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A new hybrid LED driver

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ABSTRACT

The ongoing challenge in light-emitting diode (LED) lighting is to integrate power and control circuits into a single chip to reduce the number and cost of components, minimize size, and enhance reliability. This integration requires a reduction in power dissipation on the chip, improved efficiency, and smaller magnetic components. Recently, hybrid LED drivers have been proposed to address this integration challenge. Unlike traditional transformerless single-stage LED drivers, which implement boost or buck topologies, hybrid drivers reduce pulsed voltage on power semiconductors. The proposed hybrid LED driver aims to prevent power switches from hard switching, which in turn reduces metal–oxide semiconductor field-effect transistor or MOSFETs' overheating in the integrated circuit body, increases the reliability of the chip, and alleviates electromagnetic interference or EMI issues. The proposed improvement to the hybrid driver is analyzed. The control method was suggested. Computer modelling was provided to confirm the feasibility, controllability and resulting advantages of the proposal. The proposed hybrid LED driver is attractive for circuit integration to reduce size and cost compared to the achievements of previous art.

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1. INTRODUCTION

The lighting market has made a revolutionary transition to light-emitting diode or LED lighting sources, driven by a sharp decline in the price of efficient and durable light-emitting diodes. In LED lamps, specialized LED drivers are used to interface LED crystals with an alternating line voltage and protect them from transient processes in the grid. Today, the traditional LED driver has become an expensive part than the high-tech LEDs in a lighting device as a result of the continued price reduction of LED crystals. A driver is a complex electrical device, and its price cannot be significantly reduced for objective reasons [1]-[7]. Due to complexity the reliability of the driver is limited and does not match the time to failure of light-emitting diodes significantly [8]-[14]. A long-overdue task is to find new types of LED control that are inexpensive and reliable, but one that preferably preserves most of the functional characteristics that LED drivers provide.

There is research to get rid of electrolytic capacitors to increase the life expectancy of the LED drivers [15]-[21]. However, the complexity and cost of such solutions do not decrease significantly, since most studies consider replacing the capacitor with complex circuits. There is research aiming to reduce costs and increase reliability by integrating power and control trains within a single chip. The last decade's trend in LED lighting is direct AC LED modules [22]-[25]. This is a driverless solution, the idea of which is to dynamically reconfigure and align LED strings to an alternating mains voltage. The LED module includes low-frequency switching logic synchronized with mains frequency. The LED module is connected directly to the power network. For example, consider a typical LED module circuit shown in Figure 1. Depending on the input voltage, strings LED_1 - LED_N are configured using switches Q_1-Q_N as the input voltage changes. The LED_1-LED_K strings are switched on in a stack to match the input voltage, so that $V_{LED1} + ... + V_{LED(K)} \leq Vin(t)$, for $1 < K < N$. The activated switch Q_K works as a linear current stabilizer to bridge the gap between voltage drop on the serially connected LED_1-LED_K and the continuously changing mains voltage. While the switch Q_K is activated, it shunts and turns off the rest of the LED strings LED_{K+1}-LED_N. It is possible to regulate the module current in correlation with the input voltage to obtain a good power factor.

The AC module is simple and inexpensive and does not contain high-speed power switches, a transformer, an inductor, an unreliable electrolytic capacitor, or high-frequency filters. AC modules are very attractive for integration and there are commercial chips on the market. Although they do not provide galvanic isolation, the simplicity and affordability of these circuits support their presence on the market. The increased time to failure also reduces the cost of ownership. Unfortunately, the presence of linear current stabilizers results in power losses and heat generation. Commercial chips for AC LED modules are currently available for low-power applications.

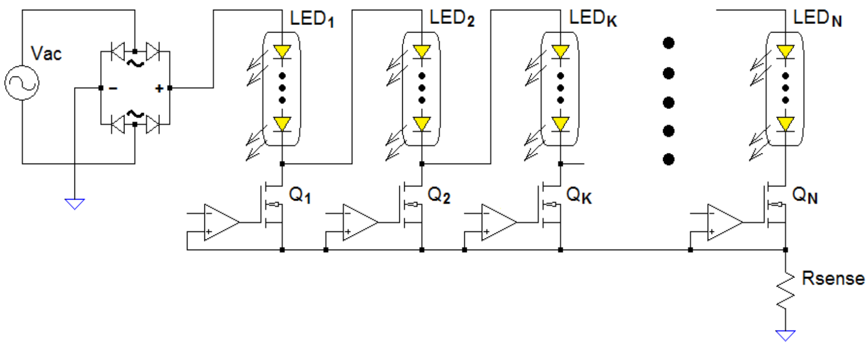


Figure 1. Conventional direct AC LED module

To improve efficiency, the hybrid LED driver is proposed [26]-[28]. In this design, configurable LED strings are synchronously adjusted to the mains voltage as it is in the direct AC LED module. To compensate for the gap of the mains voltage over the voltage drop in the LED strings, a small-power pulsed converter is used. Figure 2 illustrates the idea, which is similar to a pulsed converter with a load of configurable LED strings. Let V_1-V_N be the voltage drops of LED_1-LED_N strings correspondingly. When the input voltage is within the range of $V_1 + ... + V_K < Vin < V_1 + ... + V_K + V_{K+1}$, the switches Q_1-Q_{K-1} are non-conducting, therefore inductor L and strings LED_1-LED_K are connected in series. The switch Q_{K+1} is conducting, shunting the remaining strings LED_{K+2}-LED_N. The switch Q_K operates in switch mode to control the input current of the hybrid driver at a given input instantaneous voltage Vin. The small converter effectively compensates for mains excess voltage, the inductor L controls the input current ripple associated with switch power conversion. This converter only controls a small portion of the total output power, resulting in smaller losses than in the traditional driver. Circuit integration of a control and power metal–oxide–semiconductor field-effect transistor or MOSFETs of the hybrid LED driver is possible [28]. However, in the topology in Figure 2 slow LEDs operate in switch-pulse mode, which limits efficiency. Power transistors Q_1-Q_N and LEDs experience severe hard switching due to slow LEDs, resulting in heat generation in the driver chip. Also, electromagnetic interference or EMI noise is generated. In addition, the light intensity of the LEDs decreases in pulsed mode. To mitigate these adverse effects, it is necessary to either reduce the frequency, which will increase the inductor size, or reduce the pulse voltage. Reducing pulse voltage requires splitting of LED strings and, at the same time multiplying the number of the strings and power transistors, complicating the circuit [26].

There is a need to prevent MOSFET switches and slow LEDs from severe reverse recovery currents. In Figure 3, one can see the first proposal of the modified hybrid LED driver. The idea is to place fast-switching diodes D_1-D_N in series with LED strings to alleviate the hard switching of semiconductors. This will reduce the overheating of MOSFETS in the integrated circuit (IC) body and increase the reliability of the chip. Conduction losses of diodes are kept aside from the body of the chip and dissipate through the diodes.

The drawback is that the added diodes generate high conduction losses if the number N of LED strings is big enough. To mitigate conduction power losses Schottky diodes could be implemented. Additionally, capacitors C_1-C_N could be connected in parallel to LED strings to improve light-generating efficacy. If the number of LED strings is not large (N=2-3), then the proposed scheme offers several advantages over the traditional boost topology. These are reduced voltage pulsation on power switches by two to three times, decreased pulsation of the inductor current, an obvious reduction in electromagnetic interference, and a sufficient decrease in dynamic losses. At the same time, conduction losses are not greatly increased.

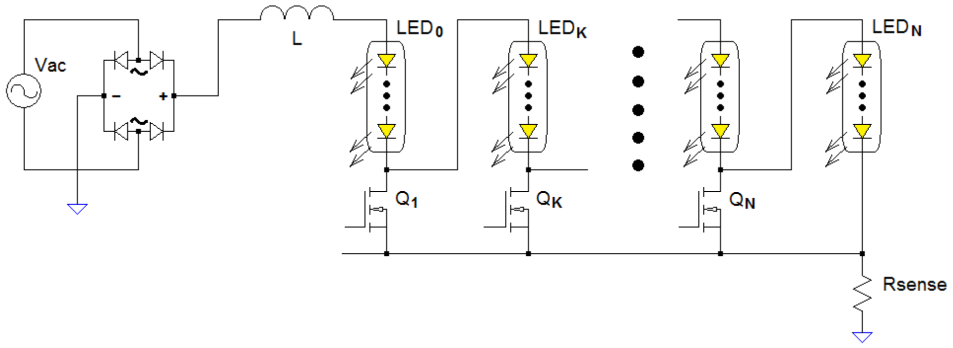


Figure 2. Hybrid LED driver of the previous art

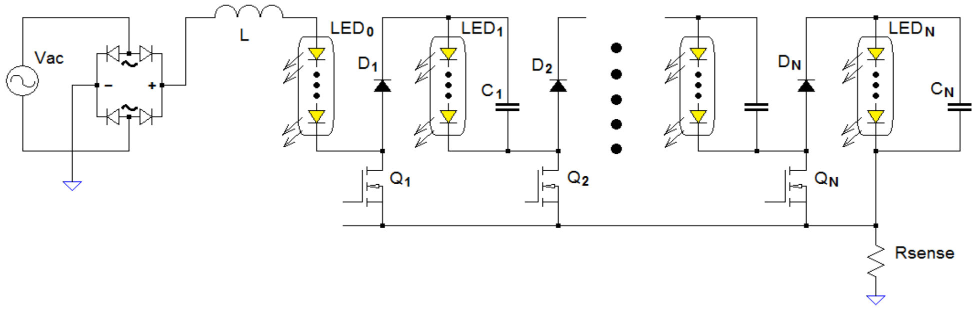


Figure 3. Proposed hybrid LED driver

The Figure 4, one can see the second proposal of the modified hybrid LED driver. As in Figure 3, diodes D_1-D_N are implemented to prevent MOSFET switches and LEDs from severe hard switching. But unlike in Figure 3, to restrain conduction losses the diodes are connected in series with corresponding MOSFETs. Because diodes are not connected in series with LED strings, only one diode conducts at a time, and only two diodes operate in switching mode complementary to each other. The possibility opens to integrate the control train, power transistors as well as diodes in one chip.

In the paper, the switch mode conversion of the second proposed driver is analyzed to reveal the advantages, as in Figure 4. The control method is suggested. Then the simulation is provided. The simulation results confirm the benefits of the proposed hybrid LED driver. This paper is organized as: i) In section 2 theoretical analysis is given, the control method of the hybrid driver is proposed, a computer model is constructed and evaluated in PSIM to prove the main advantages and controllability of the driver; ii) In section 3 the result of the simulation is presented which includes power inductor current waveform, voltage waveforms of power semiconductors, LED strings; and iii) Section 4 concludes the important findings.

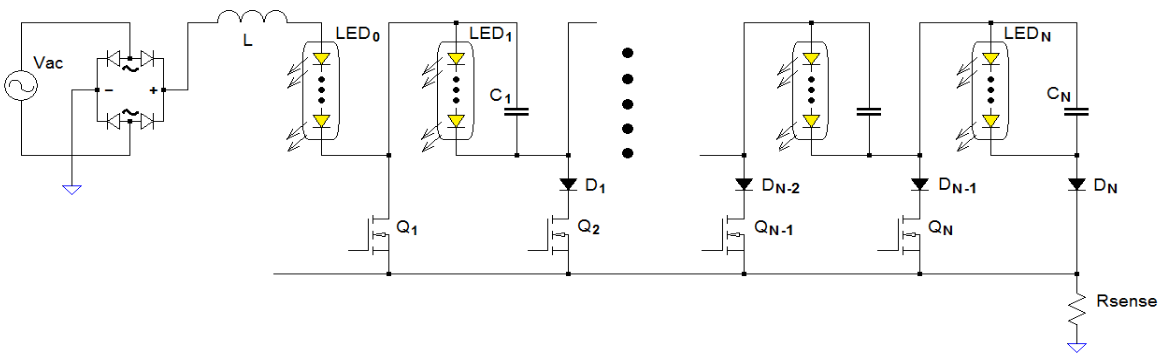


Figure 4. Proposed hybrid LED driver

2. METHOD

Multiple active power switches add relative complexity to the design. Various control strategies can be invented to manage power efficiency, power quality, and EMI generation. The proposed treatment does not pretend to be perfect but focuses only on highlighting the feasibility of the circuit and its main useful properties. To be certain, the following procedure for power switches Q_1-Q_N are proposed, as revealed in Figure 4. At a given input voltage Vin, such as $V_{LED1} + V_{LED2} + ... + V_{LED(K-1)} < Vin \leq V_{LED1} + V_{LED2} + ... + V_{LED(K)}$, stage(K) of switch mode regulation takes place: transistors Q_1-Q_{K-1} is in the cutoff state, transistor Q_{K+1} is conducting, and only power transistor Q_K is capable to regulate input current and operates in switch mode. Let us take a closer look at how the driver works at stage(K) and how the input current is regulated. At stage(K), there are only two states of the active transistor Q_K: ON-state and OFF-state, as in Figures 5(a) and 5(b).

a. Stage(K), transistor Q_K is turned on

See the equivalent circuit in Figure 5(a). Transistors Q_1 - Q_{K-1} is in OFF-state, transistor Q_{K+1} is in ON-state, transistor Q_K is in ON-state, the strings LED_1-$LED_{K-1}$are connected in series to the inductor L, the input current I_L increases as in (1) and reaches the predefined upper-level $I_{HIGH}(t)$, because the condition $V_{LED1} + V_{LED2} + ... + V_{LED(K-1)} < Vin$ is true during stage(K). Diodes D_K-D_N are reversed biased by voltages from $V_{D(K)}$ to $V_{D(N)}$ correspondingly, where $V_{D(K)} = V_{LED(K)}$, $V_{D(K+1)} = V_{LED(K)} + V_{LED(K+1)}$, ..., $V_{D(N)} = V_{LED(K)} + V_{LED(K+1)} + ... + V_{LED(N)}$.

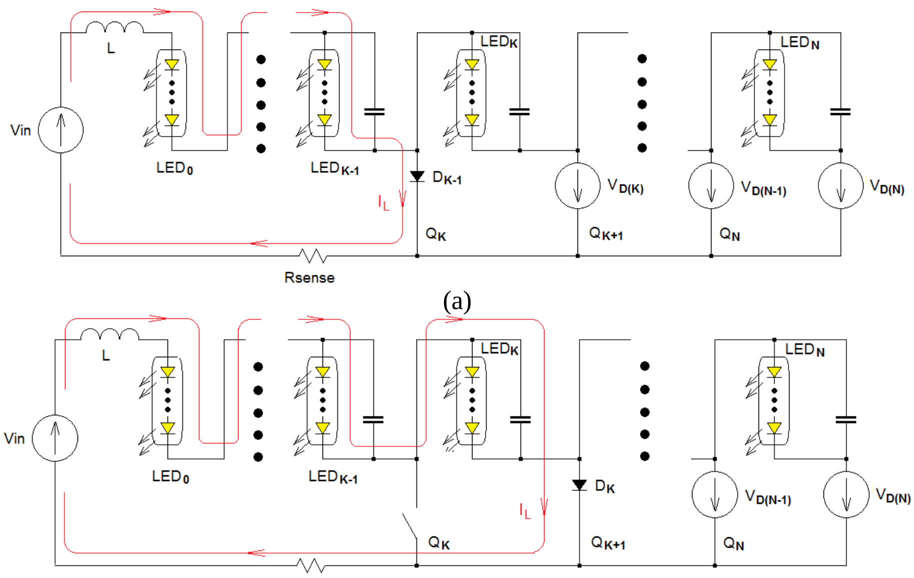
$$\frac{dI_L}{dt} = \frac{Vin - V_{LED1} - V_{LED2} - \cdots - V_{LED(K-1)}}{L} \rightarrow \left|\frac{dI_L}{dt}\right| < \frac{V_{LED(K)}}{L} \quad (1)$$

b. Stage(K), transistor Q_K is turned off

See the equivalent circuit in Figure 5(b). Transistors Q_1 - Q_{K-1} is in OFF-state, transistor Q_{K+1} is in ON-state, transistor Q_K is in OFF-state, the strings LED_1-LED_{K-1} and LED_K are connected in series to the inductor L, the diode D_K is conducting, the input current I_L decreases, as in (2), to predefined low-level $I_{LOW}(t)$ because the condition $Vin \leq V_{LED1} + V_{LED2} + ... + V_{LED(K)}$ is true during stage(K). Diodes D_{K+1}-D_N are reversed biased by voltages from $V_{D(K+1)}$ to $V_{D(N)}$ correspondingly, where $V_{D(K+1)} = V_{LED(K+1)}$, ..., $V_{D(N)} = V_{LED(K+1)} + ... + V_{LED(N)}$.

$$\frac{dI_L}{dt} = -\frac{V_{LED1} + V_{LED2} + \cdots + V_{LED(K-1)} + V_{LED(K)} - Vin}{L} \rightarrow \left|\frac{dI_L}{dt}\right| < \frac{V_{LED(K)}}{L} \quad (2)$$

Note, that the amplitude of switching voltages for the active transistor Q_K and the active diode D_K is equal to string voltage $V_{LED(K)}$ and less than $V_{LED(K)}$ for the inductor L, see (1) and (2).



(a)

(b)

Figure 5. Equivalent circuits of the proposed LED driver at stage(K): (a) transistor Q_K is in on-state and (b) transistor Q_K is in off-state

As input voltage Vin increases during stage(K) and reaches value $\geq V_{LED1} + V_{LED2} + ... + V_{LED(K)}$, then the switch Q_K turns OFF and switch Q_{K+1} works in switch mode now, thus the driver enters Stage(K+1). As input voltage Vin decreases during stage(K) and reaches value $\leq V_{LED1} + V_{LED2} + ... + V_{LED(K-1)}$, then the switch Q_K turns ON and switch Q_{K-1} works in switch mode now. Thus, the driver enters Stage(K-1).

The configuration policy of the LED strings is a critical consideration in control method design. It is determined by external parameters such as input voltage and inductor current. Finding the optimal timing for LED string interconnection is crucial for maximizing power efficiency, power quality, and minimizing EMI. Various logic could be put in to implement transitions Stage(K) ↔ Stage(K+1). For the first trial, it is suggested to configure LED strings based on the inductor's current information. For instance, in Figure 5(b), at Stage(K) if the inductor current reaches the upper boundary while the switch Q_K is in the OFF-state, then the $LED_{(K+1)}$ string will be added in series to reverse current uplift and transistor Q_{K+1} will start pulse width modulation (PWM) from the initial OFF-state. Thus, the driver will transit to Stage(K+1). Conversely, if the inductor current reaches the low boundary when the transistor Q_K is in an ON-state, as in Figure 5(a), the $LED_{(K-1)}$ will be removed from the series to reverse downslide and transistor Q_{K-1} will start PWM from the initial ON-state. Thus, the driver will transit to Stage(K-1). This way, the logic of the LED string's configuration remains immune to the noise of the input mains voltage.

A PSIM model was developed for computer simulation with a simplified circuit of the proposed driver with only 4 LED strings, as displayed in Figure 6. Choosing the voltage drop V_{LED0} of the string LED_0, as seen in Figure 4, it is possible to control skip mode at low input voltage Vin. In Figure 6, there is no LED_0 string, thus the simulated circuit generates pulsed switching down to zero input |Vin| = 0. To build a driver control for the first trial a simple hysteresis current control is implemented. The operational amplifier U1 provides reference voltages I_high and I_low, which are alternating signals of the rectified input voltage forming guiding borders for the inductor current I_L. Two comparators Comp_L and Comp_H sense inductor current I_L and compare it with references I_high and I_low. As a result of the particular realization, the ideal power factor is provided. The C-block DEMUX realizes the transition logic between Stage(K) ↔ Stage(K+1), propagates a modulated pulse signal from the flip-flop trigger to the currently active gate Gate(K), holds Gate1 - Gate(K-1) to zero, and holds Gate(K+1) - Gate(4) to high. In Figure 6 DEMUX block senses comparator outputs and utilizes the DELAY block. In DEMUX block the procedure is: i) Stage (4) is a starting stage at the first initialization; ii) If Comp_L is triggered to logic "1" and stays in this state for some timeout period DELAY, then transition Stage(K)→Stage(K-1) takes place; and iii) If Comp_H is triggered to logic "1" and stays in this state for some timeout period DELAY, then Stage(K) → Stage(K+1). For more details, in Figure 7 one can see the code text of the DEMUX block to be able to replicate the results of the simulation. In Figure 7, code variables x1-x4 and y1-y5 correspond to the input pins x1-x4 and output pins y1-y5 of the DEMUX block in Figure 6.

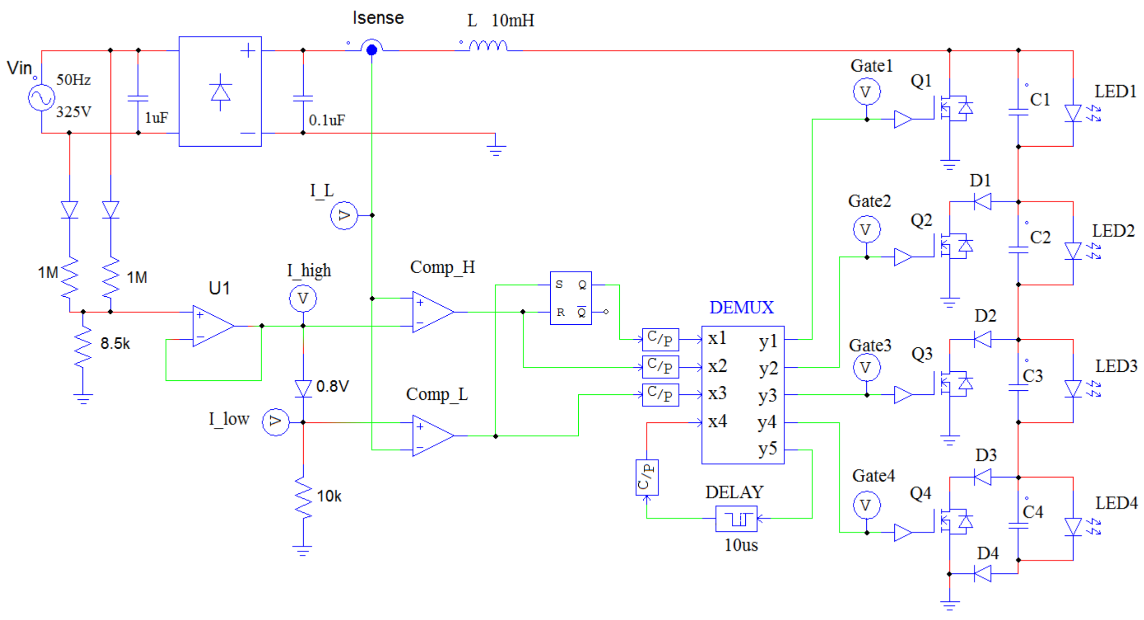


Figure 6. The hybrid LED driver circuit model for simulation

```
//The code ofthe DEMUXC-block
static int Flag1, Flag2, Gate_NUM, Timer;
double Comp1, Comp2;
double Gate;
double delay;
Gate = x1;
Comp1=x2;
Comp2=x3;
delay=x4;
if (Gate_NUM< 1) {Gate_NUM=1;}
if (Gate_NUM> 4) {Gate_NUM=4;}
if (Comp1 >= 0.5) { if (Flag1 != 1) {Flag1=1; } else if (delay>=0.5) {Flag1=0; Gate_NUM=Gate_NUM+1;} } else {Flag1=0;}
if (Comp2 >= 0.5) { if (Flag2 != 1) {Flag2=1; } else if (delay>=0.5) {Flag2=0; Gate_NUM=Gate_NUM-1; } } else {Flag2=0;}
y5=Flag1+Flag2;

select_Gate:
switch Gate_NUM
{case 1:
   y1 = Gate;
   y2 = 1;
   y3 = 1;
   y4 = 1;
break;
case 2:
   y1 = 0;
   y2 = Gate;
   y3 = 1;
   y4 = 1;
break;
case 3:
   y1 = 0;
   y2 = 0;
   y3 = Gate;
   y4 = 1;
break;
case 4:
   y1 = 0;
   y2 = 0;
   y3 = 0;
   y4 = Gate; }
```

Figure 7. The code text of the DEMUX block

3. RESULTS AND DISCUSSION

In Figure 8 one can see the resulting steady-state waveforms of the simulation for one input line half-period. Input voltage Vin=230Vrms. For convenient observation, the inductor L is chosen to be 10mH to reduce switching frequency closer to the phase frequency of an input voltage. So, one can clearly track the simulated waveforms during an input phase cycle. The waveforms obtained confirm that the proposed hybrid LED driver is operationally feasible. The design results in low losses of power transistors compared to the previous art hybrid drivers. The inclusion of rectifier diodes alleviates hard switching mode for power switches and LED strings, reducing generated EMI, power dissipation across transistors in the integrated circuit, improving chip reliability, and enabling reduction in the form factor. Since only one diode conducts at a time in the proposed driver, the diodes' conduction losses are moderate, allowing all driver diodes to be included in the integrated circuit.

The simulation proves the controllability of the circuit. The immune to input noise proposed configuration control logic of LED strings is operational. Figure 8 shows that when the inductor current rests on the upper reference value for a second time in a row, then another LED string is added in series with the active strings and the current decreases. If the current reaches the low reference value for a second time in a row, the number of connected LED strings is reduced and the current increases. The policy of the LED strings configuration is a critical consideration for the optimal timing for LED string interconnection, for maximizing power efficiency, for power quality, and for minimizing EMI.

In the considered case, a variant with electrolytic capacitors is implemented. It is seen that LEDs are supplied with continuous currents. The total power ratings of LED strings slightly decrease with index K from 1 to 3, the current and power ratings of the string with the highest index K-LED_4 is about half of any string $LED_{1\text{-}3}$, this fact could be useful for optimization. The proposed driver can be without electrolytic capacitors. It will not reduce LED efficacy due to fast diodes blocking LEDs' reverse current.

As with previous technical arts all power transistors, diodes, and inductor L experience low switching voltage amplitudes. Average currents of transistors Q_K increase with index K, but total drain voltages Vds_K decrease from transistor Q_1 to Q_4. It is a good outcome for optimizing transistors. Voltage and current ratings of diodes D_K increase with K from 0 to 4.

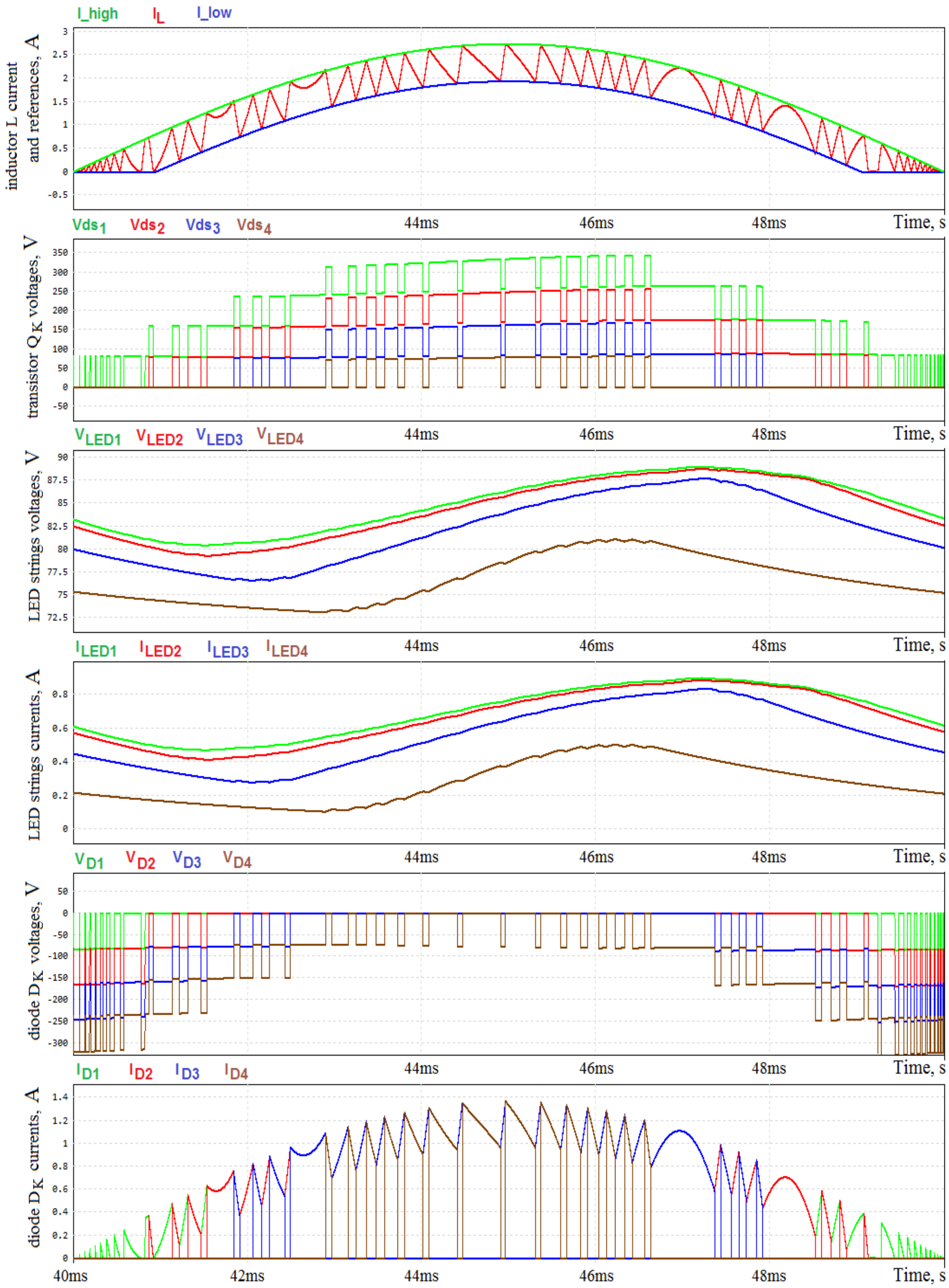


Figure 8. Simulation waveforms of the hybrid LED driver

4. CONCLUSION

There have been a lot of efforts to improve traditional LED drivers and reduce costs. As a result, hybrid LED drivers have been proposed recently with a view to circuit integration. It combines pulsed power conversion with a load of LED strings configurable synchronously with input line voltage. The advantages and drawbacks of the hybrid LED drivers are discussed, in the paper. Therefore, the new hybrid LED driver is proposed to overcome the drawbacks. The attention was paid to preventing power semiconductors from hard switching. This will reduce the overheating of MOSFETS in the integrated circuit body, increase the chip reliability, and alleviate EMI issues. Also, having overall moderate conduction loss the diodes in the proposed driver can be integrated into the chip. The proposed improvement to the hybrid driver is analyzed. To confirm the results computer modelling was provided. Simulation shows that the circuit proposed to prevent LEDs from hard switching is valid. Methods for circuit control and optimization are discussed in the paper. As the new driver is announced, further work will continue on practical implementation, where the real impact on the driver's efficiency will be evaluated as well.

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