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Two phase interleaved buck converter for driving high power LEDs

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Abstract

The goal of this paper is to evaluate an interleaved buck topology for driving high current light-emitting diodes. Low output capacitor value allows the use of non-electrolytic capacitors extending the lifetime of the converter. Converter is operated as a constant, regulated current source which increases luminous efficacy of LED compared to PWM dimmed system. Because of the low dynamic resistance of LEDs the duty cycle of the converter does not change greatly with controlled current. By setting the input voltage of the buck converter to around twice the voltage of diode strings, converter can be operated close to the 50% duty cycle, where the ripple attenuation is the highest.

Introduction

LED based luminaires are becoming more popular in the recent due to high degree of light control and big color gamut. Compared to luminaires based on traditional, incandescent light sources they do not require filters to generate saturated light. Moreover, with proper thermal management, the lifetime of light emitting diodes can extend beyond 50000 hours. Luminaire manufacturers often claim that the lifetime of a LED based luminaire is dependent mostly on the light source [1] but very often lifetime of the whole luminaire is limited by the power electronic components.

The most problematic components in the power converters are the electrolytic capacitors, which are present in the converter to smooth the current and act as intermediate energy storage. Due to high ambient temperatures reaching 60°C, which are typical in recessed luminaires, lifetime of the electrolytic capacitors can be dramatically decreased to few thousand hours [2], significantly reducing the lifetime of the whole luminaire. One way to avoid using expensive high lifetime capacitors is to use a topology that does not require big capacitances [3,4]. Then film capacitors can be used instead of electrolytic capacitors.

The progress in solid-state device's packaging allows high current concentration reaching 1.5A/mm² in state of the art devices. High intensity devices like Luminus CBT-90 require driving current of up to 13.5A. Increasing current demand by LED devices requires more powerful and efficient drivers. Interleaved converters became an industry standard for supplying high current, low voltage devices like microprocessors and they are now becoming a reasonable choice for driving LEDs. High converter bandwidth allows high PWM frequency dimming thus decreasing the audible noise due to magnetostrictive and piezoelectric effects [5]. Current distribution amongst converter phases simplifies thermal management of power switching devices.

First section of the paper describes structure of an LED based luminaire. Following, a dual interleaved LED driver is described. Next, a current measurement technique is described in detail. Finally conclusions of using an interleaved converter with LED devices are drawn.

Luminaire overview

A three-stage 700W power converter, shown in figure 1, has been designed to drive twelve high power LEDs. First two stages deal with grid requirements for low harmonic content and unity power factor. The grid voltage is boosted to 400V DC by a step up converter. The luminaire has to operate under different input voltages, ranging from 110V to 230V dependent on the country. Two boost converters are paralleled to handle high input currents at low AC grid voltage and to decrease the ripple content in both input and output current of the boost stage.

Phase shifted full bridge topology converts this voltage to 30V DC providing galvanic isolation. DC link voltage on a C_{dc} capacitor is set by the ratio of turns of the forward transformer and is controlled by adjusting the phase of the pulses that control the transistors.

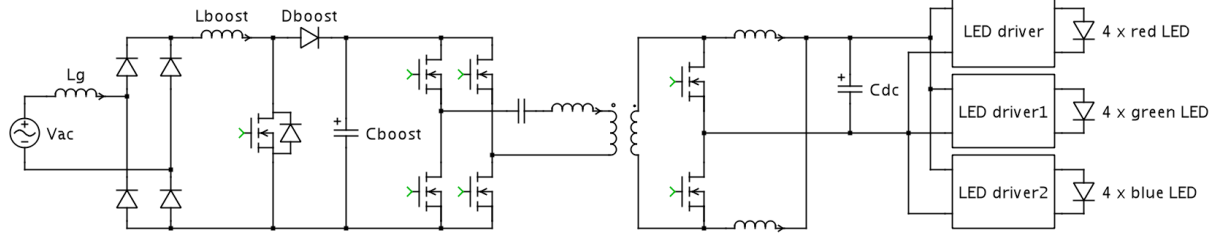


Fig. 1. Schematic diagram of power converter for RGB LED luminaire.

Table I: Forward voltages at 13.5A driving current and dynamic resistances for Luminus CBT-90 diodes [6].

	Vf min [V]	Vf typ [V]	Vf max [V]	Rd [mΩ]
red	2.0	2.4	3.0	42
green	3.6	4.3	5.3	70
blue	3.2	3.9	4.8	50

The test luminaire has been designed as a RGB lamp, consisting of three strings of four series connected Luminus CBT-90 LEDs. The forward voltages of these diodes are presented in table I. Forward voltage may vary among particular diodes in the batch, and it is also marginally dependent on the junction temperature (few mV/K). Low dynamic resistance, 168-280mΩ per string, means that the string voltage will change by approximately 2.3-3.8V at 0-13.5A current range.

In order to control the color of the light and the intensity each diode has to be dimmed individually. The typically used PWM dimming technique may cause EMI problems as 13.5A driving current would be switched with low frequency of hundreds of hertz. This low frequency could also cause thermal cycling issues. To avoid this problem amplitude dimming technique was chosen for the intensity and color control. Apart from solving the EMI problems, dimming with amplitude modulation technique increases diodes' luminous efficacy by up to 100% [7]. It is however nonlinear and requires sophisticated control algorithms [8].

Three LED drivers are connected in parallel on the input side to be able to adjust the driving current of each diode individually. As the electrical parameters of the red diodes differ significantly from green and blue diodes, the drivers have different values of the input and output capacitors to obtain similar ripple attenuation.

LED driver

Multiphase interleaved buck converters have been used for a long time as voltage regulation modules (VRMs) for microprocessors [9]. The advantages over single-phase buck converter include low ripple content in the input and output current and therefore lower values of both input and output capacitors and increased dynamic performance. The currents flowing through the capacitors are greatly reduced, increasing the lifetime of a converter. Also the capacitance required to obtain desired current ripple magnitude is much lower than in a single-phase buck converter. Large capacitance would require the

use of electrolytic capacitors that have low lifetime in high temperatures [2,3]. Ripple cancellation effect allows the use of low capacity film polyester capacitors, which have much higher lifetime than electrolytic capacitors.

These advantages are balanced by the need of more complicated control, increased gate driver losses, increased cost and current sharing problems. Mismatch in the inductor resistance values causes the current to be shared unequally between phases and consequently the phases have to be designed for a higher current than optimal. Current sharing issues can be avoided using current programmed control for each phase.

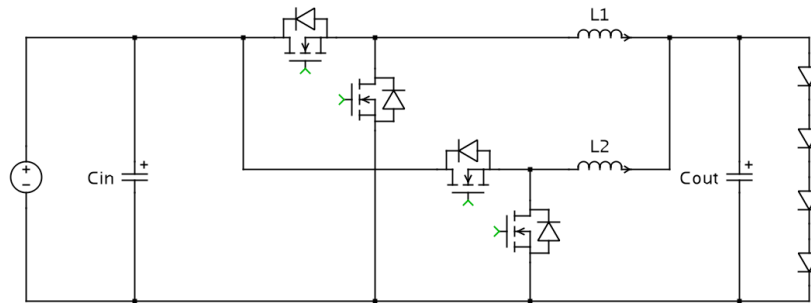


Fig 2. Schematic diagram of two phase interleaved buck converter.

Two-phase interleaved buck, a simplest variant of the topology, is shown in figure 2. Full ripple cancellation is achieved only in one working point—at duty cycle equal to 0.5. Any duty cycle other than trivial 0 and 1 will yield current ripples in input and output current as shown in figure 3.

Ripple frequency is doubled compared to single-phase converter as the PWM carrier frequencies are shifted with 180° . This reduces the demand on the value of the output capacitor further.

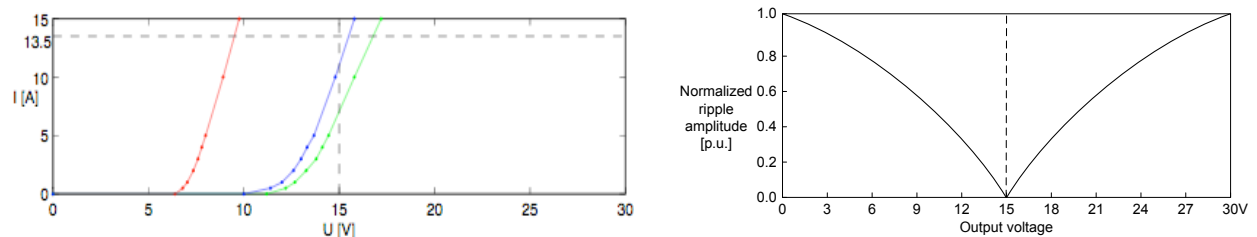


Fig. 3. Current-voltage characteristics of four series connected red, green and blue Luminus CBT-90 diodes (left) and normalized output current ripple amplitude for two phase interleaved buck (right)

The current is shared between the two phases of the converter, therefore, by halving the RMS value of the current, the conduction losses lower by a factor of four. Another advantage of this topology is that in the multiphase approach the heat sources like power MOSFETs are distributed on the PCB, making thermal management easier.

Proper selection of DC voltage between PFC stages and LED drivers will yield low ripple currents for the diodes in their whole current driving range. Using typical forward diode voltages for four diodes connected in series, the string voltages will be equal to: 9.6V, 17.2V and 15.6V for red, green and blue diodes, respectively. As red AlGaInP diode have much smaller forward voltage than green and blue InGaN this condition cannot be satisfied for all string at the same time. The input voltage for the LED drivers was chosen to be equal to 30V so that the current-voltage characteristics of the InGaN diode strings lies close to the half of the input voltage.

Both phases of the converter are separately controlled using digital average current control to achieve symmetrical current sharing. Typically a resistor is added in series with high transistor to measure the current. Its value is a compromise between the power dissipated in it and signal-to-noise ratio of current measurement signal.

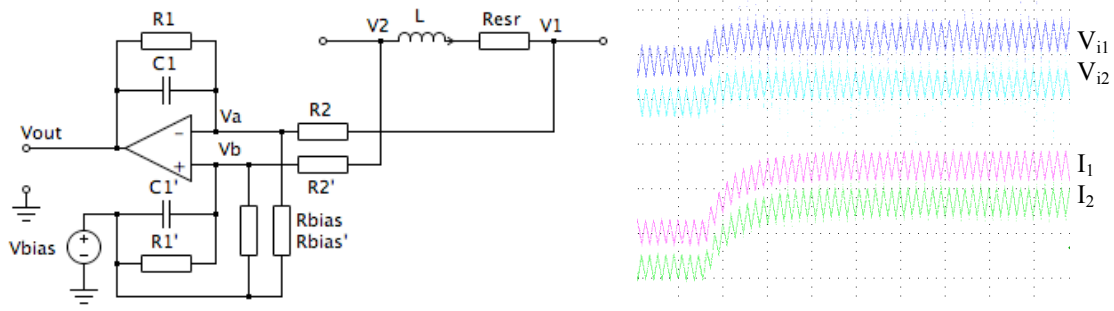


Fig 4. Current measurement circuit (left) and its measured dynamic properties when $RC > L/R$ (right).

A cheap and accurate current measurement was implemented using an inductor DCR technique. A low cost differential voltage sensing circuit based on TL072 operational amplifier measures the voltage on the inductor. Adding capacitors in parallel with the feedback resistors creates an integrating action that converts voltage on the inductor to voltage signal, which is proportional to the inductor current.

Impedance of paralleled R_1 and C_1 is equal to

$$Z_{RC} = R_1 / (1 + sR_1C_1) \quad (1)$$

Assuming that amplifier input currents are negligible currents flowing in and out V_a and V_b nodes are calculated as follows

$$I_1 - I_2 + I_{bias} = 0 \quad \text{and} \quad I'_1 - I'_2 + I'_{bias} = 0 \quad (2)$$

Subtracting above equations from each other one obtains

$$I_1 - I'_1 - I_2 + I'_2 + I_{bias} - I'_{bias} = 0 \quad (3)$$

$$Z_{RC}(V_1 - V_a - V_2 + V_b) = R_2(V_a - V_b + V_{out}) \quad (4)$$

For proper rejection of common mode voltage resistors R_1 , R_1' and R_2 , R_2' must have as close value to each other as possible [10]. Assuming that the gain of amplifier $A \rightarrow \infty$ voltages V_a and V_b can be treated as equal and transfer function of the differential amplifier circuit can be calculated as

$$Z_{RC}(V_1 - V_2) = R_2V_{out} \quad (5)$$

$$\frac{V_{out}}{V_1 - V_2} = \frac{Z_{RC}}{R_2} \quad (6)$$

Voltage on the inductor is equal to

$$V_L = I_L R_{esr} (1 + sL/R_{esr}) \quad (7)$$

Current sensing circuit is connected to the terminals of the inductor, therefore substituting equations 1 and 7 into equation 6 yields

$$\frac{V_{out}}{I_L} \cdot \frac{1}{1 + sL/R_{esr}} = \frac{R_{esr}R_1}{R_2} \cdot \frac{1}{1 + sR_1C_1} \quad (8)$$

When time constants R_2C_2 and L/R_L are equal, eq. 8 is simplified to $V_{out} = I_L R_{esr} R_1 / R_2$. Since the driver is controlled with average current control, the current is sampled in the middle of up or down ramp of the current and any mismatch in the time constants will not cause any error in steady state operation. Only the transients occurring at the current command change will be affected.

Additional R_{bias} resistors allow the use of cheap amplifier without rail-to-rail inputs by pulling up the voltage on the inputs of the amplifier. If they are connected to the same voltage and have the same value they do not change the output voltage. The values of current measurement circuit are presented in table II.

The inductance is strongly dependent on the current DC bias therefore dynamic performance of the measurement circuit will change depending on the working point of the converter.

Table II. Power stage and current measurement circuit components values

Power stage		Current measurement circuit	
MOSFET high	IRLR3636	R_1	183k
MOSFET low	IRLR3636	R_2	2k
Inductance	22 μ H	C_1	10n
Inductor ESR	12m Ω	R_{bias}	2k
Output C (green, blue ch.)	4.7 μ H		
Output C (red ch.)	10 μ H		

Efficiency

Power stage efficiency including gate driver losses has been plotted in figure 5. An electronic load has been used to reach working points defined by the blue diode current-voltage curve. Efficiency reaches 97.3% at 13.5A DC current, which is nominal driving conditions for CBT-90 diodes.

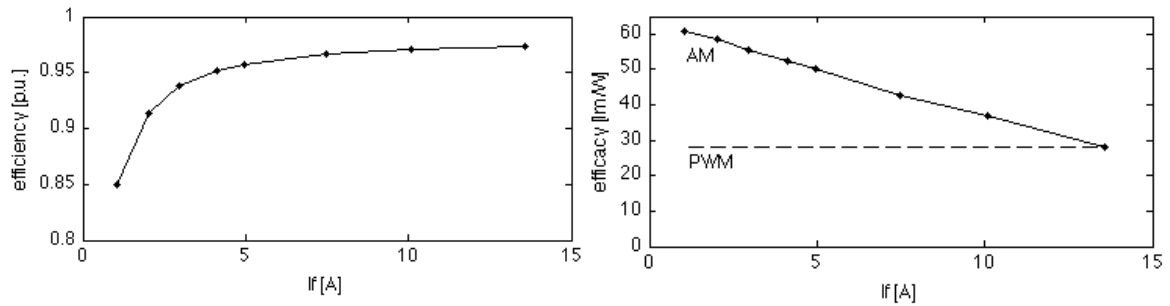


Fig 5. Measured efficiency of LED driver (left) and luminous efficacy of driver and LED (right) as a function of diode forward current

Under PWM dimming, the converter operates in two working points: full DC current and 0A. This implies that the efficiency of the PWM converter is approximately equal to the efficiency at full load. Diode efficacy remains almost constant under PWM dimming [11], therefore efficacy calculated as a diode flux to the driver input current can be approximated as constant (fig. 5).

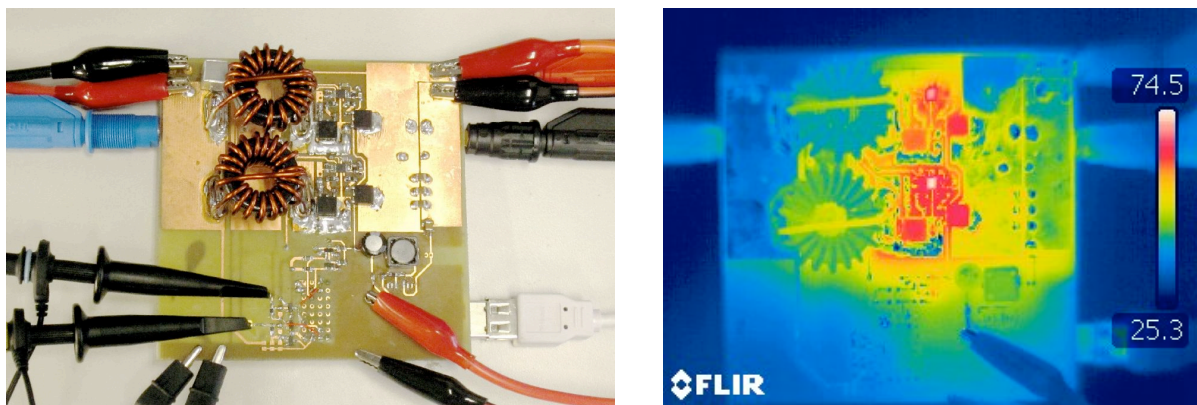


Fig 6. Prototype of the interleaved synchronous buck converter (left) and thermal image of the converter under full load at 220W output power (right)

On the other hand, under AM dimming, the efficiency of the converter is dependent on the operating point as shown in figure 5. Diode luminous efficacy is also dependent on the driving current and is bigger for lower current concentration in the junction. Overall efficacy from input power of the diode driver to diode's flux is presented in figure 5.

Converter is controlled by a TI 320F28027 Piccolo DSP. A single processor is able to control up to four interleaved LED drivers and handle color mixing at the same time together with color control algorithm.

Conclusions

Two-phase interleaved buck converter is a good candidate topology for driving high current light-emitting diodes especially when the diodes are dimmed with AM modulation. Amplitude modulation does not require high bandwidth of current controller therefore digital current controller can be implemented in a slow processor. Due to low dynamic resistance, diodes' voltage drops by around 30% at full current range thus the converter can be operated close to the 50% duty cycle. This significantly reduces the capacitance needed to obtain desired current ripple content.

Compared to PWM dimmed luminaire, the luminous efficacy of the driver-LED system has up to twice as high luminous efficacy offering power savings and lower cost of operation.

Two inductors could be combined on a single magnetic core offering additional efficiency increase.

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