Improvement in Efficiency of LED Lighting System Based on Reduction of Voltage across MOSFET

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(Manuscript received Aug. 7, 2014, revised March 6, 2015)

In this paper, a LED dimming circuit powered by the KY converter, which is named after the first capitals of two authors’ names: Kuo-Ing Hwu and Yu-Torng Yau, is presented, which is controlled based on the field-programmable gate array (FPGA). By a given dimming command and the proposed maximum gate voltage detector, the voltage across the MOSFET in the linear current regulator can be reduced so as to upgrade the efficiency of the overall system. Aside from this, each LED string takes level dimming, and is powered by the KY converter, which has an output inductor and hence upgrades the life of the output capacitor. Furthermore, via some experimental results, the efficiency based on the proposed control method is higher than that based on the traditional control one.

Keywords: KY converter, LED lighting, Efficiency

1. Introduction

Recently, the light emitting diode (LED) has got more and more attracted in the world. In the future, such a light source will replace the other light sources. As compared to the other light sources, the LED has some advantages (1), such as no Hg corresponding to environment protection, small size with resistance to vibration and pressure, high-speed response, etc. In (2), a linear current regulator for a single LED string is presented, and this can be extended and applied to multiple strings. This circuit is basically constructed by one operational amplifier, one MOSFET and one current-limiting resistor Rs. Via the virtual ground of the operational amplifier, the voltage across Rs is equal to a given reference voltage, and hence the current flowing through the LED strings can be adjusted by such a voltage. However, during the dimming period, the less the current flowing through the LED string is, the more the voltage on MOSFET, and hence the corresponding efficiency of the overall system is deteriorated (3). Therefore, the literature (4) has presented a method to improve the efficiency of the overall system, especially at light load. However, there is still some room to improve the efficiency based on this method. Consequently, in this paper, the feedback voltage is subtracted from a variable voltage reference, which is controlled by the dimming command and the maximum gate voltage detector, so as to make the voltage across the MOSFET in the linear current regulator as minimum as possible for any load. For the power stage to feed LED strings to be considered, the KY converter (5) is employed herein, which is suitable for low-power applications and always operates in the continuous conduction mode (CCM). Furthermore, the output inductor current is non-pulsating, and hence not only reduces the output voltage ripple but also prolongs the life of the output capacitor. Therefore, the level dimming circuit, together with the KY converter, is adopted herein.

2. KY Converter

Figure 1(a) shows the KY converter. The input voltage and output voltage are denoted by \( V_i \) and \( V_o \), respectively. Since the voltage across \( C_b \) follows the input voltage \( V_i \) entirely, the voltage across \( C_b \) is defined as \( V_i \). The voltage across \( L_o \) is defined as \( v_{Lo} \). Moreover, the switch \( S_1 \) has the duty cycle of \( D \) and the switch \( S_2 \) has the duty cycle of \( 1 - D \). In the KY converter, there are two operating modes described as follows.

Mode 1: As shown in Fig. 1(b), the switch \( S_1 \) is turned on but the switch \( S_2 \) is turned off. A positive voltage \( 2V_i - V_o \) is imposed on the output inductor, making this inductor magnetized. In the meantime, the capacitor \( C_b \) is discharging energy to the output load. The following equation can be obtained:

\[
v_{Lo} = 2V_i - V_o \tag{1}
\]

Mode 2: As shown in Fig. 1(c), the switch \( S_1 \) is turned on but the switch \( S_2 \) is turned off. A negative voltage \( V_i - V_o \) is imposed on the output inductor, making this conductor demagnetized. At the same time, the capacitor \( C_b \) is charged by the input voltage \( V_i \). The following equation can be obtained:

\[
v_{Lo} = V_i - V_o \tag{2}
\]

By applying the voltage-second balance principle to \( L_o \) over one switching period, the following equation can be obtained:
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\[ D \cdot (2V_i - V_o) + (1 - D) \cdot (V_i - V_o) = 0 \]  \hspace{1cm} (3)

The voltage gain of the KY converter can be obtained:

\[ \frac{V_o}{V_i} = 1 + D \] \hspace{1cm} (4)

From (4), it can be seen that the output voltage can be boosted by adjusting the duty cycle \( D \).

Moreover, unlike the traditional boost converter, the KY converter has an output inductor, which makes the output current non-pulsating. Therefore, the output voltage ripple can be reduced. In addition, this converter possesses fast load transient response, which is similar to the synchronously rectified (SR) buck converter.

\[ \frac{V_o}{V_i} = \frac{1 + D}{1} \] \hspace{1cm} (5)

If the n-channel MOSFET operates in the saturation region, the current \( i_d \) is

\[ i_d = k(v_{gs} - V_{th})^2 \] \hspace{1cm} (6)

If the n-channel MOSFET operates in the triode region, the drain-source current \( i_d \) is

\[ i_d = 2k(v_{gs} - V_{th})v_{ds} \] \hspace{1cm} (7)

Therefore, from (5) and Fig. 3(a), it can be seen that when the MOSFET operates in the saturation region and constant current mode, if the voltage \( v_{ds} \) is reduced to the knee point, \( v_{gs} \) will not be changed. However, if \( v_{ds} \) is reduced continuously, the MOSFET will enter the triode region. Consequently, from (6), one can see that if \( v_{ds} \) is reduced under the condition that the MOSFET operates in the constant current mode, which means \( i_d \) is fixed, \( v_{gs} \) will increase. Hence, which region the MOSFET operates in can be determined by the values of \( i_d, v_{ds}, \) and \( v_{gs} \), and the corresponding knee point can also be known. For that reason, the proposed method is to change \( v_{ds} \) and to detect whether \( v_{gs} \) is changed or not, so as to make the MOSFET operates in the neighborhood of the

3. Overall System Configuration

Figure 2 shows the proposed overall system configuration, which is built up by the KY converter used to provide a desired voltage for five LED strings, one maximum gate voltage detector, two analog-to-digital converters (ADCs), one voltage divider constructed by two resistors \( R_1 \) and \( R_2 \), one Butterworth filter to get the DC value of the control force created from the FPGA, two gate drivers, and five linear current regulators with each constructed by one operational amplifier, one MOSFET switch and one current limiting resistor. Sequentially, how to reduce the voltage across the MOSFET is described as follows.

4. Reduction of the Voltage on MOS

Figure 3 shows the curve of n-channel MOSFET characteristics. If the n-channel MOSFET operates in the saturation region, the current \( i_d \) is

\[ i_d = k(v_{gs} - V_{th})^2 \] \hspace{1cm} (8)

If the n-channel MOSFET operates in the triode region, the drain-source current \( i_d \) is

\[ i_d = 2k(v_{gs} - V_{th})v_{ds} \] \hspace{1cm} (9)

Therefore, from (5) and Fig. 3(a), it can be seen that when the MOSFET operates in the saturation region and constant current mode, if the voltage \( v_{ds} \) is reduced to the knee point, \( v_{gs} \) will not be changed. However, if \( v_{ds} \) is reduced continuously, the MOSFET will enter the triode region. Consequently, from (6), one can see that if \( v_{ds} \) is reduced under the condition that the MOSFET operates in the constant current mode, which means \( i_d \) is fixed, \( v_{gs} \) will increase. Hence, which region the MOSFET operates in can be determined by the values of \( i_d, v_{ds}, \) and \( v_{gs} \), and the corresponding knee point can also be known. For that reason, the proposed method is to change \( v_{ds} \) and to detect whether \( v_{gs} \) is changed or not, so as to make the MOSFET operates in the neighborhood of the
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5. Experimental Results

Before this section is taken up, there are some specifications to be given as follows: (i) the input voltage of the KY converter is 14 V; (ii) the output voltage of the KY converter is set to 20 V; (iii) the switching frequency for the KY converter is 100 kHz; (iv) the LED module consists of five LED strings connected in parallel with five LEDs per LED string; and (v) the dimming current range for each LED string is from 0.438 A to 1.75 A, i.e., from 25% to 100% of the rated output current.

Figures 4 to 6 show the waveforms for \( v_{gs1} \), \( V_o \), \( i_L \) and \( I_o \) of the KY converter under the proposed dimming topology, at 50%, 75% and 100% load, respectively. From Figs. 4 to 6, it can be seen that the proposed LED lighting system can stably operate under various dimming power levels. Furthermore, based on the proposed dimming topology, Table 1 shows the voltages across five MOSFETs, \( v_{ds1} \), \( v_{ds2} \), \( v_{ds3} \), \( v_{ds4} \) and \( v_{ds5} \), the output voltage of the KY converter, \( V_o \), and the efficiency, \( \eta \), under 25%, 50%, 75% and 100% of the rated load, whereas based on the traditional dimming topology, Table 2 shows the same measured items as Table 1. From Tables 1 and 2, it can be seen that the drain-source voltages in the proposed topology are lower than those in the traditional topology. From Tables 1 and 2 and Fig. 7, it can be seen that the output voltage of the proposed topology will vary when the output load is changed, while the output voltage of the traditional topology is always kept at 20 V. From Tables 1 and 2 and Fig. 8, it can be seen that the values of efficiency based on the proposed dimming topology are much higher than those based on the traditional dimming topology.
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Table 1. Values of $v_{ds1}$, $v_{ds2}$, $v_{ds3}$, $v_{ds4}$ and $v_{ds5}$, $V_o$ and $\eta$ under 25%, 50%, 75% and 100% of the rated load, based on the proposed topology

| Load (%) | $v_{ds1}$ (V) | $v_{ds2}$ (V) | $v_{ds3}$ (V) | $v_{ds4}$ (V) | $v_{ds5}$ (V) | $V_o$ (V) | $\eta$ (%) |
|----------|---------------|---------------|---------------|---------------|---------------|------------|------------|
| 25%      | 0.343         | 0.229         | 0.197         | 0.161         | 0.119         | 15.40      | 98.63      |
| 50%      | 0.420         | 0.319         | 0.306         | 0.208         | 0.264         | 16.40      | 98.15      |
| 75%      | 0.603         | 0.458         | 0.477         | 0.326         | 0.473         | 16.55      | 97.17      |
| 100%     | 0.762         | 0.593         | 0.620         | 0.410         | 0.832         | 17.41      | 96.30      |

Table 2. Values of $v_{ds1}$, $v_{ds2}$, $v_{ds3}$, $v_{ds4}$ and $v_{ds5}$, $V_o$ and $\eta$ under 25%, 50%, 75% and 100% of the rated load, based on the traditional topology

| Load (%) | $v_{ds1}$ (V) | $v_{ds2}$ (V) | $v_{ds3}$ (V) | $v_{ds4}$ (V) | $v_{ds5}$ (V) | $V_o$ (V) | $\eta$ (%) |
|----------|---------------|---------------|---------------|---------------|---------------|------------|------------|
| 25%      | 4.924         | 4.835         | 4.408         | 4.760         | 4.061         | 19.99      | 76.60      |
| 50%      | 4.519         | 4.407         | 4.417         | 4.322         | 4.188         | 20.02      | 78.16      |
| 75%      | 3.947         | 3.860         | 3.910         | 3.775         | 4.267         | 20.06      | 80.30      |
| 100%     | 3.572         | 3.510         | 3.596         | 3.419         | 5.083         | 19.99      | 80.85      |

Fig. 7. Output voltage comparison of the proposed topology and traditional topology

Fig. 8. Efficiency comparison of the proposed topology and traditional topology

6. Conclusion

In this paper, the proposed LED dimming strategy, together with the KY converter used to power LEDs, is presented. By detecting the gate voltage and controlling the voltage across the drain and source terminals, the MOSFET can operate in the neighborhood of the knee point to reduce the redundant power loss. Finally, a prototype consisting of a KY converter and five LED strings is implemented. Compared with the traditional topology, the efficiency at light load can be upgraded by 22.03%, and the efficiency at rated load can be improved by 15.45%.

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