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

Yuichi Noge
Nagaoka University of Technology
Niigata, Japan
noge@stn.nagaokaut.ac.jp

Jun-ichi Itoh
Nagaoka University of Technology
Niigata, Japan
itoh@vos.nagaokaut.ac.jp

***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 S_1~S_4 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 the required switches is different in each of the string, which is depending on the on voltage of the string current.

Fig. 2 shows the input current waveforms of the AC side and the LED strings. The current amplitude of the 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 S_1~S_4 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 S_1~S_4 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.

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

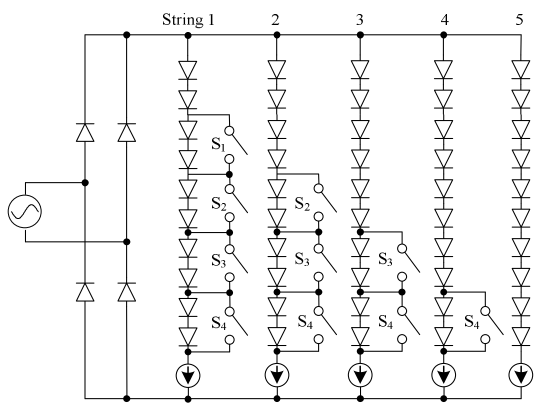


Figure 1: Equivalent circuit diagram of the proposed LED driver in the case of 5 strings.

1, The gate-source voltage V_{gs} of the MOSFETs is biased by ZD_{bias} and R_{bias}. The saturation voltage of the current regulator V_{on} is lower than V_{ZDbias} (6.8V > 3.0V typ.). Therefore, S_1~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_{cutoff} of the gate driver is obtained by (1).

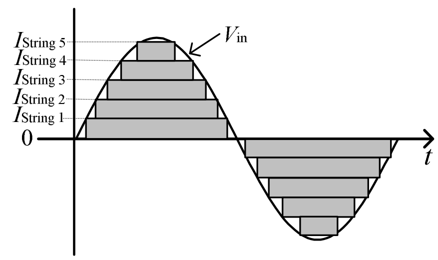


Figure 2: Current waveforms of the AC input and the LED strings.

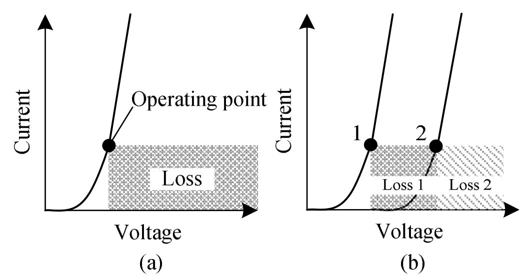


Figure 3. Loss reduction of current regulator by using multiple operating points.

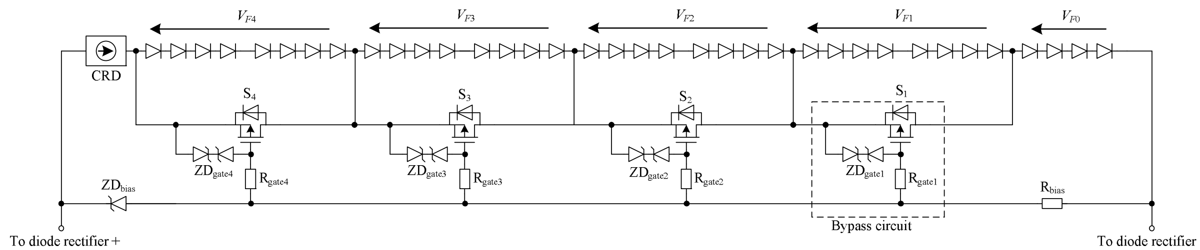
$$f_{cut\_off} = \frac{1}{\left(R_{bias} + \frac{R_{gate}}{n}\right) \cdot nC_{iss}} \qquad \text{.............................. (1)}$$

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_{cutoff} becomes 27 kHz.

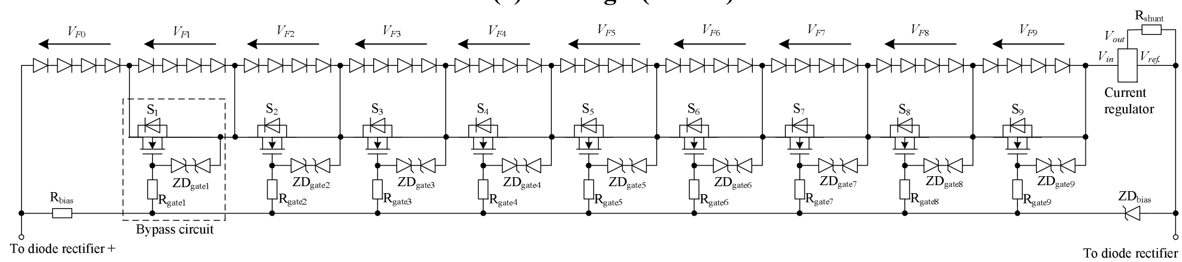
III. LOSS ANALYSIS

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.



(a) 5 strings. (PMOS)



(b) 10 strings. (NMOS)

Figure. 4. Circuit diagram of the first string.

Table 2. Circuit parameters for simulation and experiment.

(a) 5 strings.

LED	LUW_JNSH.EC (OSRAM) V_F=3.1V, I_F=20 mA, 36-series
MOSFET	5LP01SS (ON semiconductor) V_{ds}=-50 V, R_{on}=18 Ω, C_{iss}=7.4 pF
ZD_{gate}, ZD_{bias}	V_z=6.8 V
R_{bias}, R_{gate}	1 MΩ
Current regulator	NSI45020T1G (ON semiconductor) I_{str}=20 mA, V_{on}=3.5 V
Diode bridge	DF08SA (Vishay)
V_{in}	AC 100 V, 50 Hz

(b) 10 strings.

LED	LUW_JNSH.EC (OSRAM) V_F=3.1V, I_F=20 mA, 40-series
MOSFET	SSM3K15F (Toshiba) V_{ds}=30 V, R_{on}=4 Ω, C_{iss}=7.8 pF
ZD_{gate}, ZD_{bias}	V_z=6.8 V
R_{bias}, R_{gate}	1 MΩ
R_{shunt}	62.5 Ω
Current regulator	LM1086-ADJ (Texas Instruments) I_{str}=20 mA, V_{on}=3.0 V

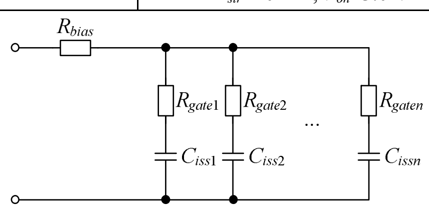
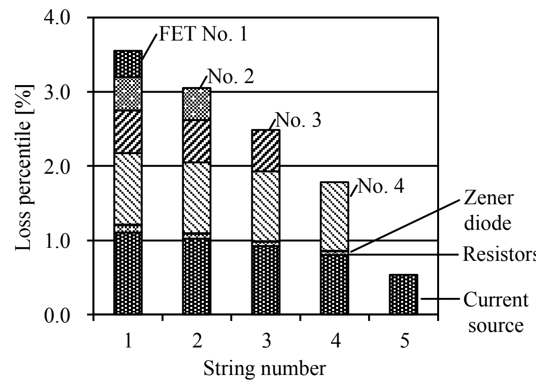
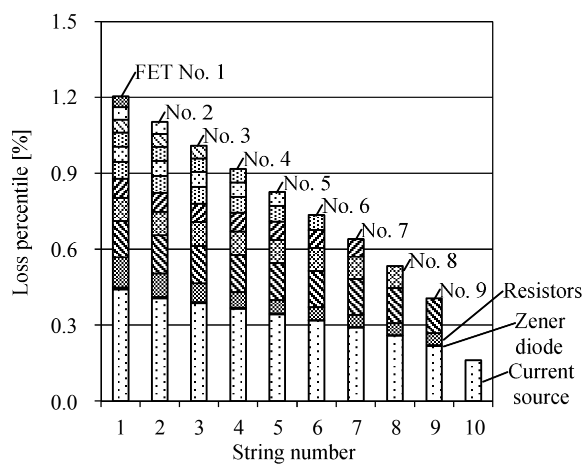


Figure 5. Equivalent circuit of gate driver.



(a) 5 strings

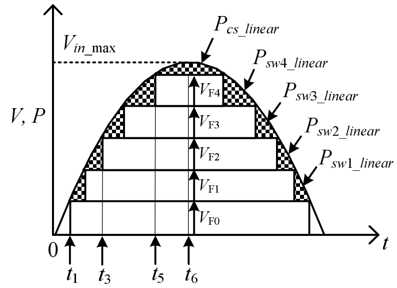


(b) 10 strings

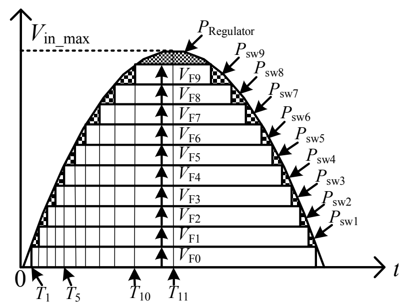
Figure 6. Loss distribution of each string.

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).



(a) 5 strings



(b) 10 strings

Figure 7. Semiconductor losses.

$$t_a = \frac{1}{\omega}\sin^{-1}\frac{\sum_{x=0}^{a-1} V_{Fx}}{V_{in\_max}} \quad (2)$$

where ω is a angular frequency of the input voltage, $V_{\mathrm{in\_max}}$ is a peak input voltage, V_{fx} is a forward voltage of the LEDs shown in Fig. 4.

The active region loss of the MOSFETs are expressed as (3)

$$P_{swa\_linear} = 4 f_{V_{in}} I_{str}\left(V_{in\_max}\int_{t_a}^{t_{a+1}}\sin\omega t dt - (t_{a+1}-t_a)\sum_{x=0}^{n-1} V_{Fx}\right) \quad (3)$$

where f_{Vin} 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).

$$P_{swa\_cond} = 4 f_{V_{in}} R_{on} I_{str}^{\ 2}(t_{n+2}-t_a) \quad (4)$$

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

$$P_{cs\_linear} = 4 f_{V_{in}} I_{str}\left(V_{in\_max}\int_{t_{n+1}}^{t_{n+2}}\sin\omega t dt - (t_{n+2}-t_{n+1})\sum_{x=0}^{n} V_{Fx}\right) \quad (5)$$

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

$$P_{cs\_cond} = 4 f_{V_{in}} I_{str} V_{on}(t_{n+2}-t_1) \quad (6)$$

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_{ds} of the MOSFET in simulation. Thus, the current is divided into a MOSFET and a LED. Therefore, the drain current of the MOSFET is decreased.

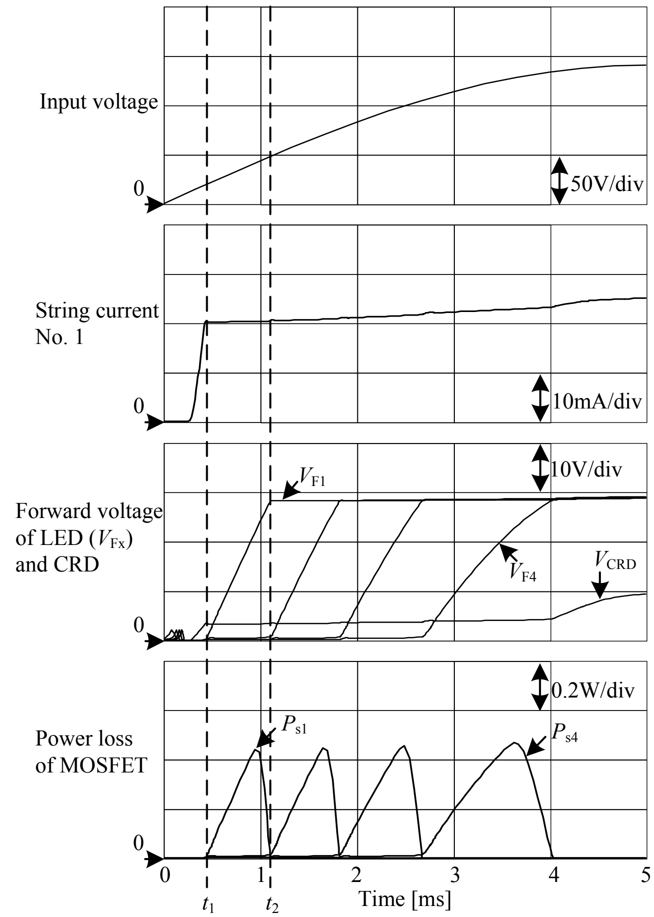


Figure 8: Simulation waveforms.

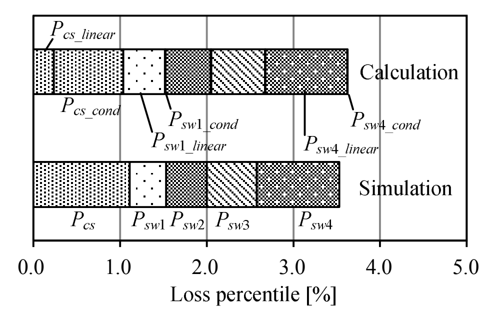


Figure 9. Loss distribution of the first string. (5 strings)

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.

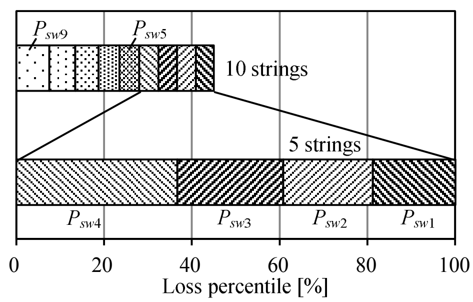
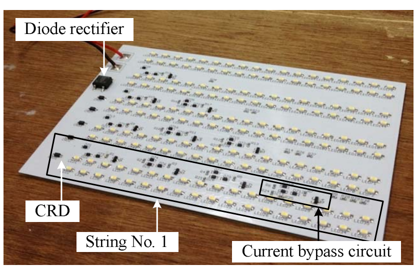


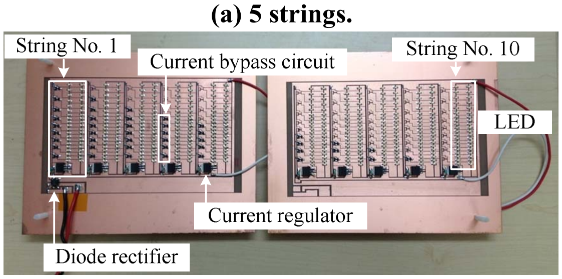
Figure 10. Switch loss comparison of string No. 1.

Table 3. Specification of 5 strings prototype and sample product.

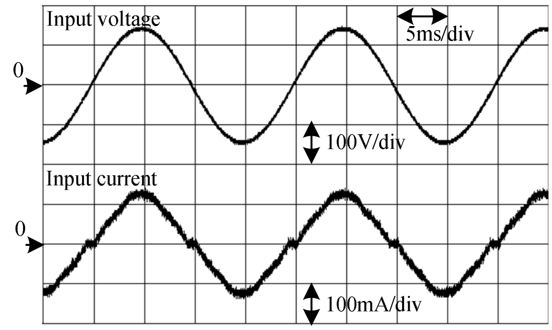
	Proposed circuit (5 strings)	Step-down chopper (Sample product)
Input power [W]	7.8 W	11.0 W
Luminous flux [lm]	751	810
Luminous efficiency [lm/W]	96	74
Power factor	0.995	0.79



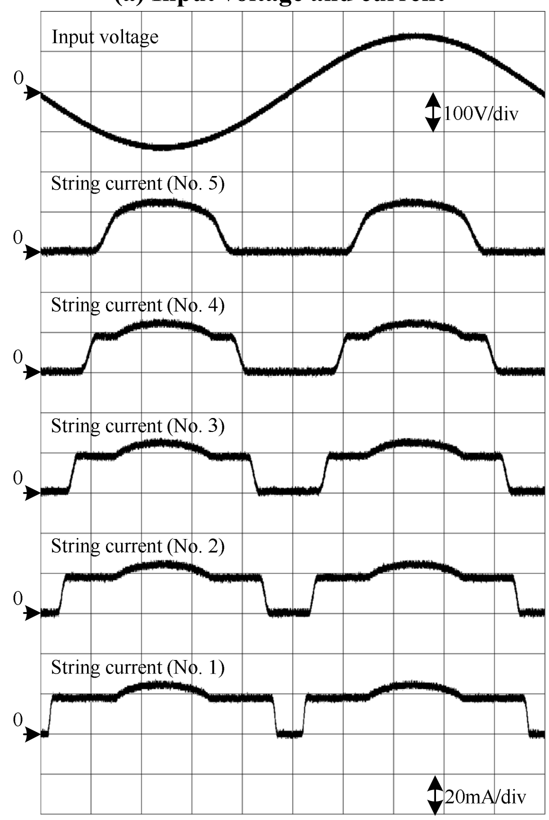
(a) 5 strings.



(b) 10 strings.
Figure 11. Prototype of experiment.



(a) Input voltage and current



(b) String current
Figure 12. Experimental waveforms of the proposed 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-don 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

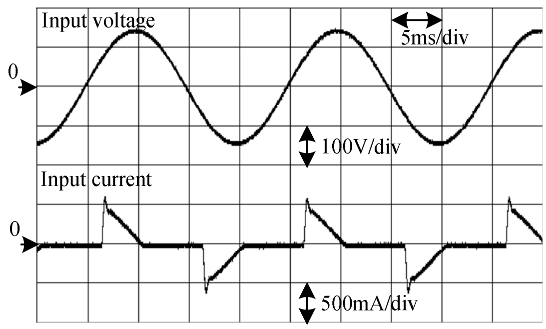
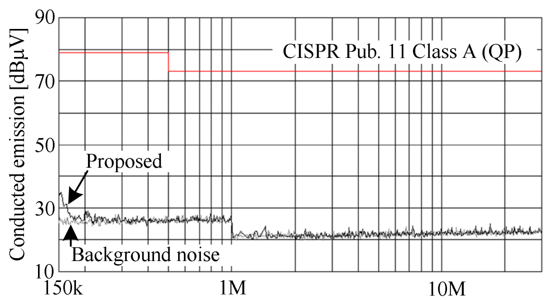
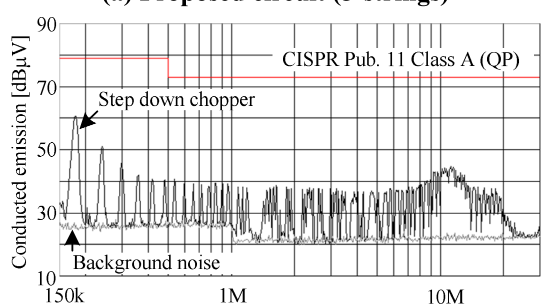


Figure 13. Experimental waveforms of the step-down chopper circuit.



(a) Proposed circuit (5-strings)



(b) Step-down chopper circuit

Figure 14. Conducted emission spectrum.

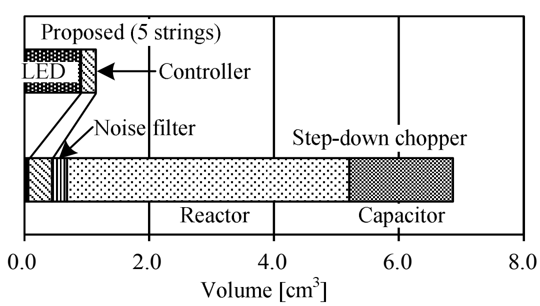


Figure 15. Volume of circuit component.

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.

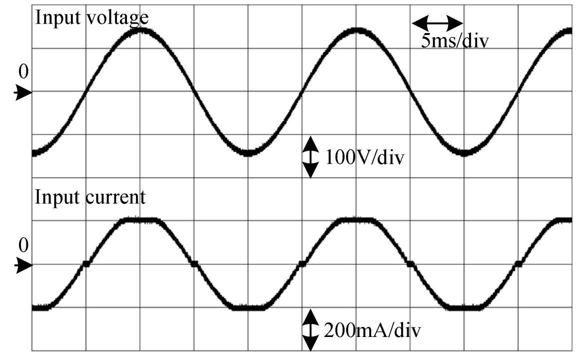


Figure 16. Experimental waveforms. (10 strings)

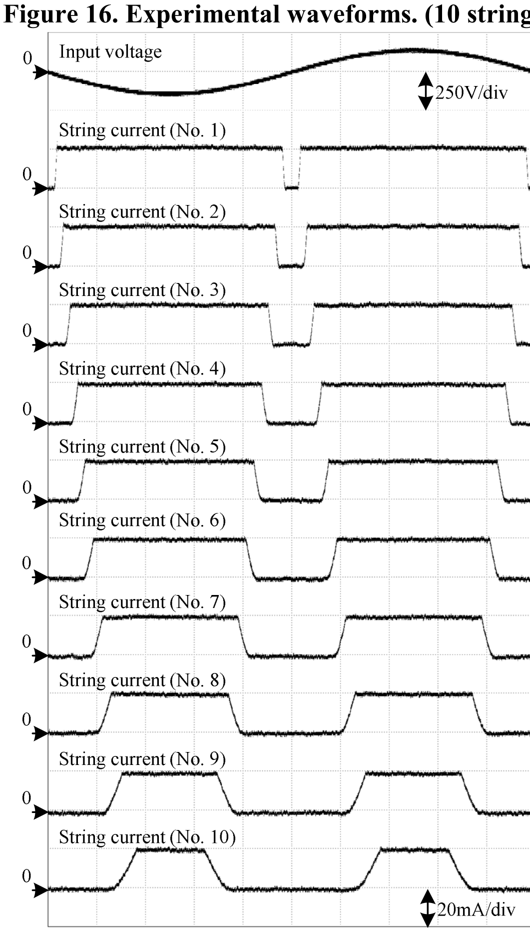


Figure 17. Experimental results of string current.

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_F 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.

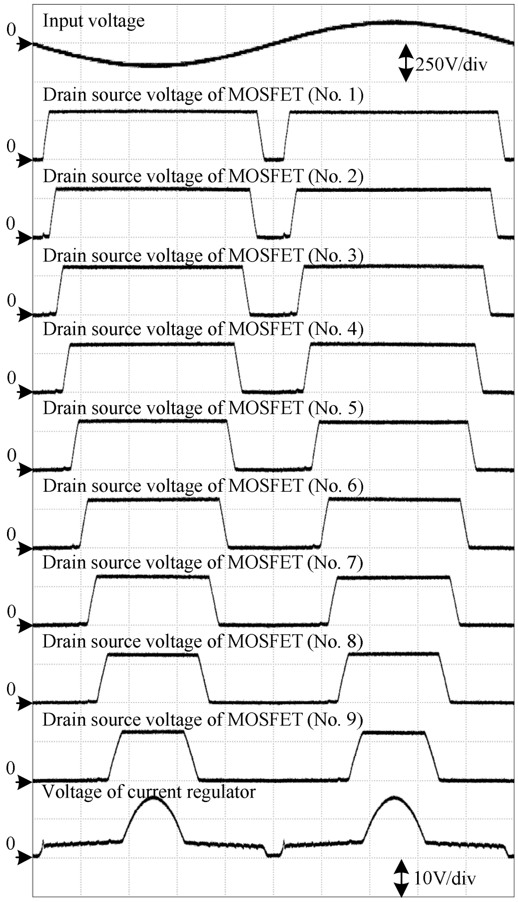


Figure 18: Experimental results of V_{ds} and V_{on}.

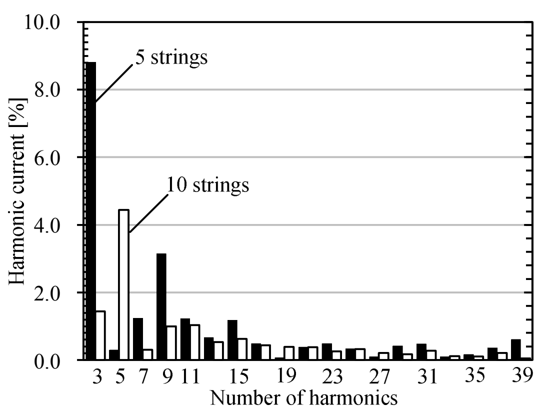


Figure 19. Input current harmonics.

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

[1] Bessho Makoto, Shimizu Keiichi : "Trends in LED Lighting and Toshiba's approach", Toshiba review, Vol. 65, No. 7 pp. 2-7 (2010)

[2] M. S. Shur and A. Zukauskas, "Solid-state lighting: Toward superior illumination," Proceedings of the IEEE, Vol. 93, No. 10, pp. 1691–1703, Oct. 2005.

[3] H. Broeck, G. Sauerlander, and M. Vendt, "Power driver topologies and control schemes for LEDs," IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1319–1325, 2007.

[4] Takashi Kunimatsu, Keita Kawabe, Toshifumi Ishida : "Development of Driver IPD for LED Lighting", Panasonic Technical Jorunal, Vol. 58, No. 1, pp. 18-23 (2012)

[5] B. Wang, X. Ruan, K.Yao, and M.Xu "A Method of Reducing the Peak-to-Average Ratio of LED Current for Electrolytic Capacitor-Less AC–DC Drivers," IEEE Transactions on Power Electronics, vol. 25, no. 3, pp. 592–601, Mar. 2010.

[6] Hideaki Fujita, "A High-Efficiency Diode-Clamped Linear Amplifier", The transactions of the Institute of Electrical Engineers of Japan. D A publication of Industry Applications Society, Vol. 127, No. 1 pp. 9-16 (2007)

[7] R. Dayal, K. Modepalli, L. Parsa "A direct AC LED driver with high power factor without the use of passive components," IEEE Energy Conversion Congress and Exposition (ECCE), pp. 4230–4234, 2012.

[8] "Sequential Linear LED Driver CL8800," Supertex inc. , DSFP-CL8800, 2012, Available: http://www.supertex.com

[9] S. Lynch, B. Choy, K. C, "MULTIPLE STAGE SEQUENTIAL CURRENT REGULATOR," International Patent, WO 2012/142495 A1, 18 Oct. 2012.