STEP DOWN CURRENT CONTROLLED DC-DC CONVERTER TO DRIVE A HIGH POWER LED MATRIX EMPLOYED IN AN AUTOMOTIVE HEADLIGHT

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***Abstract* – This paper deals with the study and the application of high power LED in automobile headlights. A new simplified SPICE model for the LED is presented and used to simulate the device. Characteristics presented by LED array such as current unbalancing have been well represented with the proposed SPICE model. An experimental set up was used to validate the model and the LED array current unbalance has been shown. The study indicates the necessity of a technique for current equalization when using parallel LEDs arrays.**

***Keywords* – Automotive headlight, DC-DC converter and LED SPICE model.**

I. INTRODUCTION

The first practical Light Emitting Diode (LED) was developed in 1962. It was made with a compound semiconductor alloy, gallium arsenide phosphide, which emitted red light and was used exclusively as indicators. In 1994, Hewlett-Packard improved the efficiency of the LED in ten times the efficiency of a red filtered light bulb. The efficiency of 25 lm/W enabled the first LED stop lights on automobiles, LED red traffic signals and single color outdoor signs. But at 3 lm/LED uses were still limited to those applications. In 1998, the pioneering work on high power LEDs began at Lumileds lighting. This company introduced the first commercial power LED. The Luxeon 1 W led operates at power level 20 times greater than the traditional 5 mm indicator led, with efficiency of 50% [1]. In 2007, it will be possible to by LEDs with a cost lower than incandescent lamps, in 2012 lower than the cost of fluorescence lamps and in 2020 lower than cost of all traditional lighting systems [2], [3], [4].

The LEDs are solid state components, so they do not have fragile envelop, are not filled with toxics gases, do not have any explosion, broken or contamination possibility. They are solid state components. So, they are very robust. Their characteristics allow to generated light and does not extinguish subtly. The light will present a gradual intensity reduction over time. They have longer useful life than incandescent lamps and discharge lamps. Their life time may be around 50,000 hours. This fact reduces the maintenance frequency of lighthing systems [5].

Automotive designers are starting to project LEDs headlights. In January 2004 the Hyundai Company showed at Detroit Automobile salon its concept car HCD-8, which used LEDs without a reflector [6]. This was possible due to the improvement in this technology over last years.

The LED current should be limited to prevent the device overheating. A resistor is not a proper solution as LED current limiter. The reason is the battery voltage that varies with time. The output voltage value a 12 volts battery car may vary from 10 volts to 15 volts depending on external temperature and electric load. Besides this fact, voltage spikes may appear in battery power source generated by motors and relays. This unregulated power source will reduce the LED useful life. Moreover, the resistor losses reduce the system efficiency.

It is expected the electric system of a car to change from the present 12 volts to 42 volts in a few years [6]. This fact reinforces the converter usage necessity. The present work proposes a DC-DC current controlled converter to power a LED headlight. The power source will be a 42 volts automotive battery. The DC-DC converter will be a modified step down converter.

II. LUXEON V LED

The power Luxeon V LED manufactured by Lumileds is more efficient than incandescent lamps. It produces more than 20 lm/W. Nevertheless, it has potential to produce more than 50 lm/W until 2005. The state of the art made possible thermal resistance reduction when compared to similar components. This reduction allows an improvement in power sourced to the component. Like any semiconductor, the junction temperature is a limiting. It can not be higher than 135 °C [7].

The LED used in this work is the Luxeon V Portable Emitter White LXHL–PW03 shown in Fig. 1. It has an average forward current of 700mA, a forward typical voltage of 6.84V, a luminous flux of 120 lm and a useful life of approximately 1,000 hours.

Fig. 1 – Luxeon V LED from Lumileds picture.

Table I permits to compare halogen lamp, discharge lamp and the Luxeon V LED.

TABLE I

Lighting source in automotive applications

Lighting Source	Power (W)	Luminous Flux (lm)	Efficiency (lm/W)
Halogen	55	1,500	27
HID	35	3,000	85
Luxeon V LED	5	120	24

The light emitted by a LED is unidirectional. Typical conventional sources such as incandescent, halogen, fluorescent or HID lamps are omni-directional, emitting light in all directions. For efficient illumination, light from these lamps must be re-directed toward the desired location using some type of optics. Luminary losses may range from 30% to 60% of initial lamp lumens, but the directed nature of the LEDs can result in fixture efficiencies of 80% to 95%, requiring fewer total lumens to provide the same level of illumination [8].

III. A NEW SIMPLIFIED LED SPICE MODEL

The forward current versus forward voltage characteristics of a p-n junction diode is mathematically expressed by equation (1) [9].

$$I_F = I_O\left[\exp\left(\frac{q\cdot V_F}{n\cdot k\cdot T}\right)-1\right] \quad (1)$$

Where:

I_F - Forward current (A).
I_O - Reverse saturation current (A).
q - Electron charge, 1.602 x 10^{-19} coulomb (C).
V_F - Forward voltage (V).
n - Ideality factor.
k - Boltzmann constant, 1.3805 x 10^{-23} (J/ºK).
T - Temperature (ºK).
Note: At room temperature (25ºC), k.T/q = 0.02569 V.

Rewriting equation (1) to get the value for forward voltage V_F, equation (2) is obtained.

$$V_F = \frac{n\cdot k\cdot T}{q}\ln\left(\frac{I_F+I_O}{I_O}\right) \quad (2)$$

The diode equation above is an approximation for low currents. However, at forward currents above hundred of milliamperes, the Ohmic losses must be including to accurately model the forward voltage.

Adding ohmic losses to equation (2) equation (3) is obtained [10], [11].

$$V_F = \frac{n\cdot k\cdot T}{q}\ln\left(\frac{I_F+I_O}{I_O}\right)+R_S\cdot I_F \quad (3)$$

Where:

R_S - Internal series resistance (ohms).

The accurately model is composed with a real diode and a series resistance, as showed in Fig. 2.

Fig. 2 - Diode model considering the Ohmic losses.

Defining $V_D(I_F)$ as the forward voltage as a function of forward current, in diode model without Ohmic losses, equation (3) can be rewritten in equation (4).

$$V_F = V_D\left(I_F\right)+R_S\cdot I_F \quad (4)$$

The experimental curve for forward current versus forward voltage, obtained with LXHL–PW03 LED at a 25°C room temperature, is shown in Fig. 3.

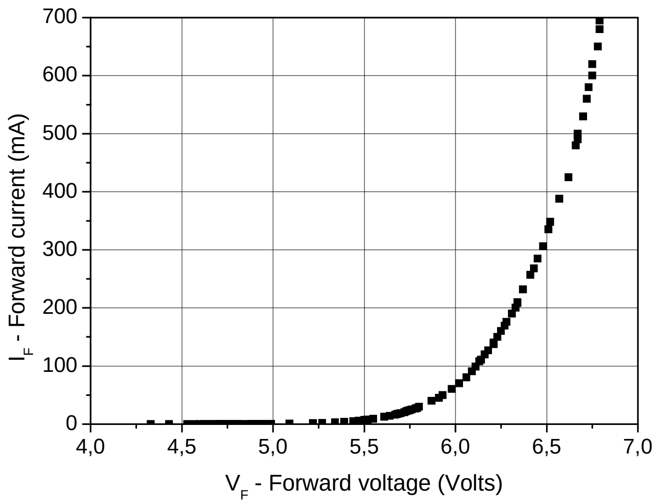

Fig. 3 – The experimental curve of the LXHL–PW03 LED @25°C.

For a current operation between 200 mA and 700 mA the linear fitting for the experimental forward current curve versus forward voltage is shown in Fig. 4.

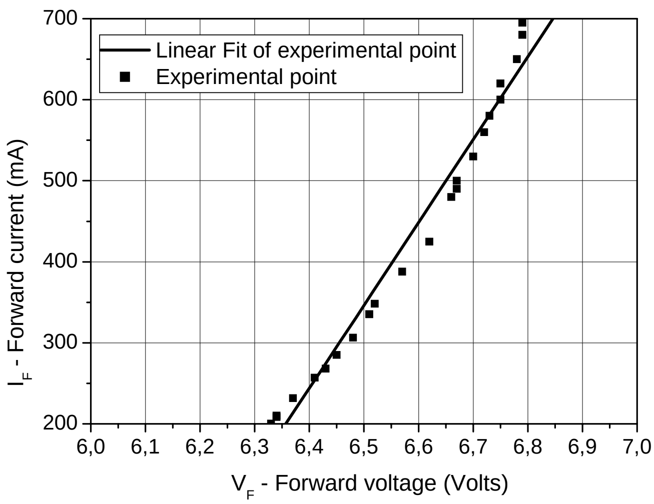

Fig. 4 – Linear fit for operation between 200 mA and 700 mA.

The forward voltage (V_D) in the diode model with no Ohmic losses is considered constant in this interval of operation. Equation (4) can be compared with the linear fitting of Fig. 4 and equation parameters can be obtained for this case. With this assumption, equation (4) for LXHL–PW03 LED @25°C can be rewritten in equation (5).

$$V_F = 6.16 + 0.98 \cdot I_F \quad (5)$$

The new simplified model for equation (5) is shown in Fig. 5.

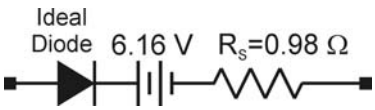

Fig. 5 – New simplified LXHL-PW03 @25°C model.

In the SPICE model a diode schottky can be used in place of the ideal diode. However, the schottky diode forward voltage should be subtracted from the source voltage. For a MBR120 diode schottky, its forward voltage of 0.42 V must be subtracted from the 6.16 V voltage source. Fig. 6 shows the LXHL–PW03 LED @25°C SPICE model using this component.

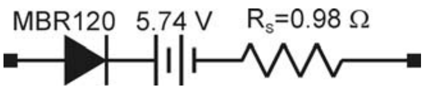

Fig. 6 – SPICE model using the MBR120.

Notice that the modeled component can be used only when the LED current is within 200mA and 700mA. This model cannot be used when a high frequency current ripple is applied to the LED, since the junction capacitance of the LED was not considered.

The influence of the temperature can be observed through the model altering the voltage source. The LED has a negative thermal coefficient for the forward voltage. The thermal coefficient for LXHL–PW03 LED is -4 mV/°C [12].

Important points should be considered when designing electronic ballast for LEDs:

- The thermal coefficient for forward voltage is negative. The hotter the LED junction, the lower the forward voltage. This characteristic causes a current unbalancing in parallel connected LEDs.
- The forward voltage can be different even for components of the same manufactured lot. The LED (LXHL-PW03) forward voltage varies between 5.43 V to 8.31 V.
- When LEDs are mounted in the heat sink, they never have the same thermal resistances. Therefore, the LEDs junction temperature will be different in practice and consequently forward voltages will also be different.

The points above are very important when LEDs are connected in parallel. The difference in the LEDS forward voltage will cause the paralleled currents unbalanced.

IV. THE PROPOSED CIRCUIT

The schematic shown in Fig. 7 is used for simulation and experimental circuit. The converter used is a modified buck topology without output capacitor. The UC3845 is used to perform the control task. The UC3845 is a fixed frequency current-mode PWM controller. This integrated circuit features a trimmed oscillator for precise duty cycle control, a temperature compensated reference, high gain error amplifier, current sensing comparator, and a high current totem pole output to drive a power MOSFET. Protection circuit includes built in under-voltage lockout and current limiting [13]. The prototype operates at 85 kHz and uses a schottky diode, D1, in commutation cell that makes possible to reduce the switch over voltage.

The LEDs are represented by two parallel arrays (LED array 1 and LED array 2 shown in Fig. 7), where each one array is composed of three series LED. For automotive application, the headlight needs more than two arrays forming a greater matrix. However, to study the unbalanced current only two LEDs arrays have been used.

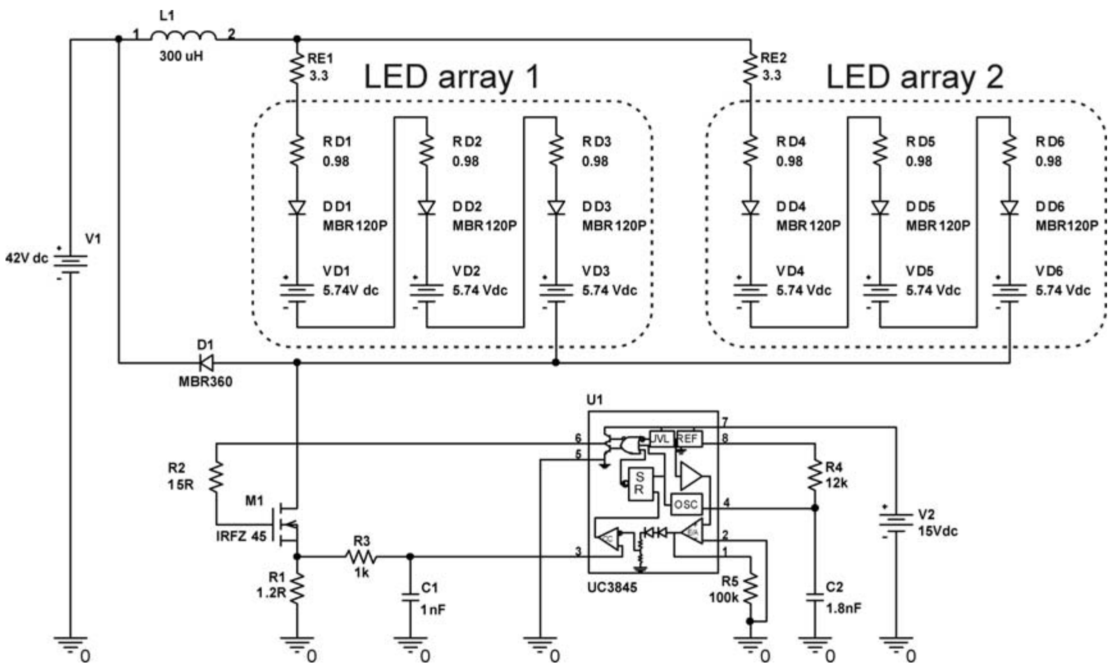

Fig. 7 – Schematic used for simulation and for the prototype.

V. SIMULATION RESULTS

The Buck inductor current is shown in Fig. 8. The high current ripple is used to verify the proposed LED model. In a real application, the inductor current ripple is reduced. Nevertheless, the inductor value is increased.

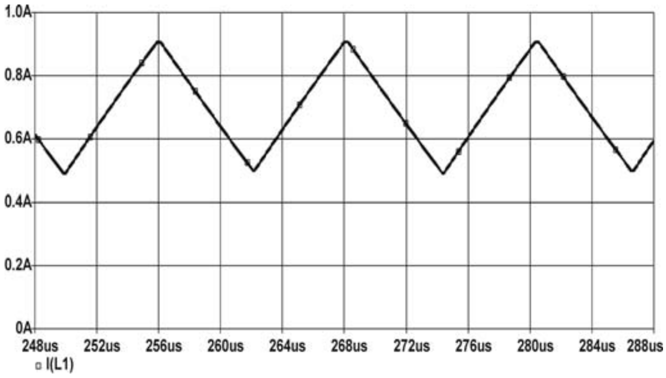

Fig. 8 – Current inductor obtained by simulation.

The voltage reduction in VD3 (VD3=5.04 V) is used to simulate the unbalanced current in the arrays. The forward current in each LEDs array is shown in Fig. 9 when using equalization resistors (RE1 and RE2).

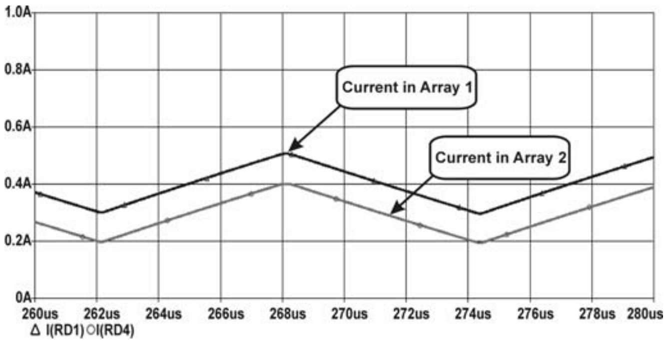

Fig. 9 – Currents in LEDs arrays with equalization resistors.

Still considering the reduced voltage in VD3, and without equalization resistors (RE1 and RE2 nulls), the forward currents in the LEDs arrays are shown in Fig. 10. Note the high unbalancing in the arrays currents. For a load nominal current of approximately 1,400 mA, the unbalancing could damage the LED array 1 and after could damage the LED array 2 too.

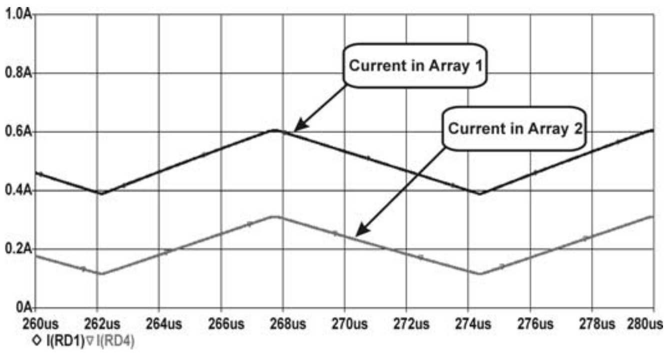

Fig. 10 – Currents in LEDs arrays without equalization resistors.

The LED (modeled by RD6, DD6 and VD6) forward voltage is shown in Fig. 11.

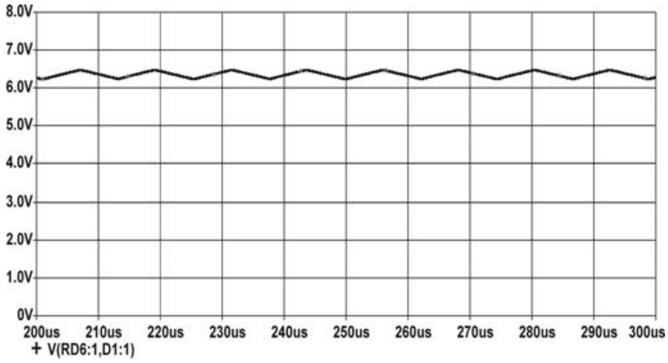

Fig. 11 – LED forward voltage.

VI. EXPERIMENTAL RESULTS

The experimental inductor current is shown in Fig. 12. Note the similarity with simulation result presented in Fig. 8.

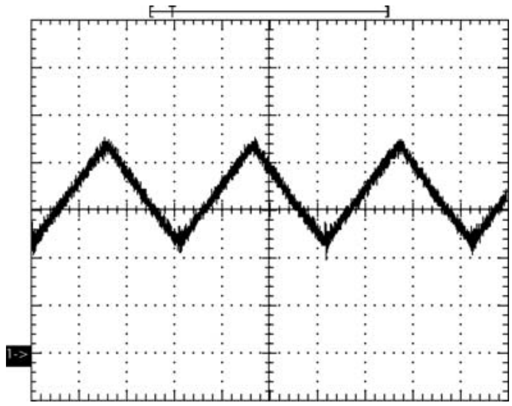

Fig. 12 – Current inductor.

(Time base: 4μs/div. Ch1: 200mA/div.)

The currents arrays are shown in Fig. 13. The circuit used is the same presented in simulation results of Fig. 9. In this case, equalization resistors were used, As can be observed, the unbalancing current was verified.

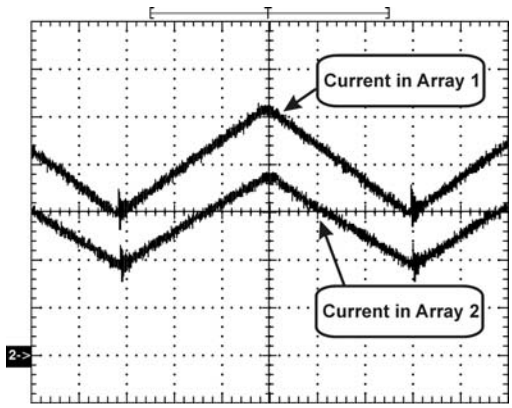

Fig. 13 – Currents in LEDs arrays with equalization resistors.

(Time base: 2μs/div. Ch1 and Ch2: 100mA/div.)

The LEDS arrays currents without equalization resistors are shown in Fig. 14. In this case the current in LED array 1 is higher than the current in LED array 2.

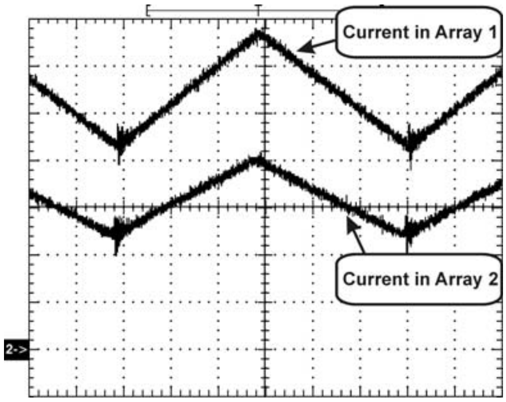

Fig. 14 – Currents in LEDs arrays without equalization resistors. (Time base: 2µs/div. Ch1 and Ch2: 100mA/div.)

Fig. 15 shows a LED forward voltage. This experimental result validates the SPICE LED model.

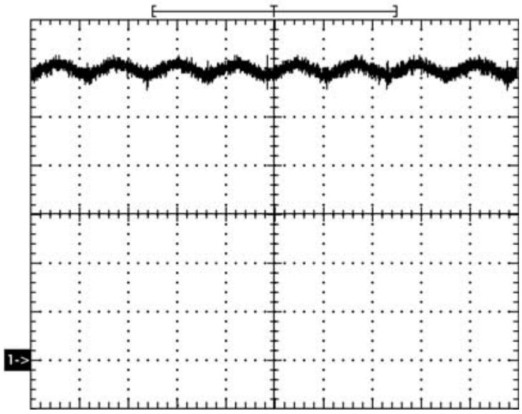

Fig. 15 – Forward voltage in one of the LEDs. (Time base: 10µs/div. Ch1: 1V/div.)

A prototype picture is shown in Fig. 16. The six LEDs are assembled in the same heat sink. These LEDs cannot be used in high junction temperature.

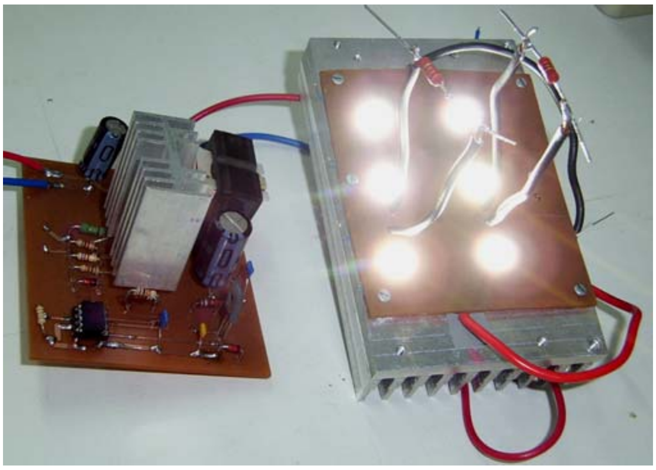

Fig. 16 – Prototype picture used in experimental set up.

VII. CONCLUSION

A SPICE model for Luxeon V LED manufactured by Lumileds was presented and proved its accordance to real component for a LED current between 200mA to 700mA. The model represents the forward voltage and temperature junction influence. Even considering the forward voltage in each LED is the same, it is impossible to get the same thermal resistance junction-heat sink. For this reason when is necessary parallel application, an unbalanced current will appear.

This unbalanced current in arrays LEDs problem and its simulation studied were showed. The simulation results were verified with experimental results. This confirms that is very important apply an equalization current technique to drive each LED array with its nominal current.

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