Abstract — A charge pump drive circuit for LED lighting is proposed. This circuit is realized with repeated use of a compact unit module consisted of a capacitor and diodes. The series-charge and parallel-discharge operation gives the efficiency better than the conventional converters with ac line input. This paper also shows how to minimize the number of modules for a given number of LEDs. A prototype implemented the charge pump drive circuit shows a maximum efficiency of 95% for 22 LEDs in series with the ac line voltage of 220 Vrms.

I. INTRODUCTION

Light emitting diodes (LEDs) are attracting public attention for general lighting these days. It is expected that LEDs will replace incandescent light bulbs or fluorescent lamps as fabrication processes, device designs and assembly technologies grow [1]-[2]. Together with the advance of LED devices, the development of driving circuit is also important to improve the performance and to reduce the manufacturing cost for LED lighting. Fig. 1 shows previously reported LED driver, which is buck type DC-DC converters [3]. The number of components is few in this driver. But DC-DC converters, such as Fig. 1, and flyback converters [4] have bulky magnetic components such as transformer and inductor. And large rms-current causes power-loss when ac line is input source. Therefore this paper proposes a compact and efficient power conversion circuit, which is a charge pump drive circuit with the series-charge and parallel-discharge operation.

In Section II, the proposed drive circuit is described in detail. Operation that drives a gate signal with low voltage IC and cascade structure are addressed in Section III. Section IV presents experimental results obtained from a prototype. Finally, a conclusion is given in Section V.

![Figure 2](a) Proposed charge pump drive circuit for LED lighting
(b) Timing diagram for switch operation

Figure 1. Previously reported LED driver

Figure 2. (a) Proposed charge pump drive circuit for LED lighting
(b) Timing diagram for switch operation
II. PROPOSED CIRCUIT DESCRIPTION

In Fig. 2(a), capacitors are used for charge pumping because they transfer the stored energy to the load next step after storing the energy. This structure may be considered to have the replica of module with a capacitor and three diodes. So output power can be changed easily according to addition of the module. The switching phase of M1 is the opposite to that of M2 as in Fig. 2(b). It results in driving the output LEDs with pulsating currents. If the average LED current is kept constant, the pulsed current does not have any effect on the emitted optical power [5].

The equivalent charging and discharging circuits are shown in Fig. 3(a) and (b), respectively, where $V_d$ denotes the forward voltage of a diode in conduction, $r_c$ the series resistance of a capacitor, and $R_L$ the load LED assuming $I_{on}$ is constant during the charging interval. If M1 switch is turned on, the current from main source flows through capacitors and diodes in series while charging capacitors as in Fig. 3(a). The voltage across a capacitor is determined by the number of modules, as in

$$V_{cap} = \frac{V_d - n(V_d + r_c I_{on})}{n}$$

(1)

where $n$ is the number of modules and $V_{cap}$ is voltage across a capacitor. And then in Fig. 3(b), if M2 is turned on, each capacitor supplies current to output load LEDs as a voltage source.

$$V_{LED} \approx V_{cap} - 2V_d - I_{on} r_c$$

(2)

The efficiency is defined as

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\frac{1}{2}V_d^2}{nV_d} = \frac{\frac{1}{2}V_d}{nV_d}$$

(4)

where a tilde (’) signifies a steady-state value and $d$ is the duty ratio [6]. Therefore, the efficiency of a driver does not depend on the values of parasitic components, or switching frequency, and it is not affected even by the load value. It depends solely on the ratio between the required output voltage and the input voltage, and the number of capacitors in the charge pump modules.

III. CONTROL OF LED DRIVER

A. A driving method for high side floating switch

Fig. 4 shows driving circuit of M1 and M2 including charge pump modules. A high voltage IC is required to drive a M2 that operates on the floating level. But when low cost LED lighting market is considered, low voltage IC is potential solution. Thus the method that drives a high side floating switch with low voltage IC, U1, is shown in Fig. 4.

If M1 is turned on, the gate of M2 is discharged through D4. So M2 is turned off. At this time, C1 is charged from the supply voltage of gate driver U1, $V_b$, as in Fig. 5(a). And then, if M1 is turned off and the voltage level of $V_c$ is driven to high voltage, Q2 is triggered by the voltage over $R_2$ in Fig. 5(b). Fig. 5(c) shows that the npn structure composed of Q1 and Q2 sources the gate charge of M2 rapidly by positive feedback action. And the turn-on delay of M2 can be changed by the adjustment of $R_3$ and $C_2$.

B. A cascade structure of charge pump modules

The proposed circuit needs more modules to generate low output power. Equation (2) is the voltage across LEDs when a driver has charge pump module shaped with single-stage. The charge pump module composed of single-stage increases the number of components in proportion to that of module. But charge pump modules can be separated into cascade stage to reduce the number of components efficiently as shown in Fig. 6. In case of cascade stage of Fig. 6, when the first stage is in charging phase, the second stage discharges in parallel because gate signals of M1 and M2 have the opposite phase.

The voltage across LEDs can be expressed as (5) for a driver with cascade stage.
Figure 5. The mode operation of driving circuit for floating switch; (a) M2-Off mode, (b) M2-On mode (triggering), (c) M2-On mode (positive feedback action)

\[ V_{LED} = \frac{V_i}{n_1 n_2 n_3 \cdots n_n} \]  

(5)

where \( n_a \) is the number of modules in \( n \)th stage. And it is assumed that forward-bias voltage of diode and the series resistance of a capacitor are omitted. The relation of the number of modules in single-stage driver and cascade stage driver is given by

\[ n = n_1 n_2 n_3 \cdots n_n \]  

(6)

to transfer the same power to LEDs ((1) = (5)). Therefore

\[ n > n_1 + n_2 + n_3 + \cdots + n_n \]  

(7)

where \( n_1 \) to \( n_n \) is the number of modules in single-stage and the sum of \( n_1 \) to \( n_n \) is a total number of modules in cascade stage.

Suppose that output voltage across LEDs is 1/16 of input voltage. If single-stage circuit is used, 16 modules needs. So LED driver requires around 16 capacitors and 48 diodes because a module has a capacitor and three diodes. But in case of cascade stage, same output voltage can be generated if first and second stage has only 4 capacitors respectively. At this structure, total 8 capacitors and 24 diodes are required with 50 \% reduction of components. Therefore it is concluded that LED driver with modules which separated into cascade stage can reduce the number of components efficiently.

Fig. 7 shows the equivalent circuit for the generalized charge pump driver with cascade stage assuming \( I_{on} \) is constant current at \( n \)th stage. The efficiency is defined as followings.

\[ \eta = \frac{P_{out}}{P_{in}} = \frac{V_{out}^2 / R_L}{dV/I_{on}} = (n_1 n_2 \cdots n_n) \frac{V_o^2}{V_i} \]  

(10)

Therefore, the efficiency of generalized driver also depends on the ratio between the required output voltage and the input voltage, and the multiplication of capacitors in the charge pump modules of each stage.

IV. EXPERIMENTAL RESULTS

A prototype of the proposed charge pump drive circuit for LED lighting illustrated in Fig. 2(a) has been built. The prototype is realized as a single-stage solution, with four modules. The white LED device used is a W42180 model that has a threshold voltage of 2.5 V. And the supply voltage is 220 \textit{Vrms} and a capacitor for charge pumping determines the charging or discharging time. We used a capacitor of 1\textmu F in a prototype.

Fig. 8 shows waveforms of driving circuit for a high side floating switch. In Fig. 8(a), \( V_{ds1} \) is drain-source voltage of M1 with source connected ground. And \( V_{gs2} \) is gate-source voltage of floating switch, M2, connected LEDs. The waveforms of Fig. 8(a) were captured in the instant of M2-off and M1-on. Shoot-through problem does not occur because \( V_{gs2} \) leads \( V_{ds1} \). From Fig. 8(b), it is
verified that output current does not have any peaking pulse.

Fig. 9 shows the waveforms of output voltage and current with an array of 22 LEDs at the switching frequency of 1kHz, 5kHz and 10kHz. The operating current of LED has an exponential curve and has enough discharging time as switching frequency gets smaller. The peak voltage of LED is around 75V and the peak current is around 600mA.

It is verified that the output power is changed by varying the switching frequency in Fig. 10. And the operation at very high frequency is no more useful because the output power is nearly flat over 20 kHz. Dimming control can be considered at the frequency below 20kHz. As the number of LEDs is fewer, the variation of output power according to frequency is larger because voltage across LEDs is already fixed by the number of module.

Fig. 11 shows power efficiency versus frequency. A maximum efficiency is 95% at the switching frequency of 10 kHz for an array of 22 LEDs. At high frequency, the efficiency goes down due to switching loss.

Fig. 12. Efficiency comparison at fixed output power
Fig. 12 shows a comparison of power efficiency at fixed output power. A maximum efficiency is all over 90% and different number of LEDs is required for high efficiency at each output power. For example, if LED lighting which generates an output power of 12W is required, using 23 LEDs is a good selection as the efficiency.

The prototype picture of proposed circuit is shown in Fig. 13.

![Prototype picture of the proposed circuit](image)

**Fig. 13. Prototype picture of the proposed circuit**

V. CONCLUSION

A charge pump drive circuit for LED lighting is proposed. A conventional driver which composed of magnetic component is bulk and has power loss due to large rms-current. But proposed charge pump driver is compact because it consists of modules with a capacitor and diodes. And output power can be changed easily according to addition of the module unit. Series-charge and parallel-discharge method can transfer input power to output LEDs efficiently. Thus it gives the efficiency better than the conventional drivers. And the efficiency of a driver depends solely on the ratio between the required output voltage and the input voltage, and the number of capacitors in the charge pump modules.

The control method and efficient structure of system based on charge pump are presented. The method that drives a high side floating switch with a low voltage IC yields a low cost system even though surrounding components are included. The charge pump module which has a structure of cascade stage can generate a required LED voltage with a half of components than single-stage circuit. Thus cascade stage method reduces the number of components efficiently and lowers the cost.

Table 1 shows features of LED driver with different driving topologies. Proposed charge pump LED driver has the improved efficiency.

Table 1. Features of LED driver with different driving topologies

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<tr>
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<tbody>
<tr>
<td>Driving method</td>
<td>Charge Pump</td>
<td>Series Resonant</td>
<td>Buck</td>
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<tr>
<td>Input Voltage</td>
<td>220 Vrms</td>
<td>220 Vrms</td>
<td>220 Vrms</td>
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<td>Output current range</td>
<td>100mA – 800mA</td>
<td>100mA – 800mA</td>
<td>700mA (max)</td>
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<td>Efficiency</td>
<td>95% @ 15W, 10kHz</td>
<td>85.7% @ 20W, 50kHz</td>
<td>75% @ 20kHz</td>
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