21.8 A Soft Self-Commutating Method Using Minimum Control Circuitry for Multiple-String LED Drivers

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Light-emitting diodes (LEDs) are widely used in general lightings due to their several advantages including high efficiency, high reliability, long life, and environmental friendliness. Recently, various converter-free methods for non-isolated LED drivers with multiple LED strings connected in series have been introduced, enabling both a higher efficiency and power factor (PF) as well as lower total harmonic distortion (THD) [1-3]. In multiple-string LED drivers, the efficiency and PF are enhanced as the number of LED strings increases because of a low overhead voltage. However, as the operational voltage range decreases, it is difficult to find a proper commutation time using input voltage sensing approaches due to input voltage noise and LED voltage variation [4]. Other concerns are EMI and EMC noise caused by high di/dt and dv/dt in hard commutations. When the LED current is high, negative effects of hard commutation become worse and the required di/dt control circuits are more complicated [5]. To meet EMI and EMC regulations for lightings without adding on-board EMI filters, soft commutation is essential. In order to overcome these problems, we propose a soft self-commutating method using a Source-Coupled Pair (SCP) and reference voltages. The conventional control circuits required for an appropriate commutation time and soft commutation are no longer necessary. The fabricated 6-string LED driver IC is capable of achieving high efficiency (92.2%), high PF (0.996) and low THD (8.6%) under the 22W/110V AC condition.

Figure 21.8.1 shows the circuit of the proposed LED driver, taking two LED strings as an example to explain the operation principle. It consists of a bridge diode, high-voltage n-channel MOSFET Source-Coupled-Pair (SCP) and voltage references. LEDs in Fig. 21.8.1 represent the group of series- and parallel-connected LEDs. In SCP operations, if the voltage difference between two input gates is higher than $\sqrt{2}V_{OV}$, where $V_{OV} = V_{GS} - V_T$, the high-biased transistor (M_2) carries all the current and the other (M_1) has no current. This is true only when V_{D1} and V_{D2} are available at the same time. In other words, the high-biased M_2 cannot carry the LED current while V_{D2} remains in a low voltage condition. If $V_{IN} > V_{LED1} + V_{LED2}$, V_{D2} starts to rise and M_2 takes the LED current from M_1. Therefore, the combination of an SCP with a incremental gate voltages and the LED strings in series enables self-commutation without any additional sensing circuitry.

Figure 21.8.2 shows the graphs of key node voltages and currents. The operation of the two-string LED driver can be summarized as the following, depending on V_{IN}: (1) when $V_{IN} < V_{LED1}$, M_1 and M_2 are turned off and there is no current flow. (2) when $V_{LED1} < V_{IN} < V_{LED2}$, $I_{LED1} = V_S / R_S = (V_1 - V_{GS1}) / R_S$ and $I_{LED2} = 0A$ (3) when $V_{IN} > V_{LED2}$, $I_{LED2} = V_S / R_S = (V_2 - V_{GS2}) / R_S$ and $I_{LED1} = 0A$. The input current can be expressed by $I_{IN} = I_{LED1} + I_{LED2}$ even under commutation periods.

The SCP with a incremental gate voltages not only determines the LED current in each mode but also plays an important role for self-commutation. During commutation between two adjacent modes, gradually rising and falling slopes are represented by I_{LED} since it directly depends on the slope of V_{IN} which is rectified from 50 or 60 Hz AC. The rising and falling of V_{D1} and V_{D2} make I_{LED1} and I_{LED2} turn on and off since the gates in an SCP are already biased by the reference voltage. As a result, a soft commutation can be achieved without high di/dt problems even in high current LED applications and there are no EMI and EMC issues without additional filters. These simple and explicit commutation methods enable us to easily expand the number of LED strings in series without suffering from commutation errors and EMI/EMC problems.

Figure 21.8.3 shows the schematic of an enhanced 6-string LED driver using op-amps. Since the main role of transistors in an SCP is a current source, adding operational amplifiers (op-amps) greatly improves the characteristics of the current source. The advantage of using op-amps can be summarized as follows: (1) increased line regulation of LED current due to a boosted output impedance, (2) elimination of the temperature dependence of I_{LED} caused by V_{GS}, (3) improved current separation in an SCP even with a gate voltage difference, and (4) reduced commutation time due to an amplified error voltage. One disadvantage of using op-amps is the occurrence of LED current increments during commutations when the bandwidth of op-amp is low or the frequency of the AC input voltage is high. The LED current of the nth string (I_{LEDn}) results in $I_{LEDn} = V_n / R_S$, where V_n is the nth reference voltage and the input current, I_{IN}, is the sum of all LED currents. Since $V_1 < V_2 < V_3 < V_4 < V_5 < V_6$, the reference voltage can be easily made using resistor voltage divider circuits.

The measured results of V_{IN}, V_{D6}, I_{IN}, I_{LED5} and I_{LED6} in Fig. 21.8.4 illustrate the operation of soft self-commutations under 22W input power conditions. Figure 21.8.4(a) and 21.8.4(b) show the measured waveforms using 110V AC input voltage. These results validate self-commutation and soft switching between two adjacent LED strings. There are no input current increments during the commutation. I_{LED5} and I_{LED6} exchange LED currents very smoothly even under approximately 250mA high current driving conditions. The measured waveforms using a 220V AC input voltage are shown in Fig. 21.8.4(c) and 21.8.4(d). The current slope is higher than that of 110V AC due to a higher input voltage slope and a lower LED current level.

Figure 21.8.5 shows the measured waveforms of V_{IN}, V_{D6}, I_{IN}, I_{LED5} and I_{LED6} under both start-up and high frequency input conditions. The start-up waveforms in Fig. 21.8.5(a) and 21.8.5(b) demonstrate that the proposed driver has instant start-up characteristics. It can be expected that the proposed driver IC has good compatibility with conventional dimming control schemes. The driver was evaluated under 110V/220V AC with a frequency of 1 kHz instead of 60 Hz in order to verify its high-frequency performance. Since the bandwidth of op-amps is optimized for low frequency applications, there are excessive current increments during commutation under 1kHz conditions as shown in Fig. 21.8.5(c) and (d). Undesirable current increments are severe under 220V AC conditions due to a higher input voltage slope.

The proposed 6-string LED driver has been fabricated in a 450V 1μm BCD process. The chip micrograph with an evaluation PCB is shown in Fig. 21.8.7. The chip size is 2.7×3.57mm² and six power transistors take up roughly 70% of the chip area. In the evaluation board, there is a bridge diode, driver IC and one resistor to set the LED current. This chip is designed to drive up to 22W under 110 V AC input voltage conditions and the maximum driving current of I_{LED6} is about 400mA. The measured efficiency, PF and THD are 92.2% (93.4%), 0.996 (0.995) and 8.6% (9.5%) under 110V/AC (220V/AC) conditions. Figure 21.8.6 shows the comparison table between this work and other commercialized products.

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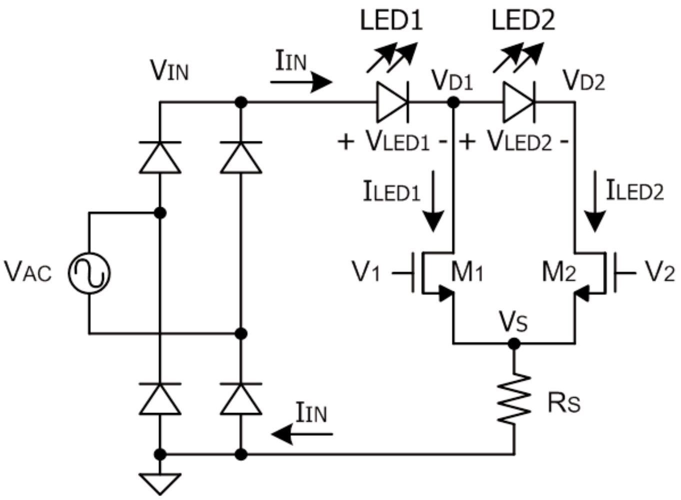

Figure 21.8.1: Schematic of the proposed 2-string LED driver for a soft self-commutation.

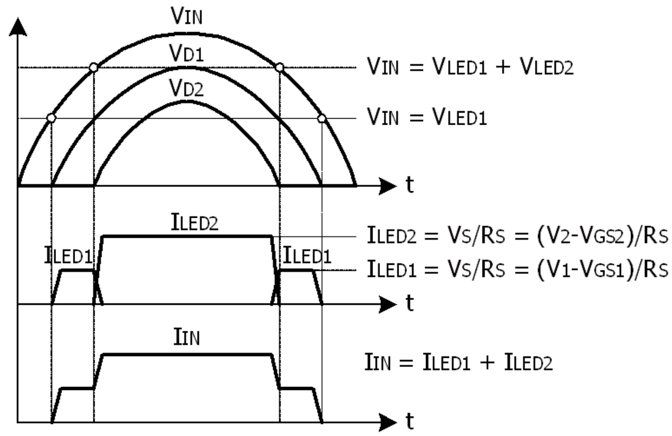

Figure 21.8.2: Timing diagram of I_{LEDs}, I_{IN}, V_{IN}, V_{D1} and V_{D2} in a 2-string LED driver.

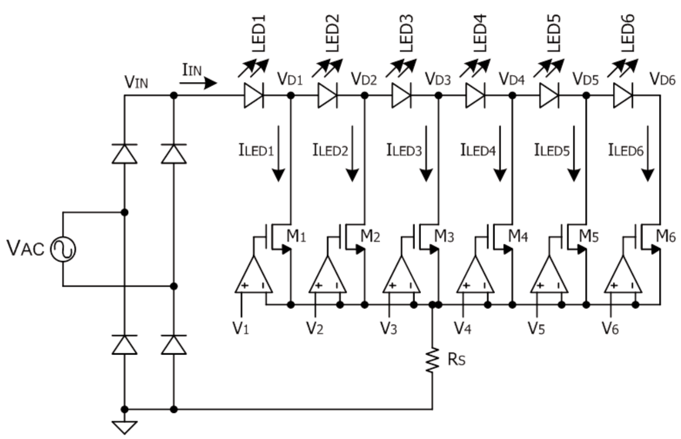

Figure 21.8.3: Schematic of an enhanced 6-string LED driver using op-amps.

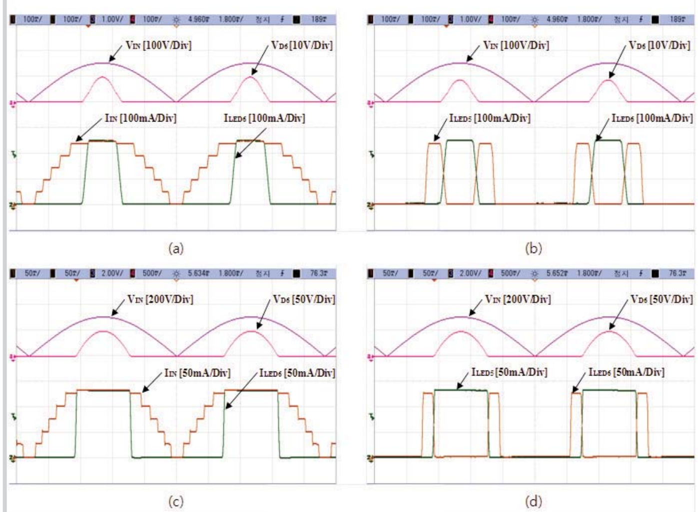

Figure 21.8.4: Measured results: V_{IN}, V_{D6}, I_{IN}, I_{LED5} and I_{LED6}. Test conditions: (a) and (b) 22W at 110V/60Hz AC, (c) and (d) 22W at 220V/60Hz AC.

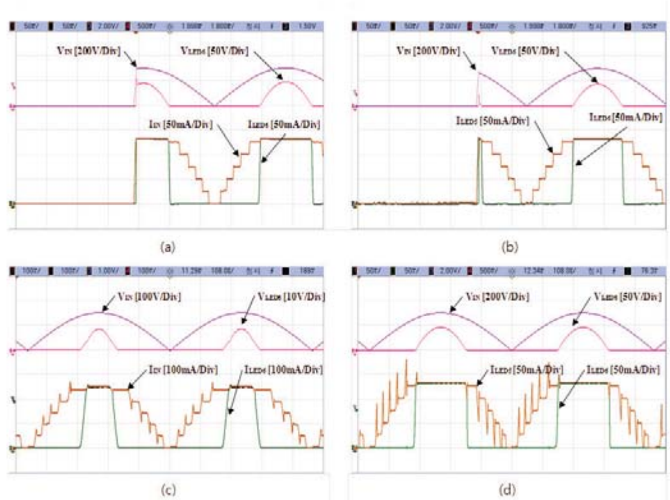

Figure 21.8.5: Measured results: V_{IN}, V_{D6}, I_{IN}, I_{LED5} and I_{LED6}. Test conditions: (a) and (b) start-up at 22W at 220V/60Hz AC (c) 22W at 110V/1kHz AC (d) 22W at 220V/1kHz AC.

Parameters	[4]	[5]	This Work
Number of LED Strings (EA)	3	6	6
Efficiency (%)	83	> 90	> 90
Power Factor	> 0.99	> 0.9	> 0.99
THD (%)	10 <	10 <	10 <
Maximum Output Current (mA)	400	115	400
Number of External Components (EA)	15	6	1
I_{LED} Line Regulation (%)	-	< 10	< 2

Figure 21.8.6: Performance comparison with recent commercial products.

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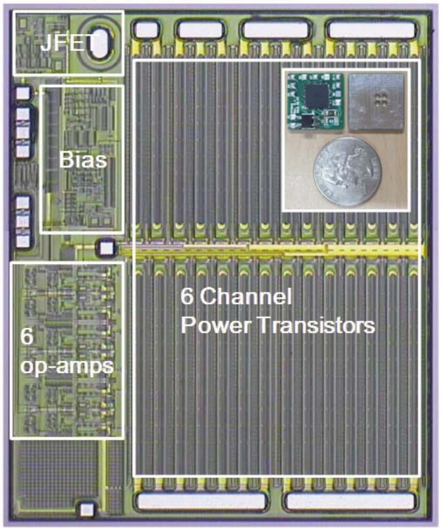

Figure 21.8.7: Chip micrograph and evaluation PCB.

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