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<th>Elimination of an Electrolytic Capacitor in AC/DC Light-Emitting Diode (LED) Driver With High Input Power Factor and Constant Output Current</th>
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Abstract—While LEDs enjoy relatively long lifetime up to 10 years, the lifetime of traditional LED drivers using electrolytic capacitor as storage element is limited to typically less than 5 years. In this paper, an ac/dc LED driver without electrolytic capacitor is studied. Compared with other methods to eliminate electrolytic capacitor, the proposed driver has the advantages of almost unity input power factor and constant output current for LEDs. The operation principle, detailed design procedure of the main circuit, and control strategy are presented. The feasibility of the proposed converter has been successfully verified by experiments.

Index Terms—AC/DC LED drivers, electrolytic capacitors, lifetime, light-emitting diodes (LEDs).

I. INTRODUCTION

LED technology has now emerged promising technology to replace conventional lighting devices [1]. Reports in [2]–[6] have demonstrated the LED color and multistring brightness control, particularly in display applications. The long lifetime of LED in the range of 80 000–100 000 h [7] stands out the relatively short lifetime problem of many existing LED drivers using electrolytic capacitors as the energy storage. It is well known that the lifetime of a high-quality electrolytic capacitor is typically 10 000 h at 105 °C. It is temperature dependent due to the use of liquid electrolyte and is reduced by half for every 10 °C rise in operating temperature [8]. The big difference in the lifetimes of the LED devices and the drivers justifies the need for eliminating the electrolytic capacitor in the LED drivers.

Recently, several methods have been proposed to eliminate electrolytic capacitors in ac/dc drivers for LED applications [9]–[15]. Fig. 1 shows the circuit diagram of the ac/dc driver for an LED application. It is known that the electrolytic capacitors in the ac/dc LED driver are used to balance the energy difference between the input pulsating power and the output constant power. Hence, if the electrolytic capacitors are reduced or eliminated in the driver, the key issue is how to tackle the I/O power imbalance.

The first approach is to modulate the line input current shape. If the peak-to-average ratio of the input pulsating power is reduced, the less storage capacitance will be needed to balance the energy difference between the instantaneous input power and the output constant power. In [9] and [10], the third- and fifth-harmonic signals are injected into the input current to reduce the peak-to-average ratio of the input power. In [11], a control strategy based on a distorted sinusoidal reference in a power factor correction (PFC) converter is proposed to modulate the line input current, which reduces the input pulsating power and allows the reduction of the output capacitance. The advantage of these methods is that traditional main circuits (such as Boost and Flyback converters) can be needed and only modifications on the control circuits are needed. However, the shortcoming of this approach is that the input power factor is reduced.

The second approach is to use pulsating current or current with relatively large ripple to drive LEDs. If the output power is pulsating and equal or close to the instantaneous input power, then no or a little storage capacitor will be needed to balance the energy difference between the input power and the output power. In [12]–[14], two kinds of topologies are proposed for the LED driver, in which LEDs are driven with pulsating current at twice the line frequency. In [15], a reliable passive LED driver is proposed with the help of the general photoelectrothermal theory for LED systems, in which LEDs are driven with relative large current ripple. This approach is suitable for applications, in which tight LED power control is not needed and reliability is critical, such as public/road lighting systems, but is not suitable for some applications in which system compactness and tight current control are of priority.

The third approach is to adopt some energy storage elements to handle the power difference [16]–[27]. From the energy storage element viewpoint, it can be classified into magnetic and capacitive elements [16]. Inductors (magnetic element) are employed as the energy storage element in [17] and [18]; when the input power is lower than the output power, the magnetic

Fig. 1. Block diagram of the ac/dc driver for LED application.
energy stored in the inductor is delivered to the output terminal to compensate the deficit; when the input power is larger than the output power, the excessive energy will be stored in the inductor. Therefore, a bulky electrolytic capacitor can be reduced or eliminated. In [19], a passive LC resonant circuit is employed as the energy storage element. The main disadvantage of the use of inductor as the energy storage element is relatively larger magnetic core loss and winding loss. Compared with inductor, the use of a capacitor (capacitive element) as the energy storage element is almost lossless. The basic concept behind the reduction or elimination of a bulky electrolytic capacitor is to utilize small capacitance with large voltage ripple for energy storage instead of large capacitance with small voltage ripple [20]. Generally speaking, the topologies using capacitor with large voltage ripple for energy storage can be categorized into series-capacitor structure [20]–[24] and parallel-capacitor structure [25]–[27]. The former one means that the capacitor handles all the I/O energy and the latter one means that the capacitor handles parts of the I/O energy. A single-stage Boost–Flyback PFC converter with large dc bus voltage ripple is proposed in [20] and [21], in which the input energy is delivered to the bus capacitor through Boost, and then the energy stored in the bus capacitor is transferred to the output through Flyback. In [22] and [23], the input energy is delivered to the storage capacitor through the Flyback or single-ended primary-inductor converter, and then the energy is transferred to the output from the capacitor through Flyback. The bulky electrolytic capacitor in these topologies is reduced or eliminated, but the efficiency of the whole system is aggravated because the entire energy is processed twice to reach the output. Recently, several topologies belonging to capacitor parallel structure have been proposed [25]–[27]. In [25] and [26], a current pulsation smoothing parallel active filter for single-stage photovoltaic (PV) power to ac grid module is presented, in which a bidirectional Buck–Boost circuit is connected in parallel to the dc bus. A three-port structure converter with dedicated power ripple port is proposed in [27], in which minimum capacitance requirement can be achieved.

A novel Flyback ac/dc driver without electrolytic capacitor for an LED application is proposed in this paper. It not only achieves near-unity input power factor, but also provides constant output current for LEDs, which is essential for applications requiring tight current control. The paper is organized as follows. Section II gives the operation principle of the driver. The detailed designs of the main circuit and control strategy are presented in Section III. The experimental results of a 13.5-W experimental prototype are shown in Section IV and a conclusion is given in Section V.

II. CIRCUIT CONFIGURATION AND OPERATION PRINCIPLE

Fig. 2 shows the circuit configuration of the proposed ac/dc LED driver. $D_{r1}$–$D_{r4}$ are the input rectifier diodes. $T_r$ is the Flyback transformer, in which $N_{p1}$ and $N_r$ are the primary and secondary windings of the traditional Flyback transformer, and $N_{p2}$ is an additional auxiliary winding. $C_o$ is the energy storage capacitor with large voltage ripple. $Q_1$–$Q_2$ are the main switches. $D_{r2}$ is the output rectifier diode. $D_{a1}$ is the freewheeling diode. $D_{a2}$ is the blocking diode to block the reverse current flowing through $Q_2$, $C_o$ is the output filter capacitor.

The key waveforms of the proposed ac/dc LED driver are shown in Fig. 3. $Q_1$ is controlled to keep the duty cycle almost unchanged in a line period and the Flyback converter is designed to operate in discontinuous current mode (DCM) so that a high input power factor can be automatically achieved. During the line period when the input power $P_{in}$ is lower than the output power $P_o$, $Q_3$ is turned on all the time and $Q_2$ is controlled to achieve the constant output current for the LED load. $C_o$ is discharged, the stored energy is delivered to the output to compensate the deficit and hence $v_{ca}$ decreases. When $P_{in} > P_o$, $Q_2$ is turned off and $Q_1$ is controlled to achieve the constant output current for the LED load. The excessive input energy will be transferred into $C_o$ and hence $v_{ca}$ increases. Therefore, the operating mode for the period of $P_{in} < P_o$ is different from that for the period of $P_{in} > P_o$. The switching sequences under different input power conditions are shown in Fig. 4. It should be noted that $i_m$ is the magnetizing current reflected to the primary winding $N_{p1}$.

A. Operating Modes When $P_{in} < P_o$

Fig. 4(a) shows the key switching sequence when $P_{in} < P_o$. There are four switching stages in a switching period, and the corresponding equivalent circuits are shown in Fig. 5.
1) Stage A1 \([t_0, t_1]\) [see Fig. 5(a)]: Before \(t_0\), \(i_p\), and \(i_m\) are zero, and the LED load is powered by \(C_o\). At \(t_0\), \(Q_1\) is turned on. It should be noted that \(Q_3\) is always ON within the period of \(p_{in} < P_o\). \(D_r1\) and \(D_r4\) (or diagonal diodes \(D_r2\) and \(D_r3\)) conduct. Assuming input voltage \(v_{in}\) remains unchanged during a switching period, \(i_m\) increases linearly as

\[
i_m(t) = \frac{|v_{in}(t)|}{L_1} (t - t_0)
\]

where \(L_1\) is the self-inductance of the primary winding \(N_{p1}\).

2) Stage A2 \([t_1, t_2]\) [see Fig. 5(b)]: At \(t_1\), \(Q_1\) is turned off and \(Q_2\) is turned on. Although \(Q_1\) is ON, no current flows through it because the dot side of the secondary winding is negative. After \(Q_2\) is turned on, \(C_a\) is discharged and \(i_m\) continues increasing linearly, assuming the voltage \(v_{ca}\) keeps unchanged during a switching period

\[
i_m(t) = \frac{v_{ca}(t) N_{p1}}{L_1 N_{p2}} (t - t_1) + \frac{|v_{in}(t)|}{L_1} (t_1 - t_0)
\]

\[
= \frac{v_{ca}(t) N_{p1}}{L_1 N_{p2}} (t - t_1) + \frac{|v_{in}(t)|}{L_1} D_1 T_s
\]

where \(D_1\) and \(T_s\) are the duty cycle of \(Q_1\) and switching period, respectively.

3) Stage A3 \([t_2, t_3]\) [see Fig. 5(c)]: At \(t_2\), \(Q_2\) is turned off; the energy stored in the transformer is released through the secondary winding to the output. Referring to (2), the magnetizing current at \(t_2\) is

\[
I_m(t_2) = \frac{v_{ca}(t) N_{p1}}{L_1 N_{p2}} (t_2 - t_1) + \frac{|v_{in}(t)|}{L_1} D_1 T_s
\]

\[
= \frac{v_{ca}(t) N_{p1}}{L_1 N_{p2}} D_2 T_s + \frac{|v_{in}(t)|}{L_1} D_1 T_s
\]

where \(D_2\) is the duty cycle of \(Q_2\).
Because $i_m$ is the magnetizing current reflected to the primary winding $N_{p1}$, the magnetizing current reflected to the secondary winding $N_s$ is $i_m N_{p1}/N_s$. The self-inductance of the secondary winding is $L_1 N_s^2/N_{p1}^2$. Hence, the secondary current $i_R$ is

$$i_R(t) = \frac{I_m(t_2) N_{p1}}{N_s} - \frac{V_o N_{p1}^2}{L_1 N_s^2} (t - t_2). \quad (4)$$

At $t_3$, $i_R$ reduces to zero. The time interval of $t_3 - t_2$ is expressed as

$$\Delta T_1 = t_3 - t_2 = \frac{I_m(t_2) L_1 N_s}{V_o N_{p1}}. \quad (5)$$

4) Stage A4 [$t_3$, $t_4$] [see Fig. 5(d)]: During this mode, no current flows through the transformer winding and the transformer is initialized. $C_o$ supplies the current to the LED load. When $p_{in} < P_o$, in order to keep the output current and thus output power constant, energy is also provided by $C_o$. Because the duty cycle of $Q_3$ is kept unchanged during a line period, the duty cycle of $Q_2$, which corresponds to energy release, should be used to regulate the output current.

B. Operating Modes When $p_{in} > P_o$

Fig. 4(b) shows the key switching sequence when $p_{in} > P_o$. There are four switching stages in a switching period, and the corresponding equivalent circuits are shown in Fig. 6.

1) Stage B1 [$t_0$, $t_1$] [see Fig. 6(a)]: Similar to Fig. 5(a), $Q_1$ is turned on and the input voltage causes the current in the magnetizing inductor to increase during this stage. It should be noted that $Q_2$ is always off during the line period when $p_{in} > P_o$.

2) Stage B2 [$t_1$, $t_2$] [see Fig. 6(b)]: At $t_1$, $Q_1$ is turned off and $Q_3$ is turned on. Then, the energy stored in the transformer is released through the secondary winding to the output. Referring to (1) and similar to (4), $i_R$ can be expressed as follows:

$$i_R(t) = \frac{I_m(t_1) N_{p1}}{N_s} - \frac{V_o N_{p1}^2}{L_1 N_s^2} (t - t_1)$$

$$= \frac{|v_{in}(t)| N_{p1}}{L_1 N_s} (t_1 - t_0) - \frac{V_o N_{p1}^2}{L_1 N_s^2} (t - t_1)$$

$$= \frac{|v_{in}(t)| N_{p1}}{L_1 N_s} D_1 T_1 - \frac{V_o N_{p1}^2}{L_1 N_s^2} (t - t_1). \quad (6)$$

In order to keep the output current constant, the released energy to the output must be constant in a switching period. At $t_2$, $Q_3$ is turned off. Referring to (6), $i_R$ at $t_2$ can be written as

$$I_R(t_2) = \frac{|v_{in}(t)| N_{p1}}{L_1 N_s} D_1 T_1 - \frac{V_o N_{p1}^2}{L_1 N_s^2} (t_2 - t_1)$$

$$= \frac{|v_{in}(t)| N_{p1}}{L_1 N_s} D_1 T_1 - \frac{V_o N_{p1}^2}{L_1 N_s^2} D_3 T_s \quad (7)$$

where $D_3$ is the duty cycle of $Q_3$.

For the proper operation of this stage, the minimum values of $v_{ca}$, $V_{ca,min}$ must satisfy

$$V_{ca,min} > \frac{V_o N_{p1}}{N_s}. \quad (8)$$

3) Stage B3 [$t_2$, $t_3$] [see Fig. 6(c)]: After $Q_3$ is turned on, the excessive energy, which is stored in the transformer, is released to $C_o$ through the primary winding $N_{p1}$ and $D_{ca}$. $C_o$ is charged and $i_m$ decreases linearly, assuming that $v_{ca}$ remains unchanged during a switching period.

$$i_m(t) = \frac{I_R(t_2) N_s}{N_{p1}} - \frac{v_{ca}(t)}{L_1} (t - t_2). \quad (9)$$

At $t_3$, $i_m$ reduces to zero. The time interval of $t_3 - t_2$ is expressed as

$$\Delta T_2 = t_3 - t_2 = \frac{I_R(t_2) N_s L_1}{V_o N_{p1} v_{ca}(t)}. \quad (10)$$

4) Stage B4 [$t_3$, $t_4$] [see Fig. 6(d)]: During this mode, no current flows through the transformer winding and the transformer is initialized. $C_o$ supplies the current to the LED load. When $p_{in} > P_o$, in order to keep the output current and power constant, the excessive energy is absorbed by $C_o$. Because the duty cycle of $Q_1$ is kept unchanged during a line period, the duty cycle of $Q_3$, which corresponds to energy release to the output, should be used to regulate the output current.

From the previous analysis, it can be seen that only two out of three main switches have switching actions during a switching period, leading to the possibility of reduced switching losses and higher conversion efficiency.

Compared with existing methods presented in [10] and [20] that reduce the input power factor when the electrolytic capacitors are replaced, the proposed LED driver can improve and achieve near-unity input power factor. The method in [10] aims to reduce the peak-to-average ratio of the input pulsating power but cannot ensure the instantaneous input power to be equal to the output power. The sizes of the output filter capacitor in [10] and [20] are 141 µF and 660 µF, respectively, for an output power of 60 W, while that in this proposal is 10 µF for an output power of 13.5 W. In addition, the energy storage capacitor in this proposal can effectively balance the I/O energy. Also, the proposed LED driver involves a parallel-capacitor structure. It has a higher conversion efficiency compared with series-capacitor structure, in which the energy storage capacitor handles all the I/O energy [20], [24].

III. CIRCUIT DESIGN AND CONTROL STRATEGY

A. Main Circuit Design

For a single-phase ac/dc driver, the input voltage can be expressed as

$$v_{in}(t) = V_m \sin \omega t \quad (11)$$

where $V_m$ is the peak value of the input voltage and $\omega$ is the line angular frequency.
Referring to Fig. 3, for an ac/dc LED driver with unity power factor and constant output current, the needed storage capacitor and its waveform can be expressed as [10]

\[
C_a = \frac{2P_o}{\omega(V_{ca,max}^2 - V_{ca,min}^2)} = \frac{P_o}{\omega \Delta V_{ca} V_{ca}} \tag{12}
\]

\[
v_{ca}(t) = \sqrt{V_{ca,min}^2 + \frac{P_o}{\omega C_a} (1 - \sin 2\omega t)} \tag{13}
\]

where \(V_{ca,max}\) is the maximum value of \(v_{ca}\), \(\Delta V_{ca} = V_{ca,max} - V_{ca,min}\) is the amplitude of the voltage ripple, and \(V_{ca}\) is the average amplitude of \(v_{ca}\).

To keep the output current constant, the average current through \(Q_3\) in a switching period must be equal to the output current \(I_o\). From (3) to (5), we can determine that when \(p_{in} < P_o\), the average current through \(Q_3\) is

\[
\frac{I_m(t_2) \Delta T_1 N_p}{2 N_s T_s} = I_o \tag{14}
\]

From (6) and (7), it can be shown that when \(p_{in} > P_o\), the average current through \(Q_3\) is

\[
\frac{1}{2} \left( \frac{|v_{in}(t)| N_p}{L_1 N_s} D_1 T_s + I_o (t_2) \right) D_3 = I_o \tag{15}
\]

For the Flyback PFC converter operating under DCM, we have [10]

\[
I_o = \frac{V_m^2 D_3^2}{4 L_1 V_o f_s} \tag{16}
\]

where \(f_s\) is the switching frequency.

Because the proposed LED driver must be operated under DCM to achieve a high input power factor, the sum of the time interval on stages 1–3 under different input power conditions must satisfy the following equations:

\[
T_{sum1} = D_1 T_s + D_2 T_s + \Delta T_1 \leq T_s \quad (p_{in} < P_o) \tag{17}
\]

\[
T_{sum2} = D_1 T_s + D_3 T_s + \Delta T_2 \leq T_s \quad (p_{in} > P_o) \tag{18}
\]

From (16), we have

\[
D_1 T_s = \frac{2 \sqrt{P_o L_1 T_s}}{V_{in}} \tag{19}
\]

From (3), (4), (5), and (14), we can obtain

\[
I_m(t_2) = \frac{2 P_o T_s}{L_1} \tag{20}
\]

\[
\Delta T_1 = \frac{N_p \sqrt{2 P_o L_1}}{V_{ac} N_p} \tag{21}
\]

\[
D_2 T_s = (1 - \sqrt{2 |\sin \omega t|}) \frac{N_{p2} \sqrt{2 P_o L_1}}{v_{ca}(t) N_p} T_s \tag{22}
\]

It can be seen that \(\Delta T_1\) is constant for a given ac/dc LED driver and \(D_1\) can reach its maximum value at the minimum input voltage, i.e.,

\[
D_{1,max} T_s = \frac{2 \sqrt{P_o L_1 T_s}}{V_{min}} \tag{23}
\]

where \(V_{min}\) is the minimum peak value of the input voltage.

Referring to Fig. 3, when \(p_{in} < P_o\), \(\sin \omega t\) and \(v_{ca}(t)\) are both monotone decreasing functions during \((3/8)T_{line}\) to \((1/2)T_{line}\); hence, (22) is a monotone increasing function and its maximum amplitude during \((3/8)T_{line}\) to \((1/2)T_{line}\) is

\[
D_{2,max} T_s = \left(1 - \sqrt{2 |\sin \omega t|}\right) \frac{N_{p2} \sqrt{2 P_o L_1}}{v_{ca}(t) N_p} T_s \Bigg|_{\omega t = \pi} \tag{24}
\]

By differentiating (22) with respect to \(t\) during \((1/2)T_{line}\) to \((5/8)T_{line}\)

\[
\frac{d(D_2 T_s)}{dt} = \frac{N_{p2} \sqrt{2 P_o L_1}}{N_p} \left( \frac{\sqrt{2 \omega V_{ca,min}} \cos \omega t + P_o F_1(t)/C_a}{[v_{ca}(t)]^{1.5}} \right) \tag{25}
\]

where \(F_1(t) = \cos 2\omega t + \sqrt{2} (\cos \omega t - \sin \omega t)\).
It can be found that both $\cos \omega t$ and $F_1(t)$ are negative values during $(1/2)T_{line}$ to $(5/8)T_{line}$. Therefore, (22) is a monotone decreasing function and its maximum amplitude is the same as (24) during $(1/2)T_{line}$ to $(5/8)T_{line}$.

Substitution of (21), (23), and (24) into (17) yields

$$F_2 = \frac{2\sqrt{P_o L_1 T_s}}{V_{\min}} + \frac{N_p V_o}{N_{p1} \sqrt{\frac{V_{c_{a\min}}^2 + (P_o/\omega \cdot C_a)}{C_a}}}$$

$$+ \frac{N_s \sqrt{P_o L_1 T_s}}{V_o N_{p1}} - T_s \leq 0 \quad (p_{in} < P_o). \quad (26)$$

From (7), (15), and (19), we have

$$D_3 T_s = \frac{N_s \sqrt{P_o L_1 T_s (2 |\sin \omega t| - \sqrt{-2 \cos 2 \omega t})}}{V_o N_{p1}}. \quad (27)$$

Combining (7), (10), (19), and (27) yields

$$I_R(t_2) = \frac{N_{p1}}{L_1 N_s} \sqrt{-2 \cos 2 \omega t \cdot P_o L_1 T_s} \quad (28)$$

$$\Delta T_2 = \frac{\sqrt{-2 \cos 2 \omega t \cdot P_o L_1 T_s}}{v_{ca}(t)}. \quad (29)$$

Substitution of (23), (27), and (29) into (18) yields

$$T_{sum2} = \sqrt{P_o L_1 T_s} \left( \frac{2}{V_{\min}} + \frac{N_s (2 |\sin \omega t| - \sqrt{-2 \cos 2 \omega t})}{V_o N_{p1}} \right)$$

$$+ \frac{\sqrt{-2 \cos 2 \omega t}}{v_{ca}(t)} \right) \leq T_s \quad (p_{in} > P_o). \quad (30)$$

For the proper operation of the proposed LED driver, (26) and (30) must be satisfied under different input powers. For a given set of specifications of a driver, parameters such as $L_1$, $N_{p1}$, $N_{p2}$, $N_s$, $C_a$, $V_{c_{a\min}}$ need to be determined. A simple design example is given as follows.

The specifications of the LED driver are $V_o = 45$ V, $P_o = 13.5$ W, $T_s = 10$ $\mu$s, and $V_{\min} = 127$ V.

From Section II, we know that the maximum voltage across $Q_1$ is $v_{ca}(t) N_s/N_{p1}$, the maximum voltage across $D_2$ is $V_o + v_{ca}(t)$, and the maximum voltage across $Q_2$ is $V_o N_{p1}/N_s + v_{ca}(t)$. The maximum peak current through $Q_1$ is $\max(\sqrt{2P_o L_1/(N_{p1}/N_s)}$, $2 |v_{in}(t)| N_{p1}/N_{p2} + |v_{ca}(t)|)$, and the maximum voltage across $Q_2$ is $V_o N_{p1}/N_s + v_{ca}(t)$. It can be seen that the choice of the Flyback transformer merely determines the voltage stress and current stress of devices. Hence, the choices of the turns ratio and devices can be combined. Arbitrarily, we choose $N_{p1}$

$$N_{p2} : N_s = 2:2:1.$$  

Fig. 7 shows the left-hand terms of (26) as the function of $C_a$ and $L_1$ under different $V_{c_{a\min}}$. To keep the DCM operation of the proposed driver, the choices of $C_a$ and $L_1$ must guarantee that the corresponding value of $F_2$ is lower than zero. It can also be found that the smaller the $V_{c_{a\min}}$, the proper value of $L_1$ becomes lower for a special $C_a$, which means relatively larger peak current in the primary and secondary devices.

The appropriate choice of parameters based on (26) only means that the driver operates properly during the line period of $p_{in} < P_o$. Inequality (30) must be verified with the chosen parameters to check whether it is suitable for the period of $p_{in} > P_o$.

For example, $C_a = 5 \mu F$, $L_1 = 300 \mu H$, and $V_{c_{a\min}} = 150$ V based on (26) are chosen initially. Then, we can substitute these parameters into (17) and (30), and $T_{sum}$ is shown in Fig. 8 under different input powers during a line period. It can be found that $T_{sum} < T_s$ in the whole line period, which means that the chosen parameters can ensure the driver to operate under DCM.

Based on the chosen $C_a$ and $V_{c_{a\min}}$, the values of $V_{c_{a\max}}$ and $V_{ca}$ can be calculated by (12). Then, the voltage stress of devices can be determined.

**B. Control Strategy Design**

In [25] and [26], a current hysteresis control is used to force a double-frequency current to flow through the inductor to eliminate the low-frequency PV current ripple. In [27], the voltage shape of the storage capacitor, which leads the line voltage by $45^\circ$, is controlled. In this paper, a simple control over the average voltage amplitude of the storage capacitor is employed. The control diagram block of the proposed ac/dc LED driver is shown in Fig. 9.

Compared with the traditional Flyback converter, the main switch $Q_1$ in the proposed driver is not directly controlled by
the output current feedback. $Q_1$ is controlled by the feedback of the average voltage amplitude of $v_{ca}$, $v_{ca}$ is sensed through photodetector P521 and sent to a passive RC low-pass filter ($R = 5.1$ kΩ and $C = 2.2$ μF) for comparison with the reference voltage $V_{ref}$. The difference is amplified through proportional-integral regulator PI1 (1.5 + 100/s). The output voltage of PI1, $v_{EA1}$, is compared with a sawtooth signal (Pin5 of SG3525) to generate a switching signal for $Q_1$. $Q_2$ and $Q_3$ are directly controlled by the output current feedback. $I_o$ is sensed through a 1-Ω resistor and amplified 10.1 times, and then compared with the reference. The difference is amplified through regulator PI2 (37 + $7.4 \times 10^4$/s). To guarantee effective turn-on signals of $Q_2$ and $Q_3$ following the turn-off signal of $Q_1$, $v_{EA2}$ is added to $v_{EA1}$ for comparison with the sawtooth signal. The outputs of U1 and U3 are XORed (CD4030) with the output of U2, respectively. A coefficient 0.33 (formed by 100 and 200 kΩ) is introduced to smooth the transition period from $p_{in} < P_o$ to $p_{in} > P_o$ or vice versa. The rectified input voltage is sensed to determine the line period of $p_{in} < P_o$ or $p_{in} > P_o$.

**IV. EXPERIMENTAL RESULTS**

In order to verify the effectiveness of the proposed LED driver, a prototype has been built and tested in the laboratory. The load consists of an LED string using 15 CREE cool white LEDs (model number: XREWHT-L1-WG-Q5-0-04) in series. The key components of the circuit are listed in Table I. It can be found that only a 10-μF output filter capacitor is employed. In contrast, if a conventional flyback converter is adopted for the same LED load and assuming that the output voltage ripple is 1 V, a 950-μF output filter capacitor is required according to (12).

Fig. 10 shows the experimental waveforms of $v_{in}$, gate-source voltage of $Q_2$, $v_{gs}(Q_2)$, gate-source voltage of $Q_3$, $v_{gs}(Q_3)$, and $I_o$ at 110- and 220-VAC input, respectively. It can be seen that $Q_3$ is turned on all the time and $Q_2$ is controlled to achieve the constant output current when $p_{in} < P_o$, and $Q_2$ is turned off all the time and $Q_3$ is controlled to achieve the constant output current when $p_{in} > P_o$, which confirms the previous analysis.

Fig. 11 shows the experimental waveforms of $v_{in}$, gate-source voltage of $Q_2$, $v_{gs}(Q_2)$, gate-source voltage of $Q_3$, $v_{gs}(Q_3)$, and $I_o$ at 110- and 220-VAC input, respectively. It can be seen that $Q_2$ is controlled to achieve the constant output current when $p_{in} < P_o$ and $p_{in} > P_o$. It can be seen that $Q_2$ is turned on after the turn-off of $Q_1$ to compensate the insufficient energy when $p_{in} < P_o$ and $Q_3$ is turned off and the excessive energy is delivered to $C_a$ when $p_{in} > P_o$, which agrees well with the expected switching sequence in Fig. 4.

<table>
<thead>
<tr>
<th>$Q_1$, $Q_2$</th>
<th>STW12NK80Z (800V/10.5A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_3$</td>
<td>IRF640 (200V/18A)</td>
</tr>
<tr>
<td>$D_{a1}$, $D_{a3}$</td>
<td>MURS160T3 (600V/1A)</td>
</tr>
<tr>
<td>$D_{a2}$</td>
<td>STTH208 (800V/2A)</td>
</tr>
<tr>
<td>$C_a$</td>
<td>3 μF/630V</td>
</tr>
<tr>
<td>$C_o$</td>
<td>10 μF/100V</td>
</tr>
<tr>
<td>$L_1$</td>
<td>230 μH</td>
</tr>
<tr>
<td>$N_{ps1}$ : $N_{ps2}$ : $N_s$</td>
<td>30:30:15</td>
</tr>
<tr>
<td>$f_s$</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>
Fig. 10. Waveforms of $v_{in}$, $i_{in}$, $v_{ca}$, and $I_o$ under (a) 110-V AC input; (b) 220-V AC input.

Fig. 11. Waveforms of $v_{in}$, $v_{gs(Q_2)}$, $v_{gs(Q_3)}$ and $I_o$ under (a) 110-V AC input; (b) 220-V AC input.

Fig. 12. Waveforms of $v_{gs(Q_1)}$, $v_{gs(Q_2)}$, $v_{gs(Q_3)}$, $i_p$, and $i_R$ when (a) $p_{in} < P_o$; (b) $p_{in} > P_o$.

Fig. 13 shows the measured input power factor versus the input voltage. It can be seen that the input power factor of the proposed LED driver is above 0.97. It should be noted that the input power factor decreases when the line voltage increases, that is mainly because there is a small $LC$ ($C = 47$ nF) filter between the ac mains and the input rectifier bridge. When the line voltage increases, the 47-nF capacitor will produce more reactive current and the input current (into the rectifier bridge)
will decrease due to the constant output power. Under these two factors, the input power factor decreases.

Fig. 14 shows the measured conversion efficiency versus the input voltage for a 13.5-W prototype. The conversion efficiency decreases with the increasing line voltage. The main reason is that the switching losses of the three switches, which are sensitive to voltage variation, are the dominant power loss component and the conduction losses are comparatively small due to the originally small input current.

V. CONCLUSION

Despite the long lifetime of modern LED devices, the relatively short lifetimes of electrolytic capacitors in many existing LED drivers limit the lifetime of the overall LED systems. To overcome this problem, we propose a Flyback ac/dc driver without using electrolytic capacitor. The proposed circuit allows the use of small capacitance with large voltage ripple for energy storage. Consequently, non-electrolytic capacitors can be used in this circuit. The operation principles, features, and designs have been illustrated in a practical prototype. The experimental results show that the driver can generate a sinusoidal input current with near-unity power factor and simultaneously provide a constant output current for the LED load.

REFERENCES

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