulse of the boost converter all eight channels are switched sequentially one by one by applying the concerned switching patterns to the control transistors T_1–T_8 from the 3×8 decoder, which is driven by a 3-bit binary up-counter. The counter changes its states every 0.66 μs, which generates the required pattern to control the channels by the decoder. Since the unwanted switching activities are eliminated, the proposed LED driver consumes a total power of 8.746 W when the supply voltage is 12 V and the temperature is 27 °C with frequency of operation of the boost converter of 93.75 kHz. The individual currents are exhibited in Figure 8. The first channel gets the maximum current of 304 mA, whereas the eighth channel gets the minimum current of 299.4 mA. The individual channel currents for one cycle are shown in Figure 9. The current balancing error in each channel with corresponding individual channel currents are listed in Table 3. The maximum current balancing error of the proposed LED driver is 0.775%, minimum current balancing error is 0.019%, and average current balancing error is 0.451%, whereas the maximum current balancing error of the existing LED driver is 2.04% and the minimum balancing error is 0.12%. The prototype of the proposed single-inductor 8-channel LED driver, which is controlled by the Xilinx Spartan-6 FPGA board, is depicted in Figure 10. The LED array has 8 channels or strings of LEDs with 9 LEDs in a string for a total of 72 LEDs in the display panel. These 8 channels or strings are controlled by the digital circuits such as a 3-bit binary up-counter and 3×8 decoder

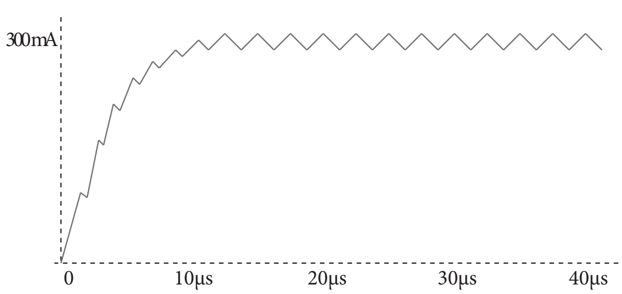

Figure 6. Inductor current of the proposed LED driver.

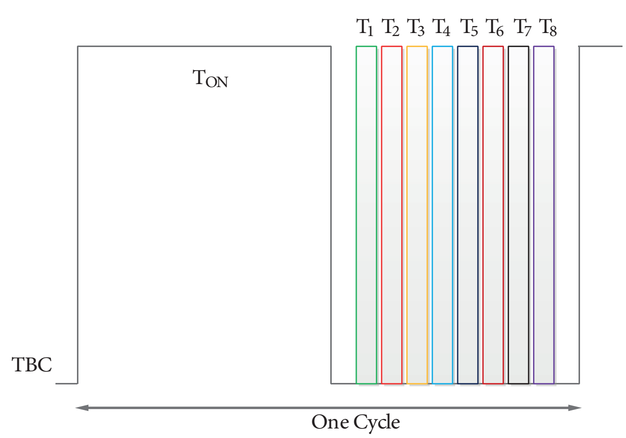

Figure 7. Control pulses to individual channel in the proposed LED driver.

modules. These digital circuits are implemented in the Xilinx Spartan-6 FPGA board. The total current is uniformly distributed to all channels or strings of LEDs in a time division multiplexing manner by the proposed system so that the proposed LED driver can be used for larger displays. The list of components used in the prototype of the proposed LED driver are displayed in Table 4. The prototype of the proposed LED driver has been realized as hardware.

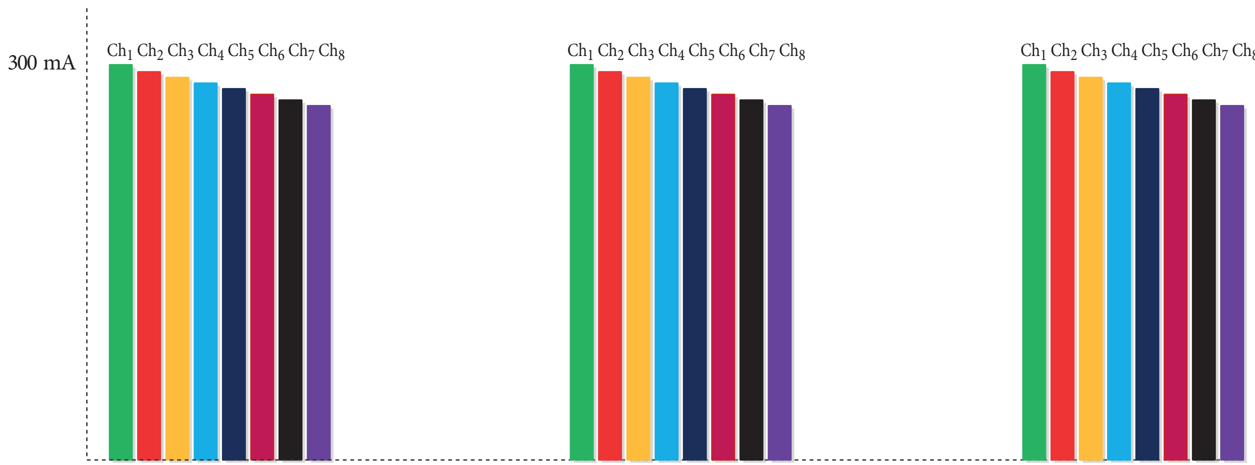

Figure 8. Individual channel currents of the proposed LED driver.

The comparative analysis of the experimental results of the proposed and existing LED drivers are listed in Table 5. The existing and proposed LED drivers were designed to deliver a current of 300 mA to each channel with supply voltage of 12 V and switching frequency of 93.75 kHz. The experimental verification of the synchronization between CLK1 (switching pulse of power MOSFET T_{BC}) and CLK2 (switching pulses of MOSFETs $T_1 - T_2$) has been performed using CRO, which is exhibited in Figure 11. The number of channels present in the existing LED driver is three, whereas the proposed LED driver has eight channels. The Spartan-6 FPGA kit consumes 0.576 W of power. The proposed LED driver has peak power efficiency of 96.26% without the Spartan-6 FPGA kit and 89.92% with the FPGA kit. The peak power efficiency of the existing LED driver without the PSoC kit is 93% and it is 85.6% with the PSoC kit.

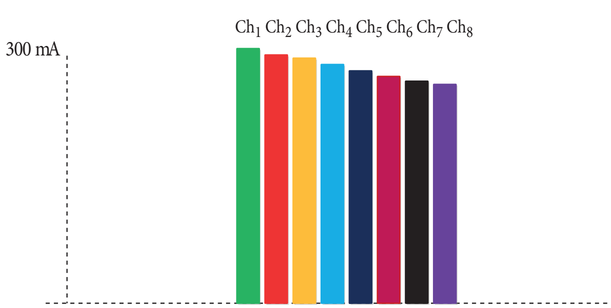

Figure 9. Individual channel currents in one switching cycle.

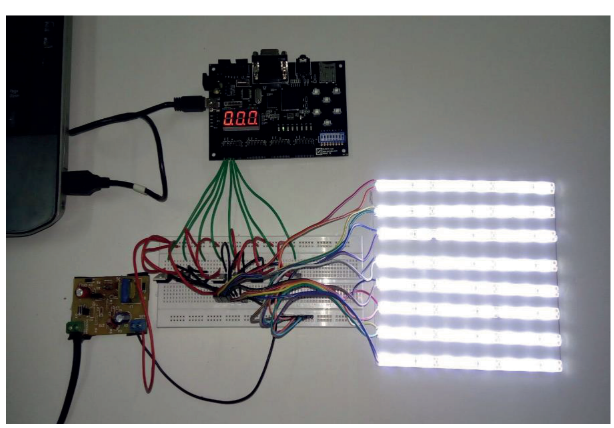

Figure 10. Prototype of the proposed single-inductor 8-channel LED driver, controlled by the Xilinx Spartan-6 FPGA board.

Table 2. Simulation parameters.

Simulation tool	Cadence Virtuoso ADE
Technology	GPDK 180 nm
Switching frequency	93.75 kHz
Counter clock frequency	1.5 MHz
Supply voltage	12 V
Temperature	27 °C
Analysis	Transient
Inductor (L)	1 mH
Capacitor (C)	10 μF

Table 3. Individual channel currents and current balancing error.

Currents	Value (mA)	Average current = 301.66 mA difference current (mA)	Current balancing error (%)
I_{ch1}	304	2.34	0.775
I_{ch2}	303.3	1.64	0.543
I_{ch3}	302.7	1.04	0.344
I_{ch4}	302.1	0.44	0.145
I_{ch5}	301.6	0.06	0.019
I_{ch6}	300	1.66	0.550
I_{ch7}	300.2	1.46	0.483
I_{ch8}	299.4	2.26	0.749

Table 4. List of components used in the prototype of the proposed LED driver.

Device	Part number	Description
Spartan-6 FPGA	XC6SLX9	Mimas V2 Spartan 6 FPGA Development Board with DDR SDRAM
Switches	IRF 540	N-channel Trench MOS transistor, 100 V, 22 A
Inductor	24S100C	1 mH, 1.6 A
Capacitor	106TTA050M	10 μF, 50 V
Diodes	DB22320	Schottky, 30 V, 1.5 A
Gate driver	FAN7382	Monolithic half-bridge gate driver IC
LEDs	CITRA GHH8987GV	White LED strip lights

5. Conclusion

A novel decoder-based digitally controlled single-inductor eight-channel low-power LED driver for display backlight applications has been presented in this paper. The switching sequences were generated by the 3-bit binary up-counter and the 3 $\times$ 8 decoder. Unwanted switching activities are completely removed in the

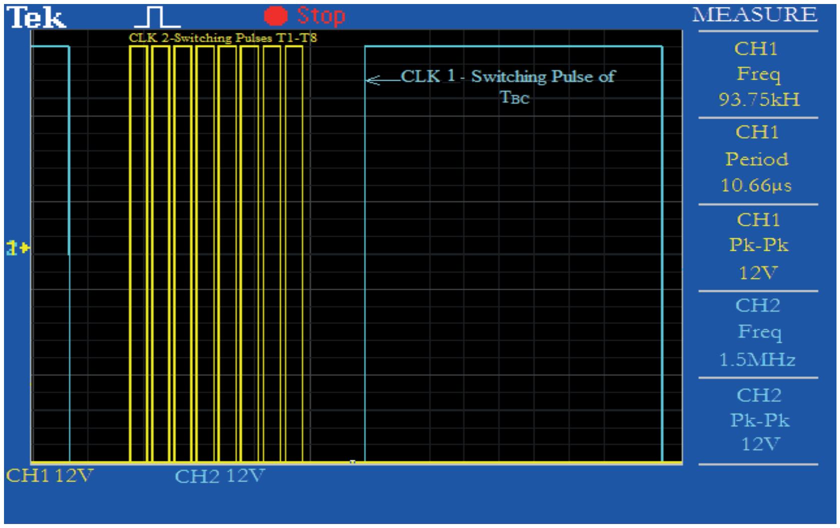

Figure 11. Experimental verification: synchronization of CLK1 and CLK2 (switching pulses of T_{BC} (CLK1) and $T_1 - T_8$ (CLK2)).

Table 5. Comparative analysis of measured experimental results.

Parameter	[8]	Proposed work
Input voltage	9–12 V	12 V
Switching frequency	93.75 kHz	93.75 kHz
Output voltage	16–23 V	24 V
Max. LED current/channel	300 mA	300 mA
No. of channels	3	8
Peak efficiency	93% w/o PSoC 85.6% with PSoC	96.26% w/o FPGA 90.13% with FPGA
Max. current balancing error	2.04%	1.33%
Min. current balancing error	0.12%	0.019%
Average current balancing error	-	0.451%

proposed LED driver, which in turn optimizes the dynamic power consumption. The proposed LED driver consumes total power of 8.746 W when the simulation is performed at 27 °C with the frequency of operation of the boost converter set to 93.75 kHz, whereas the existing LED driver consumes total power of 12.4 W. The proposed LED driver is designed to deliver current of 300 mA to each channel and the average current is 301.66 mA, which results in maximum current balancing error of 0.775% in the proposed design whereas the maximum current balancing error of the existing LED driver was 2.04%. Minimum current balancing errors of the proposed and existing LED drivers are 0.019% and 0.12%, respectively. The proposed LED driver has peak power efficiency of 96.26% without the Spartan-6 FPGA kit and 89.92% with the FPGA kit, whereas the peak power efficiency of the existing LED driver without the PSoC kit is 93% and it is 85.6% with the PSoC kit. Hence, the proposed decoder-based low-power LED driver with novel switching scheme outperforms the existing LED driver.

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