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Interleaved DCM Buck-Boost PFC LED Driver

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***Abstract*— In this paper, an overview of interleaved DCM buck-boost PFC LED driver is presented. The proposed LED driver is designed to operate in discontinuous inductor current conduction mode (DCM) to make use of its obvious benefits such as inherent high power factor and low THDi, simple control (single loop control), excellence efficiency due to inherent zero current switching at turn-on time of the switches and inherent zero diode reverse recovery loss. The adoption of an interleaving technique can reduce the size of passive power components, which can enhance LED driver's performance and efficiency. This benefit reduces costs, size and weight of LED drivers. The computer software simulations was used to simulate the performances of the proposed LED driver. Experimental results indicate that the characteristics and operations of the LED driver are similar to the simulation results. In addition, the prototype of interleaved DCM buck-boost PFC LED driver was implemented and tested in laboratory, PF 0.9918 and efficiency 92.67%.**

***Keywords*— LED Driver, Interleaved Buck-Boost PFC, Discontinuous Inductor Current Conduction Mode**

I. INTRODUCTION

In a LED luminaire, the LED driver is very important element along with LED chips. The high efficacy of LED luminaire is contributed from the high efficiency LED driver. Nowadays, the LED driver is developed to improve features such as higher efficiency, lower profile, lower costs as well as better power quality. High power factor (PF) and low total harmonics distortion current (THDi) are usually major targets of development.

There are three groups of power range of LED drivers [1] namely low power (<25W), medium power (25W-100W) and high power (>100W). The LED drivers can be divided into three options according to the criteria of PF and input THDi characteristics. 1) Low power LED driver without PFC function, it is lowest cost, poor PF (about 0.5-0.6) and terrible THDi (>100% of THDi) [2]. 2) LED driver with passive PFC, it is acceptable PF (0.8-0.9) and fair THDi. However, it is not suitable for medium and high power applications and 3) LED driver with active PFC (PF>0.95, THDi<15%)

A non-isolated topology offers the high efficiency and the low cost. There are three basic non-isolated topologies that can be applied as the active PFC. The boost converter is the most popular topology due to the simple gate driving circuit for a MOSFET switch, it is often designed at the boundary condition and the continuous inductor current conduction mode, resulting in the need of the double loops controller in the control circuit. The important restriction of the boost PFC is the output voltage must be greater than the peak of the input voltage, then it is not suitable for the low voltage LED modules.

The buck converter is not suitable for high power factor and low THDi applications because it produces the input current distortion at the zero-crossing point [4] as illustrated in Fig 1.

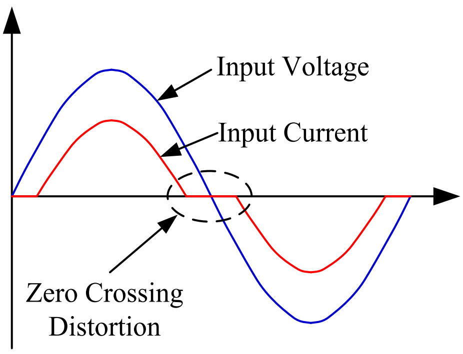

Fig 1. Input current distortion of PFC buck converter.

The buck-boost topology has many advantages. In the DCM operation, it offers natural high PF and low input current distortion with the simple single control loop [3]. With a single sensor at the LED current control loop, the LED driver eliminates the requirement for additional input sensors for input current control as in BCM and CCM, it can achieve natural PFC at the input. Due to inherent zero-current switching at turn-on time of the switch and inherent zero diode reverse recovery loss, the overall efficiency of the circuit is satisfying. However, the single channel buck-boost PFC LED driver has poor power density because it has very high peak and RMS current on passive element. The interleaved buck-boost topology can provide higher power density, lower ripple currents and higher overall efficiency comparing to the single channel.

The solution that solves all the problems mentioned above, the interleaved DCM buck-boost PFC LED driver is presented in this paper.

II. Analysis of The Proposed LED Driver

A. The Operation of DCM Buck-Boost PFC Converter

Fig. 2 shows the conventional buck-boost PFC converter. The AC sinewave input voltage V_{in} is applied to the input of converter. The diode bridge rectifier (DB) converts the AC sinusoidal voltage to the DC voltage waveform, V_g. The switch SW works according to the PWM signal. When it is turned on, the current I_{SW} rises from zero to the peak of inductor current I_L ($I_{SW}= I_L$), then it falls to zero when the SW is turned off. The current I_{SW} represents the input side of bridge diode (I_{DB}) which $I_{DB} = |I_{SW}|$. The I_{DB} is filtered (averaged) by L_f and C_f lowpass filter network resulting in the input current (I_{in}) achieves the sinusoidal waveform and is in phase with the input voltage waveform (V_{in}).

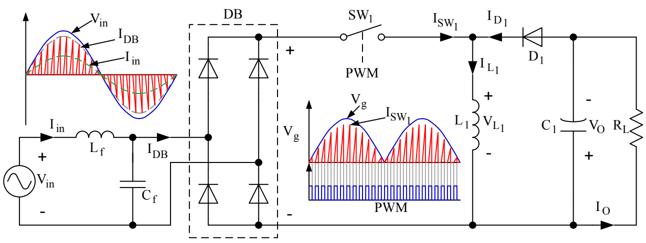

Fig 2. Conventional buck-boost PFC converter.

B. Power Factor Analysis

The analysis of the power factor circuit can be considered by using the parameters as follows; the RMS value of input voltage (V_{in_rms}), the peak value of input voltage (V_M) and the angular frequency of AC input voltage (ω). Then v_{in} can be expressed as

$$v_{in}(t) = V_M sin(\omega t) = \sqrt{2}V_{in\_rms} sin(\omega t) \quad (1)$$

From (1), the inductor L peak current (I_{L_pk}) is

$$I_{L\_pk}(t) = \frac{V_M|\sin(\omega t)|D}{Lf_{sw}} \quad (2)$$

Where D is the duty cycle, and f_{sw} is the switching frequency.

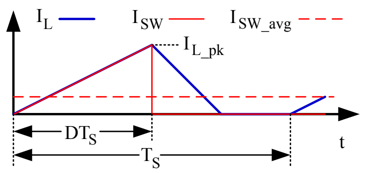

Fig 3. Waveforms of inductor filter current and switch current.

From Fig. 3, if the switching frequency and the duty cycle are constant, the average switch current (I_{SW_avg}) of each switching cycle can be given as

$$I_{SW\_avg} = \frac{DI_{L\_pk}}{2} \quad (3)$$

Based on (2) and (3), the average switch current and the average input current can be expressed as

$$i_{in}(t) = I_{SW\_avg} = \frac{V_M|\sin(\omega t)|}{2Lf_{sw}}D^2 \quad (4)$$

From (1) and (4), the input power is expressed as

$$P_{in} = \frac{(DV_M)^2}{4Lf_{sw}} \quad (5)$$

From (5), the duty cycle D can be expressed as

$$D = \frac{2\sqrt{Lf_{sw}P_{in}}}{V_M} \quad (6)$$

Assume the RMS value of the input current is I_{in_rms}, using (4) and (5), the PF can be expressed as

$$PF = \frac{P_{in}}{V_{in\_rms}\, I_{in\_rms}} = \frac{(DV_M)^2/4Lf_{sw}}{\frac{V_M}{\sqrt{2}}\sqrt{\frac{1}{T_{L/2}}\int_0^{T_{L/2}}[i_{in}(t)]^2 d(t)}} = 1 \quad (7)$$

The equation (7) indicates that the ideal DCM buck-boost PFC converter has the unity PF [5].

C. Interleaved Topology

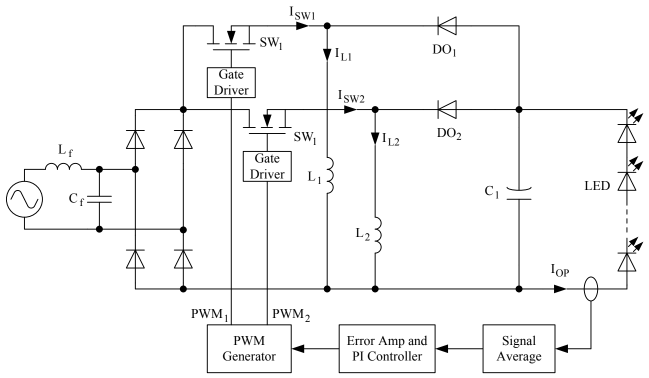

Fig 4. Proposed interleaved DCM buck-boost PFC LED driver.

As Fig. 4, the interleaved DCM buck-boost PFC LED driver is shown. SW_1, L_1, and DO_1 are the components of the phase 1 buck-boost converter. Similarly, SW_2, L_2, and DO_2 are the components of the phase 2 converter. The input power of the converter is divided and converted by both circuits as

$$P_{Ph1} = P_{Ph2} = \frac{P_{in}}{2} \quad (8)$$

Where P_{Ph1} and P_{Ph2} are the divided input power of each converter, then the duty cycle of phase 1 is the same value as the phase 2.

$$D_1 = D_2 \quad (9)$$

From (6), (8), and (9), the duty cycle of each phase can be expressed as

$$D_1 = D_2 = \frac{\sqrt{2}\sqrt{Lf_{sw}P_{in}}}{V_M} \quad (10)$$

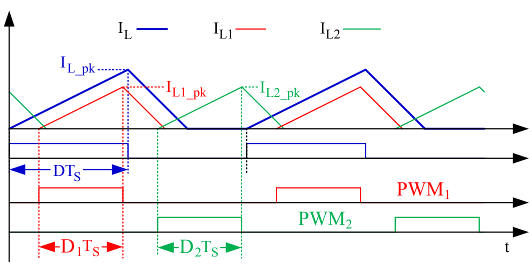

Fig 5. Comparison of inductor current of the conventional buck-boost (I_L) converter and the interleaved buck-boost converter (I_{L1} and I_{L2}).

The inductor peak currents (I_{L1_pk} and I_{L2_pk}) can be given as:

$$I_{L1\_pk}(t) = I_{L2\_pk}(t) = \frac{V_M|\sin(\omega t)|D_1}{\sqrt{2}Lf_{sw}} \quad (11)$$

As Fig. 5, the peak inductor current of the interleaved converter is lower than the conventional converter. For the interleaved converter, the reduction of total inductor energy is 50% as (12) [6].

$$E_{interleaved} = \sum_{i=1}^{2}\frac{1}{2}L\left(\frac{I}{2}\right)^2 \quad (12)$$

III. Simulation and Experimental Results

In this section, the result of two simulation cases is compared and the measurement results of the interleaved driver prototype are presented. For the simulations, first one is the conventional DCM buck-boost PFC converter. The second is the interleaved topology.

The parameter values for the simulation and the experimental are set as 60 W of rated power (P_{in}), input voltage (V_{in}) 220 Vac, output voltage (V_O, V_{OP}) 196 V, output current (I_O, I_{OP}) 300 mA, load resistance (V_O/I_O, R_L) 650 Ω, output capacitance (C, C_1) 180 µF, switching frequency (f_{sw}) 62.5 kHz, inductance (L, L_1, L_2) 820 uH, simulation duty cycle (D) from (6) 35%, and experimental duty cycle (D_1, D_2) from (10) 27.749%

The prototype of the interleaved buck-boost PFC LED driver for high voltage LED applications was built. Inductors are made from EE19 ferrite core. The DPAC (TO-252) medium power MOSFET R6004END are used, resulting in compacting the LED driver is achieved. The input power of the prototype is 61.02W and the efficiency is 92.67%.

A. Inductor Currents

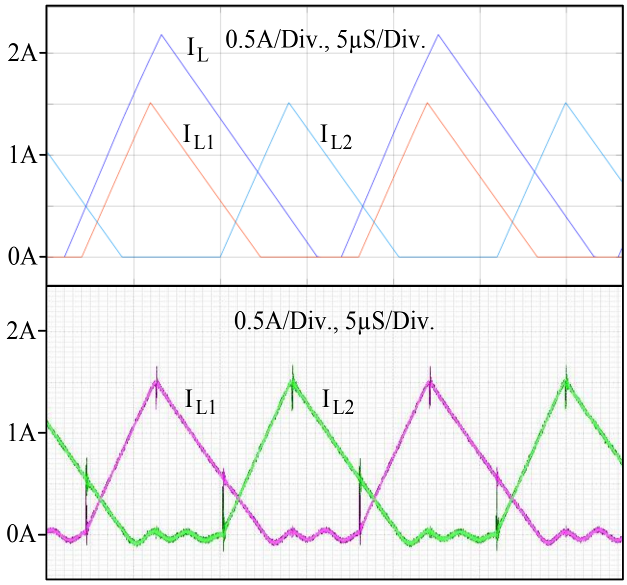

Fig 6. The simulation result of inductor current of conventional converter (I_L) compares with inductor currents of interleaved converter (I_{L1} and I_{L2}) and the waveforms of inductor currents of the interleaved converter prototype.

As Fig 6 (upper), The inductor current waveform of the conventional converter (I_L) has the peak value as 2.18 A and the RMS value is 0.82 A. The inductor currents of the interleaved converter (I_{L1} and I_{L2}) have the peak value as 1.51 A and the RMS value is 0.48A. The reduction of the peak current resulting from the reduction of the duty cycle. The peak to peak of ripple input current of interleaved topology is lower than the conventional about 45%, resulting in better EMI effect and input filter circuit cost effective.

Fig 6 (lower) shows the inductor currents of the interleaved prototype, that have the peak value as 1.483 A and the RMS value is 0.475 A. The waveform from the oscilloscope is nearby the simulation result.

B. Output Capacitor Ripple Current

From Fig. 7 (upper), from the simulation, the output capacitor ripple current of conventional converter (I_{C_rms}) has the RMS value as 0.53 A, the output capacitor RMS ripple current of interleaved converter (I_{C1_rms}) is 0.41 A. The reduction of RMS ripple current, resulting in the reduction of power loss on ESR of the capacitor, has a great effect on prolonging the capacitor lifetime caused by lower heat generation on the capacitor body (lower case temperature). The Fig.7 (lower) shows the waveform of C_1 ripple current of the prototype, the RMS value is 0.47 A.

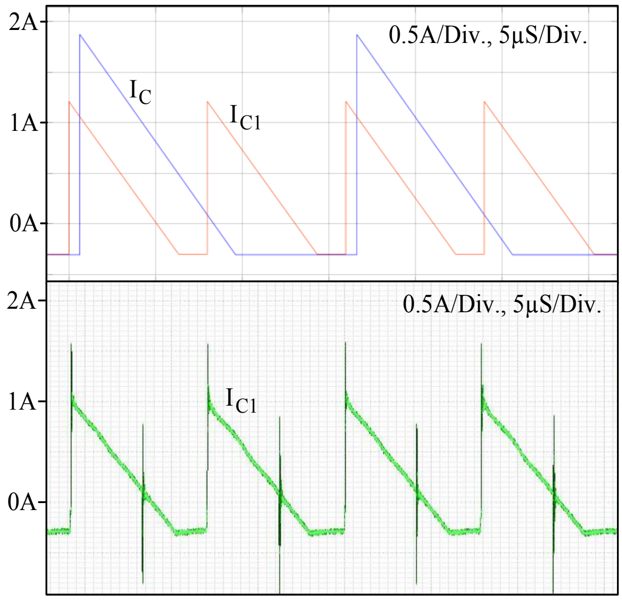

Fig 7. Output capacitor ripple current of conventional converter (I_C) compares with capacitor ripple current of interleaved converter (I_{C1}) and the ripple current waveform (I_{C1}) of the prototype.

C. Input Current and Voltage Waveform

As Fig. 8 (upper), the input current waveform has the peak value as 365 mA and the RMS value is 275 mA. The peak value of input voltage is 310 V and the input power from the simulation is 60.27 W and PF is 0.9995.

Fig. 8 (lower) shows the input voltage and current waveforms of the prototype. The input current has the RMS value as 276.67 A and the RMS input voltage is 220.31 V. The PF is 0.9918 and the THDi is 2.632%.

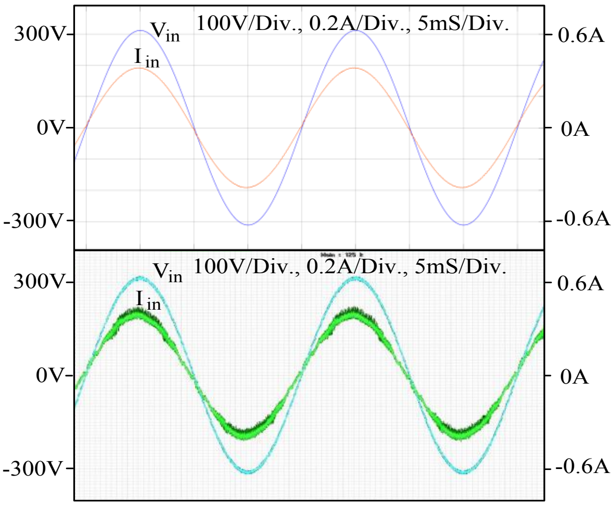

Fig 8. Input current and input voltage waveform of interleaved converter from the simulation and the experimental.

D. Low Frequency Output Capacitor Ripple Current

Fig.9 shows the prototype's low frequency ripple current of the output capacitor. The RMS value is 0.389 A. The capacitor generates heat by the ripple current since it has resistance called ESR. The capacitor ripple current is consisting of line and switching frequency ripple current, both have the effect to the heat generation.

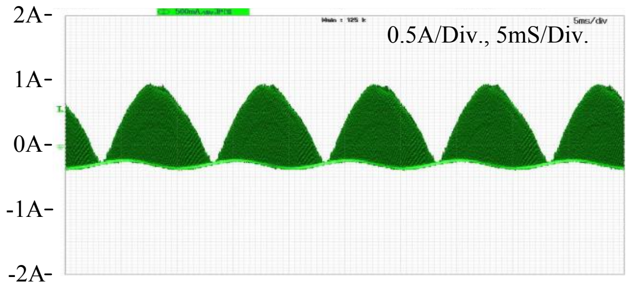

Fig 9. Low frequency output capacitor ripple current waveform.

E. Conventional and Interleaved LED Driver Comparison

As Fig. 10, the conventional driver uses the high performance core shape PQ2620 for the inductor. By using the peak current to flux density calculation, the maximum magnetic flux density is 297 mT. The interleaved prototype uses the cost effective core shape EE19 with 308 mT of maximum flux density. The dimensions of PQ2620 inductor is 2.0x2.7x3.0 cm and the dimensions of EE19 inductors is 1.6x1.9x1.5 cm. Based on the information above, it can be calculated as 43.7% of the total inductor volume reduction.

The dimensions of the conventional LED driver prototype is 11.5x3.5x2.6 cm and the dimensions of interleaved driver is 9.6x3.5x2.2 cm. Therefore, the interleaving technique can result in 29.4% of the driver volume reduction. In the same way, the power density of the conventional driver is 3.69 W/in^2 and 5.23 W/in^2 for the interleaved LED driver, respectively.

The RMS ripple current of the output capacitor conventional driver is 0.524A and 0.398A for interleaved driver. The capacitor case temperature of conventional driver is 38.7º C and 36.3º C for the interleaved driver. The temperature difference between both cases is 2.4º C. This results in 1.18 times of the electrolytic capacitor lifetime prolonging.

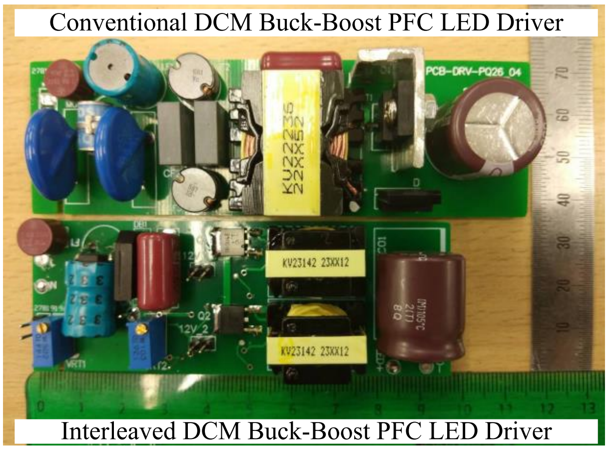

Fig 10. Photograph of conventional and interleaved Buck-Boost PFC LED driver prototype.

IV. Conclusion

The interleaved DCM Buck-Boost PFC LED driver is proposed in this paper. By using simple single loop controller, the high PF and low THD$_i$ LED driver is achieved. The simulation results show the reduction 30.7% of the peak inductor current, 41.5% of the RMS inductor current and 22.7% of the output capacitor ripple current. The power factor of prototype reaches 0.9918, the THDi of the input current is 2.623% and the maximum efficiency is 92.67%.

V. Acknowledgement

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