Linear PFC regulator for LED lighting with the multi-level structure and low voltage MOSFETs.

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Abstract—This paper proposes a linear PFC regulator for LED lighting applications. The proposed circuit is small in size because the circuit structure consists of only semiconductors and resistors without any reactors and electrolytic capacitors. The current bypass circuit which is connected in parallel to the LED string consists of single MOSFET, two zener diodes and two resistors. The MOSFET is operated in an active state by a self-bias circuit. Thus, an external controller and high voltage gate drivers are not required. The proposed circuit is experimentally validated by using a 15 W prototype. From the experimental results, the THD of input current is 5.1 % and the power factor is 0.999. In addition, the simulation loss analysis demonstrates an efficiency of 91.6 % for a 15.2 W prototype.

I. INTRODUCTION

LED lighting market has grown rapidly due to the advantage of extended life-time and improved luminance, with the significant improvement in the manufacturing process of LEDs [1][2]. In the conventional AC LED driver, a converter is composed of a power factor correction (PFC) rectifier and a DC-DC converter. The conventional converter requires electrolytic capacitors in the DC link, however, it is well known that the life-time of electrolytic capacitor is shorter than that of LED. The converter with discontinuous current mode (DCM) operation that uses no electrolytic capacitor has been proposed to extend the life-time of a converter [3-5]. However, the switching and conduction losses of the semiconductor switch are increased due to the large peak current. In addition, the conducted EMI occurs in the input lines because of the switched mode power supply (SMPS). Therefore, SMPS requires a bulky EMC filter to suppress electromagnetic noise.

On the other hand, a diode-clamped linear multi-level amplifier is proposed to obviate the need for passive EMI filters and improve efficiency in the AC motor drive [6]. The linear multi-level concept is possibly applied for an AC LED driver as a linear PFC regulator [7-9]. These circuits are constructed from only semiconductors without any passive components. However, high voltage rating operational amplifiers and MOSFETs are required. Hence, the losses will be increased due to the large quiescent current of the operational amplifiers and the high on-resistance of the MOSFETs.

In this paper, a linear PFC regulator for LED lighting with the multi-level current bypass circuit is proposed. The proposed circuit can be operated by a self-bias circuit without any external controllers. In addition, the voltage rating of the MOSFETs can be reduced to $V_{in\max}/(n+1)$ ($n$: Number of the series current bypass circuits). Thus, the loss of the MOSFETs can be reduced.

II. PROPOSED CIRCUIT

Fig. 1 shows the equivalent circuit diagram. The rectified input voltage is applied to the LED strings. The current bypass switches S1~S4 are connected in parallel to the LED string. The off state voltage of the switches is clamped to the forward voltage of parallel connected LEDs. The number of switches is different in each of the string, which is depending on the on voltage of the LED string.

Fig. 2 shows the input current waveforms of the AC side and the LED strings. The current amplitude of each string is limited to constant value. Firstly, in the case that the input voltage $V_{in}$ is increased from the zero point, all of the switches are turned on. Then, the switches S1~S4 are turned off accordingly which is subjected to input voltage. As a result, the input current is increased in proportional to the input voltage.

Fig. 3 shows loss reduction strategy of current regulator by using multiple operating points. When the input voltage is changing, the current bypass switches S1~S4 will be operated to vary the forward voltage of the LED string.

Fig. 4 shows the circuit diagram of the first string in the case of 5 and 10 strings. The current bypass circuit consists of a single MOSFET, two zener diodes and a single resistor. The operation is as follows.
Table 1. Comparison of LED driver circuits.

<table>
<thead>
<tr>
<th></th>
<th>Proposed circuit (5 and 10 strings)</th>
<th>Step-down chopper(4)</th>
<th>Single switch converter(4)</th>
<th>Sequential linear(8)(9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input current</td>
<td>Sinusoidal</td>
<td>Low power factor</td>
<td>Sinusoidal</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>Lighting flicker</td>
<td>Large</td>
<td>Small</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>Element deciding life time limit</td>
<td>LED</td>
<td>Electrolytic capacitor</td>
<td>LED</td>
<td>LED</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>88.3, 91.6</td>
<td>&gt;80</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Reactor volume</td>
<td>-</td>
<td>Large</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>Capacitor volume</td>
<td>-</td>
<td>Large</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>EMI filter</td>
<td>-</td>
<td>Required</td>
<td>Required</td>
<td>-</td>
</tr>
<tr>
<td>Input power factor</td>
<td>0.995, 0.999</td>
<td>0.7~0.8</td>
<td>0.98</td>
<td>&gt;0.95</td>
</tr>
</tbody>
</table>

1. The gate-source voltage \( V_{gs} \) of the MOSFETs is biased by \( Z_{D_{bias}} \) and \( R_{bias} \). The saturation voltage of the current regulator \( V_{on} \) is lower than \( V_{ZD_{bias}} \) (6.8V > 3.0V typ.). Therefore, \( S_1 \sim S_9 \) are turned on.

2. The input voltage \( V_{in} \) becomes higher than the LED forward voltage \( V_{F0} \), so the LEDs of \( V_{F0} \) are turned on.

3. \( V_{in} - V_{F0} \) is applied to the drain-source of \( S_1 \) (\( V_{ds1} \)). In this area, \( S_1 \) is operated in an active state.

4. If \( V_{in} \) becomes higher than \( V_{F0} + V_{F1} \), \( S_1 \) is completely turned off due to the negative bias of \( V_{gs1} \).

5. The operation of 2~4 is repeated until \( V_{in} \) reaches the maximum value.

As a result, the LED string is operated as a constant current and variable voltage.

Table 2 shows the circuit parameters of the proposed circuit at 5 and 10 strings.

Fig. 5 shows the equivalent circuit diagram of MOSFET gate driver. The frequency response of a gate drive circuit can be decided by a time constant of a bias resistor \( R_{bias} \) and input gate capacitances \( C_{iss} \). The cutoff frequency \( f_{cut-off} \) of the gate driver is obtained by (1).

\[
f_{cut-off} = \frac{1}{\left( \frac{R_{bias} + R_{gate}}{n} \right) \cdot nC_{iss}} \quad \text{(1)}
\]

where \( n \) is a number of series bypass MOSFETs. The frequency response should be determined to be higher than twice of input power supply frequency. For example, by using the parameters in the Table 2 (a), \( f_{cut-off} \) becomes 27 kHz.

III. LOSS ANALYSIS

A. Simulation based analysis

The loss analysis of the proposed circuit is now discussed, which is carried out using a PSPICE circuit simulator (Tina, Texas Instruments). The losses are dominated by the conduction loss of the current source and the switching loss of the MOSFETs. The switching losses of the MOSFETs are varied with the \( dV/dt \) rate of \( V_{in} \). The loss analysis shows an efficiency of 91.6 % at 10 strings including the diode rectifier.
B. Calculation based analysis

Fig. 7 shows the semiconductor loss of the first string. The hatching areas indicate the losses of the switches and the current regulator. Fig. 8 shows an example of the loss waveforms of the current bypass MOSFETs and current regulative diode (CRD). During $t_1$ to $t_2$, $S_1$ is operated in active region. The time period of the active region is given by (2).

![Circuit diagram of the first string](image)

**Table 2. Circuit parameters for simulation and experiment.**

<table>
<thead>
<tr>
<th>(a) 5 strings</th>
<th>(b) 10 strings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LED</strong></td>
<td>LUW_JNSH.EC (OSRAM)</td>
</tr>
<tr>
<td></td>
<td>$V_f$=3.1V, $I_f$=20 mA</td>
</tr>
<tr>
<td><strong>MOSFET</strong></td>
<td>5LP01SS (ON semiconductor)</td>
</tr>
<tr>
<td></td>
<td>$V_{ds}$=-50 V, $R_{on}$=18 Ω, $C_{iss}$=7.4 pF</td>
</tr>
<tr>
<td><strong>ZD$<em>{gate}$, ZD$</em>{bias}$</strong></td>
<td>$V_f$=6.8 V</td>
</tr>
<tr>
<td><strong>$R_{bias}, R_{gate}$</strong></td>
<td>1 MΩ</td>
</tr>
<tr>
<td><strong>Current regulator</strong></td>
<td>NSJ45020T1G (ON semiconductor)</td>
</tr>
<tr>
<td></td>
<td>$I_{str}$=20 mA, $V_{on}$=3.5 V</td>
</tr>
<tr>
<td><strong>Diode bridge</strong></td>
<td>DF08SA (Vishay)</td>
</tr>
<tr>
<td><strong>$V_{in}$</strong></td>
<td>AC 100 V, 50 Hz</td>
</tr>
</tbody>
</table>

![Equivalent circuit of gate driver](image)

![Loss distribution of each string](image)

Figure 5. Equivalent circuit of gate driver.

Figure 6. Loss distribution of each string.
where $\omega$ is a angular frequency of the input voltage, $V_{in\_max}$ is a peak input voltage, $V_{F_{x}}$ is a forward voltage of the LEDs shown in Fig. 4.

The active region loss of the MOSFETs are expressed as

$$P_{\text{act\_linear}} = 4f_{v_{in}}I_{av}\left(V_{in\_max}\sum_{n=0}^{1}\sin\omega t_{n}\right)$$

(3)

where $f_{v_{in}}$ is a frequency of the input voltage, the first term shows the integrated value of the input voltage, the second term shows the total voltage of LEDs.

The conduction loss of the MOSFETs are expressed as (4).

$$P_{\text{con\_cond}} = 4f_{v_{in}}R_{on}\left(t_{n+2} - t_{n}\right)$$

(4)

The active region loss of the current regulator is expressed as (5)

$$P_{\text{act\_linear}} = 4f_{v_{in}}I_{av}\left(V_{in\_max}\sum_{n=0}^{1}\sin\omega t_{n}\right)$$

(5)

The conduction loss of the current regulator is expressed as (6).

$$P_{\text{con\_cond}} = 4f_{v_{in}}I_{av}V_{on}\left(t_{n+2} - t_{n}\right)$$

(6)

Fig. 9 shows the loss comparison results of the first string by comparing between the calculation and simulation. The calculated loss is slightly higher than that of simulation. The reason is that forward current of the LED is flowed at the peak of $V_{dh}$ of the MOSFET in simulation. Therefore, the drain current of the MOSFET is decreased.

Fig. 10 shows the loss comparison between the 5 string type and the 10 string type. The active region loss can be decreased by increasing the number of bypass circuits. When the number of bypass circuits increased to 9, the active region loss is 46% decreased.

IV. EXPERIMENTAL RESULTS

Table 3 shows the specification of the proposed circuit and the sample product of step-down chopper circuit.
Fig. 11 shows a prototype. The proposed circuit can be mounted on a single sided PCB with no holes. The circuit parameters are as same as shown in Table 2.

Fig. 12 shows the input current and the string current waveforms obtained by using the 5 strings type. The input active power is 7.8 W. Good sinusoidal waveform is achieved in the input current. The input current THD and the power factor are 9.8% and 0.995, respectively.

Fig. 13 shows the input voltage and current waveforms obtained by using step-down chopper circuit. The input current waveform is distorted by capacitor input diode rectifier.

Fig. 14 shows conduction noise in the proposed circuit and the step-down chopper circuit. Red line is the limit of CISPR Conduction noise in the step-down chopper circuit is attenuated to -19 dB lower than the limited line. On the other hand, conduction noise in the proposed circuit is almost as same as the background noise. Therefore, the conduction noise can be reduced by using the proposed circuit.

Fig. 15 shows the volume of each component that be composed of the passive components, semiconductors and noise filters. The component volume of the proposed circuit is 83% smaller than the sample product.

Fig. 16 shows the input current and the string current waveforms obtained by using the 10 strings type. The input
active power is 15 W. The input current distortion becomes lower than the 5 strings type. The input current THD and the power factor are 5.1% and 0.999, respectively.

Fig. 17 shows the current waveforms of the LED strings. A conduction time of each string is controlled by the number of current bypass circuits. In addition, the string current is limited at 20 mA by the current regulator.

Fig. 18 shows the drain-source voltage waveforms of the first string MOSFETs. In the transient of $V_{ds}$, the MOSFET is operated in saturation region. Then, in the constant $V_{ds}$ area, it is operated in active region. In addition, the maximum $V_{ds}$ is limited by $V_I$ of the parallel connected LEDs. Therefore, low voltage rating (30 V) MOSFETs can be used to achieve high efficiency.

Fig. 19 shows the input current harmonics from the experimental results. It can be confirmed that the low order harmonic components in the input current are lowered by increasing the number of the current bypass circuit.
V. CONCLUSIONS

This paper proposed a linear PFC regulator for LED lighting with a new multi-level current bypass circuit. Features of the proposed circuit are the implementation of low voltage of MOSFETs, no electrolytic capacitors are required and a simple gate bias circuit without any external controllers. The experimental results have confirmed the validity of the proposed circuit structure.

REFERENCES