Current-Ripple-Based Control Strategy to Achieve Low-Frequency Ripple Cancellation in Single-Stage High-Power LED Driver

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***Abstract*—This paper proposes a new current-ripple-based control strategy for the Series Ripple Cancellation Converter (Series RCC), which eliminates LED light flicker caused by Power Factor Correction (PFC) stage and significantly reduces its output capacitance. Instead of sensing two differential output voltage signals as in existing voltage-ripple-based control strategy, the proposed current-ripple-based control strategy achieves series ripple cancellation only by sensing the LED current information. The proposed control strategy significantly simplifies the control circuitry. In addition, the proposed control strategy allows input voltage of the Series RCC to tightly track its output voltage peak value with no extra control circuit, thus minimizing the RCC component voltage stress as well as the RCC loss. A 100W, 150V-0.67A experimental prototype has been built to demonstrate the advantages of the proposed method.**

I. INTRODUCTION

The low-frequency current ripple in the LED output current will cause LED flicker problem that is harmful to human visual system [1-3].

The principle of Series Ripple Cancellation (Series RC) is to cancel the double line frequency ripple voltage from the single-stage LED driver using an additional small power converter (Series Ripple Cancellation Converter, Series RCC) that is connected in series with the PFC output. As a result, a pure DC voltage is obtained and is applied to the LED string to produce DC LED current [4-7]. It has been reported in [4-6] that the existing Series RC can significantly reduce the total output capacitance of LED driver without sacrificing the Power Factor (PF), thus enabling the use of long-life film capacitors. Also, Series RC features the reduced voltage stresses of the auxiliary stage components and thus can provide a higher efficiency which is a significant advantage over the existing Parallel Ripple Cancellation (Parallel RC) methods [8-10].

The existing series RCC solutions include two categories: (a) winding-connected RCC [4, 5, 7] and (b) floating capacitor RCC[7, 11]. The winding-connected Series RC method has an additional winding from the main transformer to provide the auxiliary voltage as the input of the ripple cancellation converter (RCC). In [7, 11], a floating capacitor full-bridge-type ripple compensator is proposed to remove the auxiliary winding and diode from the main PFC stage by controlling the power flow of this auxiliary circuit with an additional loss offset control loop, making the input side capacitor of the auxiliary circuit floating and rendering a more flexible solution for both isolated and non-isolated LED driver applications, as shown in Fig. 1.

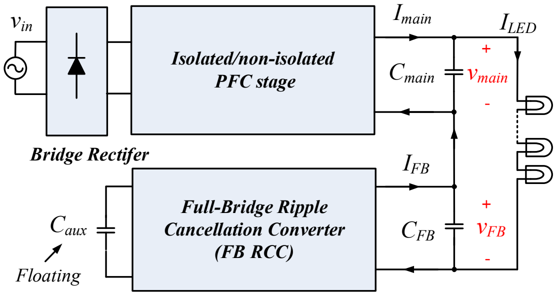

Fig. 1. The existing LED driver method with floating capacitor series ripple cancellation

However, all of the above mentioned series ripple cancellation converters proposed in [4, 5, 7, 11] employ the voltage-ripple-based feedback control strategy and therefore suffer from the relative complex and uneconomic signal-sensing circuits. The typical block diagram of the existing voltage-based feedback control strategy is shown in Fig. 2(a), where the two series-connected output voltages (the main PFC stage output voltage, v_{main}, and the cancellation stage output voltage, v_{FB}) are sensed simultaneously to achieve the ripple cancellation. The key block diagrams in the ripple cancellation loop are highlighted in Fig. 2(a). The corresponding sensing circuit for the RCC is given in Fig. 2(b) where two differentials to single-end voltage conversion circuits are required.

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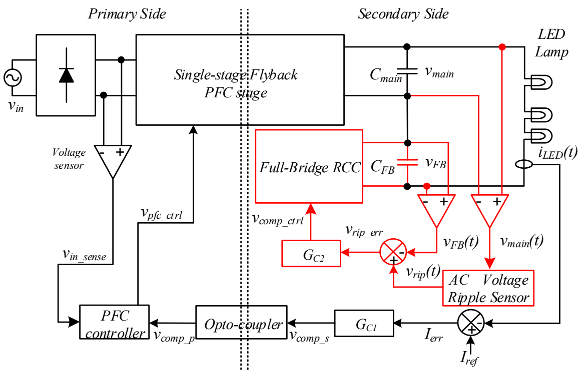
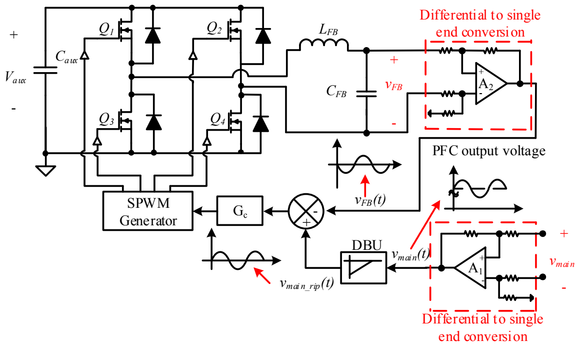


(a) Complete Block Diagram



(b) Implementation circuit of RCC part

Fig. 2. The existing voltage-ripple-based control strategy for series ripple cancellation

This paper proposes a current-ripple-based feedback strategy aiming to achieve the series cancellation based on sensing LED current only. As the LED current is also a basic controlled item for the main stage PFC controller, the sensing circuit to achieve Power Factor Correction (PFC) in the main stage can be also used to achieve series ripple cancellation (Series RC), which significantly simplifies the control circuit.

This paper is organized as follows: Section II introduces the principle of the proposed method, Section III discusses the main advantages of proposed control method, Section IV provides the experimental results, and Section V concludes the paper.

II. Proposed Current-Ripple-Based Feedback Control Strategy

A. Proposed System Block Diagrams

The proposed control strategy is current-ripple-based and consists of two current control loops: (i) the main PFC stage control loop regulating the average LED current and (ii) the current-ripple-based control loop suppressing the double-line-frequency LED current ripple. The input side and output side of PFC stage is isolated (as shown by a double dotted line in the center of the figure). The complete control diagram is given in Fig. 3, where the proposed current-ripple-based control loop is highlighted in red.

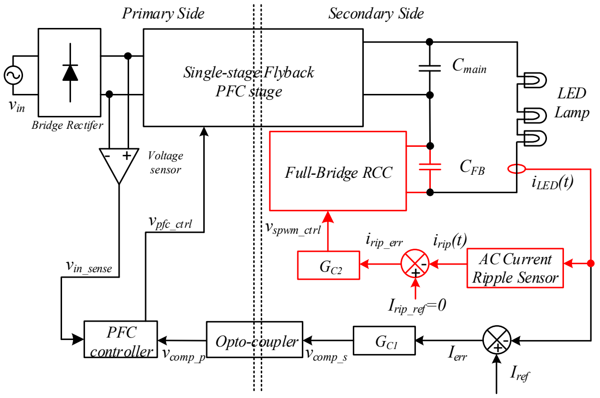


Fig. 3. Proposed current-ripple-based control strategy for series ripple cancellation

This highlighted loop includes one AC current ripple sensing block and one compensation network (G_{C2}). The ripple cancellation rule is straightforward: the double-line-frequency current ripple (i_{rip}) is sensed by blocking the DC component of the LED current (i_{LED}) and then it is controlled to approach a non-ripple reference (I_{rip_ref}=0), generating the error signal (i_{rip_err}). Based on this error signal, the compensation network regulates the SPWM control signal (v_{spwm_ctrl}) to force the full-bridge RCC to generate an out of phase double-line-frequency voltage ripple and the resulting LED current, $i_{LED(t)}$ to be non-ripple (i_{rip}=0). In this way, the double-line-frequency component in the LED current is significantly suppressed. It is noticed from Fig. 3 that both the PFC controller output (v_{pfc_ctrl}) and the proposed current ripple suppression controller output (v_{spwm_ctrl}) are based on the LED current (i_{LED}), rather than the output voltage signals. Therefore, the PFC controller and the current ripple cancellation controller share the same LED current sensing circuit in the proposed control strategy. In practical implementation, to avoid the negative part of the sensed AC current ripple signal, a level shifter is applied to both the sensed current ripple (i_{rip}) and its reference ($I_{rip\_ref}=V_{bias}$) in the experiment.

B. Power Structure and Control Circuit

The power circuit of the flickering-free LED driver with an isolated single-stage Flyback PFC stage is shown in Fig. 4, where a floating capacitor full-bridge inverter is used as the series RCC (highlighted in the blue box).

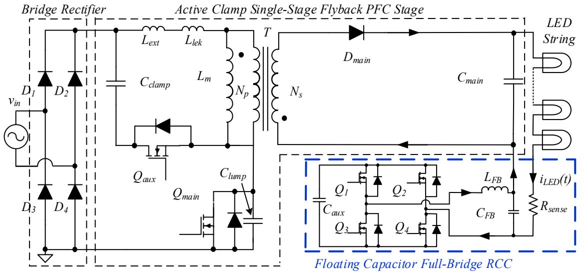


Fig. 4. The flickering-free LED driver with Full-Bridge RCC[11].

The proposed current-ripple-based control strategy simplifies the original controlling circuit in [11] by removing two differential sensing to single-end voltage conversion circuits. The detailed control circuit for the FB RCC (the highlighted blue part in Fig. 4) is illustrated in Fig. 5.

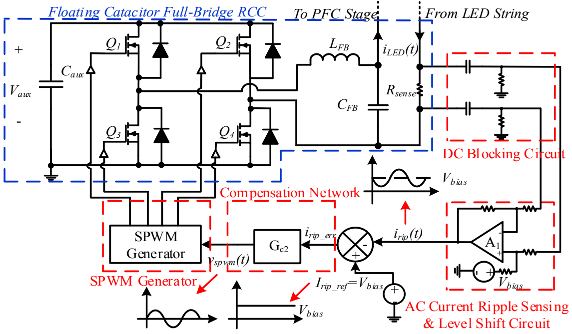


Fig. 5. Proposed current-ripple-based controller circuit.

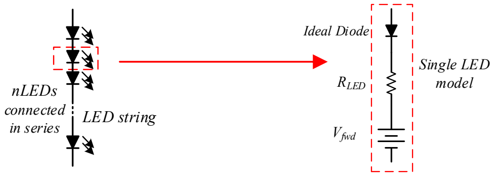
With the proposed control strategy, the Full Bridge RCC rebuilds a reversed AC voltage ripple to cancel the double line frequency current ripple in the LED output current. The peak to peak value of the main stage's output ripple voltage V_{ripple} can be evaluated via the LED current, I_{LED}, and the output capacitance, C_{main}, as shown in (1).

$$V_{ripple}=\frac{P_{in}}{\omega\times C_{main}\times V_{LED}}=\frac{I_{LED}}{2\pi\times f\times C_{main}} \tag{1}$$

III. Advantages of the proposed current-ripple-based ripple cancellation method

A. Ripple cancellation performance

An LED load could consist of several LED chips connected in series, as shown in Fig. 6(a).The linear model of each LED chip is shown in Fig. 6(b). It consists of an equivalent voltage source (V_{fwd}) in series with an ideal diode and a small resister (R_{LED}).The relationship between the LED voltage and the current is dependent on the characteristics of the LED load, and is expressed in (2). The resistance and forward voltage of a LED load is dynamic with the forward current, but can be considered constant for a given average output current.



(a) LED string load (b) Equivalent circuit model of a single LED

Fig. 6. Equivalent circuit model of LED string load

The relationship between the LED voltage and current ripple is expressed in (3).

$$I_{LED}=\frac{V_{LED\_string}-nV_{fwd}}{nR_{LED}} \tag{2}$$

$$\Delta I_{LED}=\frac{\Delta V_{LED\_string}}{nR_{LED}} \tag{3}$$

Given the low equivalent resister characteristic as well as the nonlinearity of the LED load, even a small LED voltage ripple ($\triangle V_{LED\_string}$) may result in a large LED current ripple ($\triangle I_{LED}$). This assigns a tough task for the existing strategy proposed in [4, 5] intending to cancel the current ripple by limiting the voltage ripple when the voltage ripple is too small to be detected.

In addition, compared to the voltage-ripple-based cancellation method requiring two differentially sensed voltage signals, the proposed current-ripple-based method only senses the current ripple and compares it to a zero reference (a DC voltage), potentially avoids the error due to the mismatch between the two sensing circuits, and thus leading to a more effective solution to cancel the current ripple.

B. RCC input voltage auto-tracking for minimizing the RCC loss at different loads

In order to adept different LED-load combinations, customer requires the drivers to handle a wide output voltage range under the rated output current. The ratio of the highest output voltage over the lowest output voltage is usually higher than 1.5 times (e.g. V_{LED}=90~150V). With the existing ripple cancellation technologies proposed in [4, 5], given the auxiliary winding turn ratio is fixed, the component voltage rating has to be overdesigned under the low output voltage operation (e.g. V_{LED}<150V) to fit the voltage stress at the highest output voltage operation (e.g. V_{LED}=150V), resulting a non-optimal solution in terms of the component voltage stress as well as the FB RCC efficiency.

As to the ripple cancellation method with a floating capacitor proposed in [11], the peak to peak value of the double line frequency voltage ripple in PFC output, V_{ripple}, is only proportional to the LED output current I_{LED} as well as the PFC output capacitance C_{main}, given the line frequency f_{line} is fixed. Therefore, the voltage stress of the floating capacitor (C_{aux}) is designed based on the highest LED current I_{LED} as the worst case and can be reduced close to but a bit higher than the peak voltage ripple at full load. However, since the floating capacitor voltage is regulated and fixed when the design is done, the floating capacitor voltage can be way higher than the peak of the low frequency voltage ripple under the light LED current load, resulting in the unnecessary loss in FB RCC.

The proposed current-ripple-based method can achieve optimization of the ripple cancellation with the minimum floating capacitor voltage regardless the LED output voltage (V_{LED}) and loads (I_{LED}) by nature. The mechanism is as follow: As shown in Fig. 4, the FB RCC input voltage V_{aux} voltage is initially charged to exceed the peak value of V_{ripple} by I_{LED} due to its unidirectional flowing characteristic and then the voltage start decreasing due to the loss in the FB RCC. This results V_{aux} to be less than V_{ripple} where the sinusoidal peaks are lost. The resulting LED current presents small drop (less than its nominal value) at each valley of v_{FB}. The small distortion makes the RCC consumes less energy during each positive half cycle than that it receives during each negative cycle, offsetting the RCC loss. The current bumps are fixed when the energy saved by the distortion equals to total RCC loss in each 120Hz cycle. As a result, the RCC input voltage is auto-tuned and kept very close to but a bit less than the peak value of output voltage without extra input voltage regulation loop. Since the FB RCC loss is in proportional to its input voltage (given the fixed output AC voltage), with the proposed current-ripple-based method, the FB RCC component voltage stress and the loss are minimized. It should be noticed that the voltage-ripple-based control strategy can also achieve auto-tracking but is not sensitive enough for the low-equivalent-resister LED loads, therefore an additional loss offset loop is added [11] to enhance the ripple cancellation performance.

IV. EXPERIMENTAL VERIFICATION

The parameters of a 100W proposed LED driver are shown in Table 1.

A. Ripple cancellation performance

Fig. 7(a) and Fig. 7(b) show that the proposed method produces a very small LED driving voltage ripple @120Hz (0.23V RMS when V_{LED}=150V; 0.12V RMS when V_{LED}=90V) with only 60.7μF total output capacitance (C_{main}+C_{FB}). According to (1), when using conventional single-stage LED drivers, such a small ripple voltage can be only achieved when the output capacitance is increased to 2760μF. Therefore, the total required output capacitance of conventional single-stage solution is reduced by 97.8%!

B. FB RCC input voltage auto-tracking performance

Corresponding to (1), Fig. 8(a) and Fig. 8(b) present the same 37V voltage ripple of main stage (CH1) at the same LED current (CH4, 0.67A) but the different LED voltages (V_{LED}=150V in Fig. 8(a) and V_{LED}=90V in Fig. 8 (b)). Fig. 8(a), Fig. 8(c) and Fig. 8(d) show the different main stage voltage ripples (CH1) corresponding to the different LED currents (CH4) at the same LED voltage (V_{LED}=150V). According to the analysis in III(B), with small bumps occur on the LED output current, the average value of input voltage V_{Caux} (CH3) is able to be auto-tuned close to the CH1's peak values (FB RCC output voltage, v_{FB}) under all the given conditions: (a)V_{LED}=150V, I_{LED}=0.67A (b) V_{LED}=90V, I_{LED}=0.67A (c) V_{LED} =150V, I_{LED} =0.4A (d) V_{LED} =150V, I_{LED} =0.2A. So that the RCC components' voltage stress is reduced and the RCC efficiency can be improved.

Table 1. Prototype Parameters Values

Specifications of LED driver

Line input voltage (v_{in})	110V
LED output voltage (V_{LED})	90~150V
Rated LED output current (I_{LED})	0.67A
Rated power (P_O)	100W
Line frequency (f)	60Hz

Active Clamp Single-stage Flyback PFC Stage

Output Capacitor (C_{main})	56 μF (250V Film Cap)
Switches (Q_{main} Q_{aux})	SPP11N80C3
Diode (D)	C3D16060
Turns Ratio (N_p:N_s)	1.2:1
Magnetizing Inductance (L_m)	1300 μH
Internal Leakage Inductor (L_{lek})	33 μH
External Leakage Inductor (L_{ext})	15 μH
Active Clamp Capacitor (C_{clamp})	470 nF (400V Film Cap)
Single-stage PFC Controller	NCP1652A

FB RCC Stage

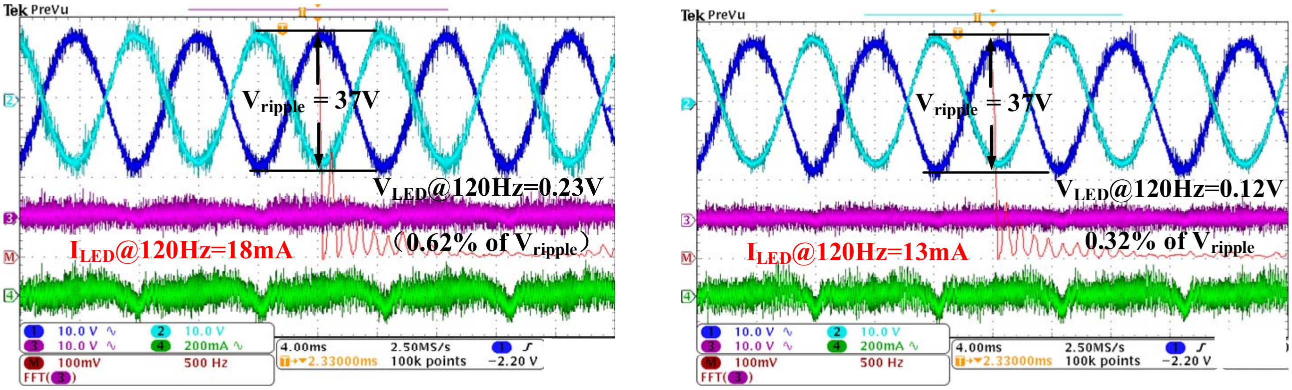
Switching Frequency (f_{sw})	156 KHz
Input Floating Capacitor (C_{aux})	10 μF×12 (50V 1206 Ceramic Cap)
Output Inductor (L_{FB})	22 μH
Output Capacitor (C_{FB})	4.7 μF×1 (50V 1206 Ceramic Cap)
Full-bridge Switches (Q_1~Q_4)	TPN11003NLLQ×4 (30V, 11mΩ)

LED String Load

LED Chip Part Number	XMLEZW-02-0000-0B00T527F (15~27pcs for different load combination)
Forward Voltage/pcs (V_f) Typ	6 V
Max Current (I_{max})	2 A
Luminous Flux/pcs @ 670 mA	270 lm

C. System efficiency and power factor correction performance

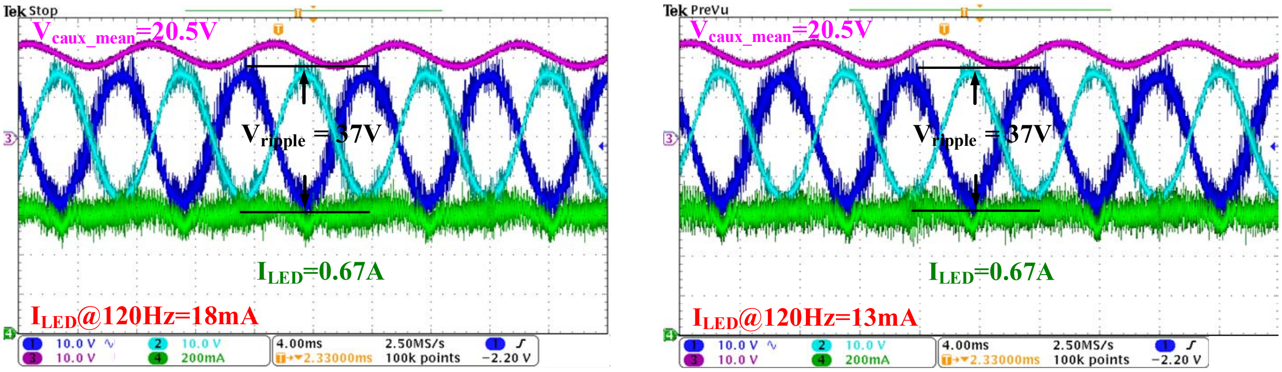
With the help of RCC input voltage auto-tracking mechanism, the experimental prototype shows a system efficiency of 91% and 92% (given v_{in}=110Vac and 220V). Fig. 9 shows the corresponding input voltage and input current waveforms of proposed method, which has achieved the PFs of 0.990 and 0.953. More experimental results under the universal AC input are shown in Fig. 10, where a peak system efficiency of 92.5% has been achieved. The FB RCC stage loss is generally less than 1% under different input voltage, as shown in Fig. 11. Dimming performance of the proposed LED driver is also given in Fig. 12. Under both the nominal input voltages (110Vac and 220Vac), the half-load (P_O=50W, V_{LED}≈150V) system efficiency are generally higher than 88.5% and the PF are over 0.9.



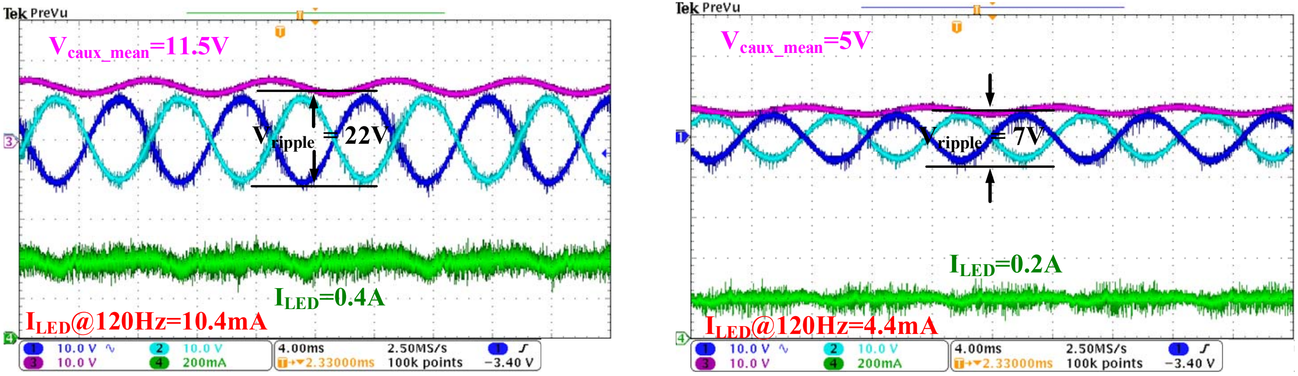
(a)V_{LED}=150V I_{LED}=0.67A (P_o=100W, 27 LED chips) (b) V_{LED}=90V I_{LED}=0.67A (P_o=60W, 15 LED chips)

CH1: AC coupled PFC stage output voltage (v_{main_ac}) CH2: DC coupled FB RCC output voltage (v_{FB})
CH3: AC coupled LED string voltage (V_{LED_ac}) CH4: AC coupled LED string current (I_{LED_ac})
CHM: FFT of AC coupled LED string current ($I_{LED\_ac\_FFT}$)

Fig. 7. Key waveforms of the proposed current-ripple-based ripple cancellation method, when V_{in}=110Vac, I_{LED}=0.67A



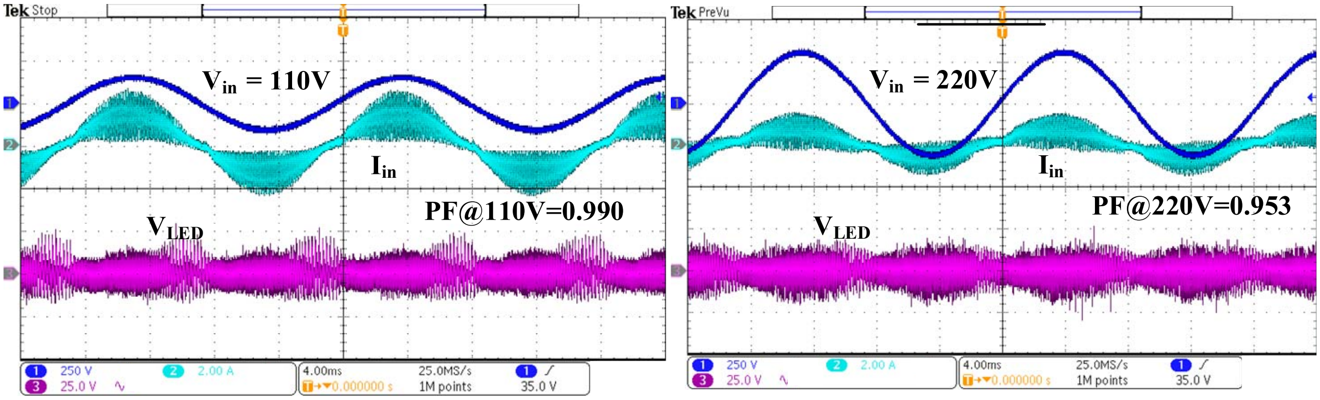
(a) V_{LED}=150V I_{LED}=0.67A (P_o=100W, 27 LED chips) (b) V_{LED}=90V I_{LED}=0.67A (P_o=60W, 15 LED chips)



(c) V_{LED} =150V I_{LED} =0.4A (P_o =60W, 27 LED chips) (d) V_{LED} =150V I_{LED} =0.2A (P_o =30W, 27 LED chips)

CH1: AC coupled PFC stage output voltage (v_{main_ac}) CH2: DC coupled FB RCC output voltage (v_{FB})
CH3: DC coupled FB RCC input voltage (V_{Caux}) CH4: DC coupled LED string current (I_{LED})

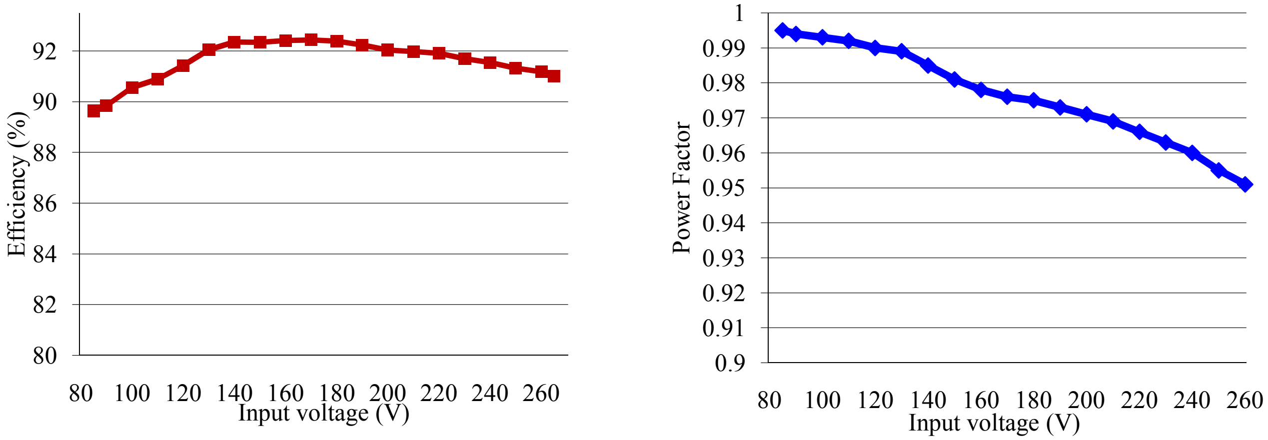
Fig. 8. FB RCC input voltage auto-tracking performance, when V_{in}=110Vac.



(a)V_{in}=110V (b) V_{in}=220V

CH1: AC input voltage (v_{in}) CH2: AC input current (i_{in}) CH3: AC coupled LED lamp voltage (V_{LED})

Fig. 9: Input current and output voltage of the proposed LED driver, when V_{in}=110Vac & 220Vac, V_{LED}≈150V, I_{LED}=0.67A, P_O=100W



(a) System efficiency. (b) Power factor.

Fig. 10. Performance of the proposed LED driver with FB RCC at full load, when C_{main}=56 μF, V_{LED}≈150V, I_{LED}=0.67A, P_o=100W.

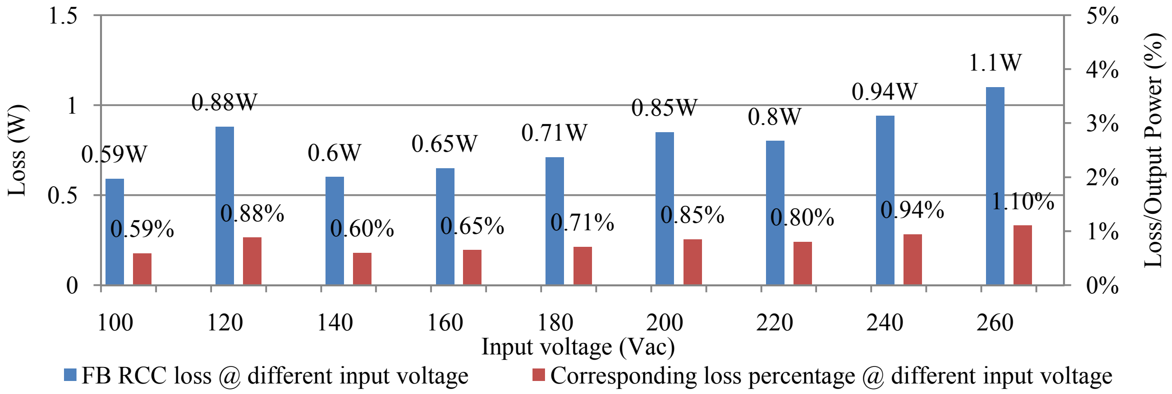
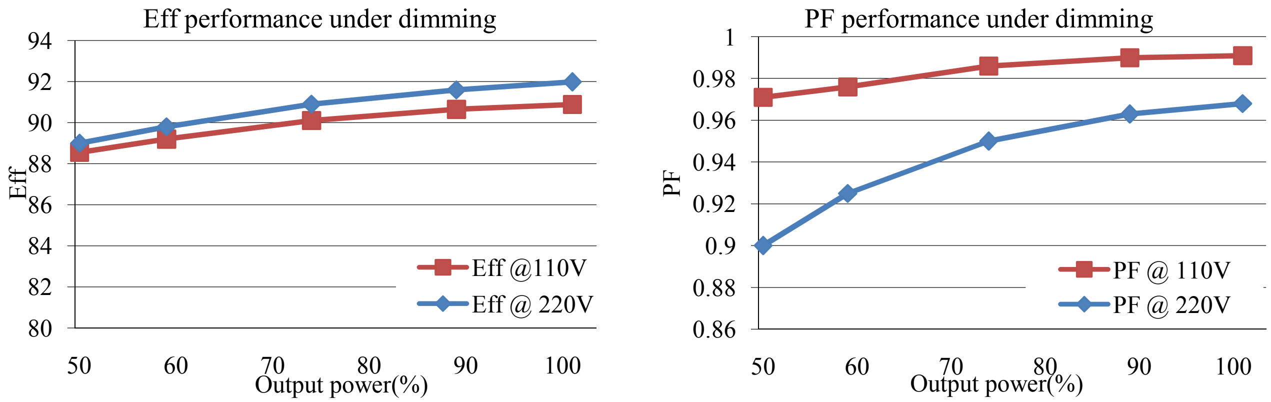


Fig. 11: FB RCC stage loss in proposed LED driver when V_{LED}≈150V, I_{LED}=0.67A, P_o=100W.



(a) System efficiency.

(b) Power factor.

Fig. 12. Dimming Performance of the LED driver under the proposed current-ripple-based ripple cancellation method, when C_{main}=56µF, V_{LED}≈150V.

V. CONCLUSION

This paper proposes a current-ripple-based control strategy to improve performance and simplify the control circuitry of the series ripple cancellation converter. The proposed scheme eliminates LED flickering and reduces required output capacitance. Also, the proposed method has a unique tracking and efficiency improvement mechanism under different loads and different output voltage, which has been verified through the experiment. Extensive experimental results are provided to demonstrate the performance.

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