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High Voltage LED Supply Using a Hysteretic Controlled Single Stage Boost Converter

Abstract. *High voltage-gain transformerless single-stage boost converter requires extreme duty ratios. Hysteretic control can be a solution to achieve this goal, otherwise unaffordable with common PWM integrated circuits. With this technique voltage gains around 100, and duty cycles higher than 99% are feasible. As a possible application, a typical 50 W halogen-based car spot-light, is replaced by an array of 200-300 standard LED's in series consuming 8 -12 W. Although series connection simplifies current control and dimming, a high voltage current-source is required.*

Streszczenie. *Beztransformatorowe, jednostopniowe przekształtniki typu boost o wysokim wzmocnieniu napięciowym wymagają ekstremalnie wysokich współczynników wypełnienia. Regulator histerezowy jest rozwiązaniem pozwalającym na osiągniecie tego celu w przeciwieństwie do innych powszechnie stosowanych układów typu PWM. W tej technice sterowania napięcie może być wzmacniane około 100 razy, a współczynnik wypełnienia sygnału sterującego może przekraczać 99%. W testowanej aplikacji typowy reflektor halogenowy o mocy 50W zastąpiono szeregową matrycą 200-300 standardowych diod LED o sumarycznej mocy 8-12W. Zastosowane połączenie szeregowe ułatwia regulację prądu i natężenia oświetlenia, wymaga natomiast wysokonapięciowego źródła prądu.(**Zasilacz wysokonapięciowy lamp LED oparty na jednostopniowym przekształtniku typu boost ze sterowaniem histerezowym**)*

Keywords: LED drivers, High Voltage Gain, Hysteretic Control, Silicon Carbide.
Słowa kluczowe: sterownik LED, wysokie wzmocnienie napięciowe, regulacja histerezowa, węglik krzemu.

Introduction

Lighting applications based on LEDs are becoming more popular. Their superior longevity, low maintenance requirements, and high-efficiency (lumen/Watt) are the main reason of their commercial success. Among these new applications, we find: LCD backlighting, automobiles, traffic lights, general purpose lighting.

Efficient-lighting is also possible using gas-discharge lamps. These lamps have different light spectrums and color rendering depending mainly on the gas mixture, and internal pressure, but require complex ballasts.

Light emitting diodes (LED's) have a higher efficiency and life-time that many discharge lamps, work always at ambient temperature, and have less complicated drivers.

Consequently, LED systems should play an important role in automobile and general purpose lighting. For instance, according to Table I, a 50 W car halogen bulb should produce the same light than a LED-based 8 W lamp. Nevertheless, high-power devices are still less efficient than 20 mA-5mmø conventional ones. Thus, to make a powerful light-spot, the combination of small devices in a LED array is still required, and the most common technique.

Considering N devices, different matrix form factors can be used to create a LED array, from the most extreme cases, where all the LEDS would be connected in series or in parallel, to available commercial lamps where M strings, each one with N LEDs in series, are connected in parallel.

The main advantage of a pure-series array is that all devices operate naturally at the same current. No special circuit, strategy or additional control is required to balance currents among parallel branches. The main drawback is also evident. A light spot with high number of LEDs should be supplied at high voltage. This option, analyzed in this work, is attractive for its simplicity, avoids the balancing current problems of parallelized structures, and implies an interesting challenge in high-voltage devices, applications, and high gain step-up conversion, especially for automotive and portable applications.

In this paper we present a single-stage boost converter capable to increase the voltage up to 900 V, from a 9 V car-battery, as shown in the experimental results.

This output voltage is sufficient to supply 280 white-LEDs in series at their nominal current, 20 mA. The only limiting factor is the switching devices voltage breakdown. In this context, promising silicon-carbide devices will help to increase the output voltage.

The keypoint of the whole system, protected under patent, is the hysteretic controller which has two important tasks. By one side, hysteretic control makes feasible converter duty-ratios above 99% unaffordable with PWM technologies. By other side, assures converter operation at DCM-CCM border, eliminating the diode turn-off losses and achieving voltage gains around 100, as proved with an experimental prototype.

Review on LED Driver Circuits

As explained before most common technique of achieving a considerable light-output in a LED-based spot is placing a high number of small power LED's in a series-parallel array, where for practical purposes the number of parallelized branches is minimized, favoring the device series connection.

The simplest possible driver is used in the LED spots of E14 and E27 standard fittings, se Fig. 1. These lamps include up to 3 parallelized branches of 20-26 series devices. Although there is nothing to balance the branches currents, its simplicity, low size, and efficiency make this driver remarkable. Realize that the capacitor is the key part, capable of blocking all the grid voltage to supply a even single 3V LED, with a negligible power dissipation as capacitor voltage lags the current 90º.

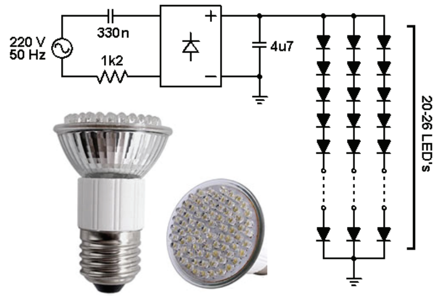

Fig.1. Commercial LED-based spot and driver circuit

To adapt the previous driver to an equivalent DC voltage supply, the 330n capacitor should be replaced by a big-sized power resistance, or a buck-based converter.

(1) $$P_R = \underbrace{[220-3.2\times 26]}_{V_R}\times\underbrace{[0.02\times 3]}_{I_R} = 8.2W$$

(2) $$P_{LED's} = \underbrace{[3.2\times 26]}_{V_L}\times\underbrace{[0.002\times 3]}_{I_L} = 5.0W$$

To improve current balancing, many LED drivers include a linear current regulator per branch [1]. This solution has a poor operating efficiency because the voltage drop across the linear regulators cannot be minimized. In fact, the current regulator input voltage V_o must be adjusted for the worst case. Feeding all the branches with the same current, the worst case is given by the highest voltage drop branch, operating at the lowest temperature, when LED's forward voltage is higher.

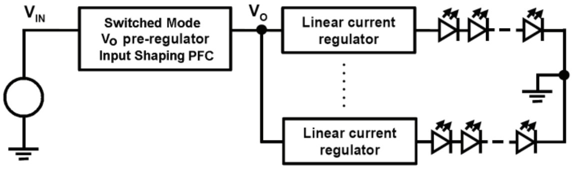

Fig.2. Simple strategy for current balancing

To increase the driver efficiency, a very common solution in the literature is to make the current regulators input-voltage Vo to be adaptative [2, 3]. Another option [1] to increase efficiency uses switched-mode current sources to balance LED branches, but the cost increases.

Different converters are proposed as PFC voltage pre-regulators. Among them, boost [2, 3, 5], buck [4], or galvanic isolation converters like forward or flyback [6]. Concerning its control, PWM technique is the most used, although this technique is not reliable to achieve extreme duty ratios, around 98%, as required in our boost driver. In fact, the main problem with exteme duty ratios is the noise effect on the PWM comparator, causing false switching.

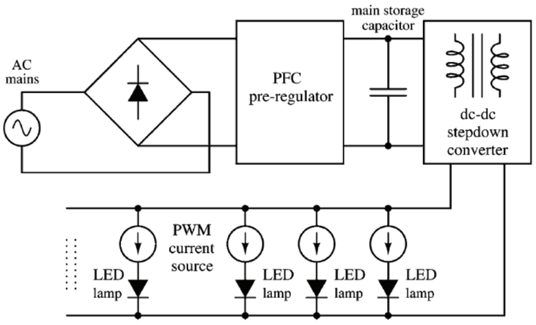

Fig.3. Driver using PWM current sources

Other works [7], instead of parallelizing diverse sets of LED in series, with the consequent current sharing problems, connect those sets in series using DC-to-DC converters, in a master-slave structure, where only of the converters is regulated, the master. This structure can be seen in Fig. 4, were each converter is responsible to fed a little branch of LEDs in series. This structure is especially attractive when some LED set has a very different voltage, because has a different number of devices, or if all the sets have the same LED number, the devices have a different forward voltage.

Although this structure requires too many converters, the main drawback of this topology is that direct current control of all LEDs series is not possible, because the duty cycle of the slave's branches is imposed by the master, with no feedback from the slaves. Besides, the current is only the same at the converters inputs, no at their outputs. Finally, when a LED breaks, open circuit appears, and all the remaining LEDs are turned-off.

The solution proposed here, is less expensive, different forward voltage devices are also compatible, and protecting each four-five LEDs with a zenner diode, only when a few LEDs turn-off, if there is an open circuit breaking the chain of LEDs in series.

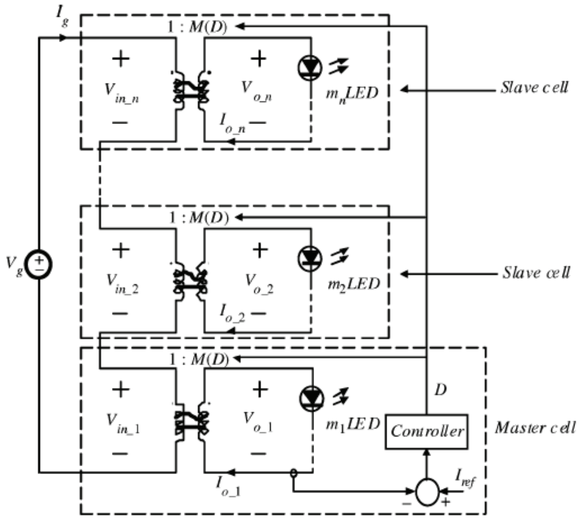

Fig.4. Driver without current regulator per branch

High Voltage-Gain Converters

As we have decided to organize the LED array in a pure series configuration, with a single current branch, the lamp driver may require a high output voltage. Besides, if the LED-lamp must be supplied from a low voltage source, as happens with a car-battery headlight, then a high voltage-gain converter will be required.

Two types of converter topologies can be used for Boost operation: the isolated an the non isolated. The isolated converters can provide high voltages in the output, such as, the flyback, push-pull, forward, or tapped Boost. However, these converters could require snubbers to attenuate the voltage peaks caused by the transformer flux-leakage inductances. Using a transformer, although contributes to voltage gain, increases the cost, volume and losses [7, 8, 9, 10]. This can be partially compensated if active clamps [8] are introduced to reduce those losses.

Research on transformerless ballast/drivers pursues a reduction in losses, size, and cost. Nevertheless, for the applications previously mentioned, the required voltage gain is too high for a conventional PWM-controlled boost, so several approaches have been proposed to increase the voltage gain. Some of them are, cascaded boost, tapped boost, or diverse boost derived converters integrating some switched capacitor/inductor stages [11], like the voltage lift types [12], for instance. Anyway, these converters are very complex, and the overall cost is increased. Unfortunately, to achieve a high voltage gain, many stages are required, especially in the switched capacitor case.

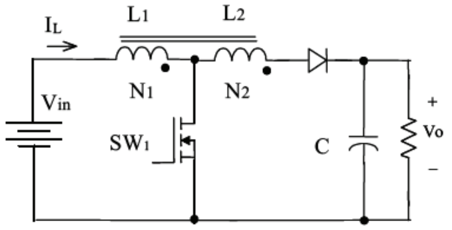

Fig.5. Tapped boost switch converter

Proposed Converter Operation

A classical single-stage boost converter has very few elements, but to provide a high voltage gain, is of utmost concern to generate a extreme duty cycle.

This work presents a single-stage Boost converter achieving a high voltage gain with an extremely duty ratio. To avoid PWM noise sensibility, and switching instability a hysteretic controller is used. In addition, this kind of control assures the converter operation at DCM-CCM boundary, and the zero current mosfet turn-ON and diode turn-OFF. This improves other approaches where this problem is solved by means of adding structures to switch at zero current or voltage [12].

Fig. 6 depicts the converter circuit, including the hysteretic controller, and the control loop.

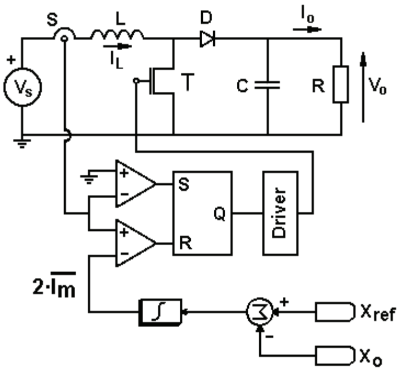

Fig.6. Boost converter with hysteretic converter

DCM-CCM boundary operation

In order to achieve, the highest output voltage as possible using commercial devices, we have made the converter using conventional silicon technology. Although emerging silicon carbide (SiC) technology is very promising, at this point, is still difficult to find shottky diodes over 600V, and therefore an hyperfast bipolar diode from IXYS has been used instead. Table 1 summarizes the used devices.

Table 1. Switching devices at experimental prototype

INFINEON CoolMos **IPW90R120C3**	900 V	36 A	0.12 Ω	270 nC	36 €
	V_{BD}	I_{MAX}	R_{on} - V_f	Q_g - t_{rr}	cost
DSEP 30-12CR IXYS HiperDynFredt	1.2 kV	30 A	1.5 V	20 ns	3.2 €

Shottky diodes are majority-carrier devices, no charge is stored during their ON-state, and very fast turn-OFF without reverse recovery peak is possible. Nevertheless, bipolar diodes are minority-carrier devices, and some charge Qf according to the ON-state current, and carrier life-time is stored inside. Then a reverse-recovery peak Irr appears during the diode turn-off to empty the stored charge. This process causes switching losses, unless diode turn-OFF be at zero current, imposing inductor DCM operation.

By other hand, working at deep DCM conditions, to preserve the input average current in order to satisfy the load requirements, the input current peaks would be much higher (fig. 8), increasing all devices RMS currents, and therefore, the conduction losses of mosfet and diode.

In fact, as deeper is the DCM mode, higher is the current stress, and therefore the conduction losses. Consequently, the DCM-CCM boundary is the working zone with the lowest conduction losses, but keeping diode turn-OFF at zero current.

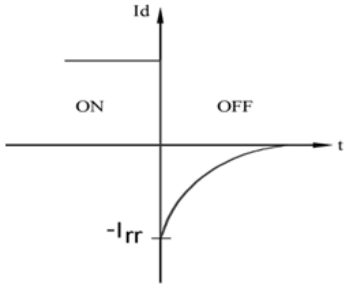

Fig.7. Idealized turn-OFF of a bipolar diode

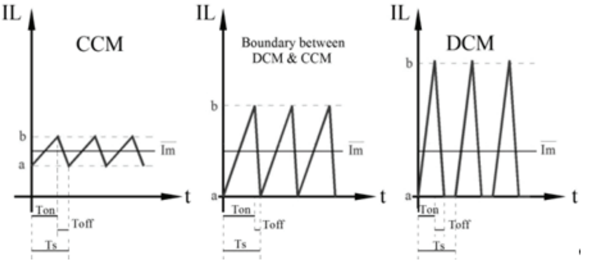

Fig.8. Inductor current at CCM, border, and DCM

The conduced losses and the RMS currents of inductor, mosfet, and diode have been calculated for all conduction modes, and given at Table 2. To find these expressions, a very-high voltage-gain hypothesis is assumed. At these conditions, the OFF-state, where the diode conducts to charge the output capacitor, has a negligible duration. That is, $T_{OFF} << T_{ON}$, and then $T = T_{ON} + T_{OFF}$, or equivalently $D = D_{ON} + D_{OFF} \approx D_{ON}$.

Table 2. Conduction losses and RMS currents

		Inductor	Mosfet	Diode
RMS Current	DCM	$\frac{2}{\sqrt{3D}}\overline{I_m}$	$\frac{2\sqrt{D_{on}}}{\sqrt{3D}}\overline{I_m}$	$\frac{2\sqrt{D_{off}}}{\sqrt{3D}}\overline{I_m}$
	Border	$\frac{2}{\sqrt{3}}\overline{I_m}$	$\frac{2\sqrt{D_{on}}}{\sqrt{3}}\overline{I_m}$	$\frac{2\sqrt{D_{off}}}{\sqrt{3}}\overline{I_m}$
	CCM	$\overline{I}_m < \sqrt{\overline{I}_m^2 + \frac{(b-a)^2}{12}} < \frac{2}{\sqrt{3}}\overline{I}_m$	$I_{L(RMS)} \cdot \sqrt{D_{on}}$	$I_{L(RMS)} \cdot \sqrt{D_{off}}$
Conduction losses		$\frac{4}{3} R_L \overline{I}_m^2$	$\frac{4}{3} R_{on} D_{on} \overline{I}_m^2$	$\frac{2}{\sqrt{3}} V_f \overline{I}_m \sqrt{D_{off}}$

To calculate the averaged input current Im, the only data required is the switching period T_S, because at DCM-CCM boundary $D_{ON} \approx 1$, as deduced form high gain hypothesis.

$$\overline{I_m} \approx \frac{V_S}{2\cdot L} D_{ON} T_S \approx \frac{V_S}{2\cdot L} D_{ON} \tag{3}$$

$$\overline{I_m} = \frac{P_O}{\eta V_S} \Rightarrow P_O = \frac{\eta V_S^2 T_S}{2L} \tag{4}$$

Neglecting the efficiency η effect, the input current I_m, and the output power P_o are both proportional and directly controllable by adjusting the switching period T_S (4). In fact, the converter behaves like a Loss Free Resitor, due the input current I_m is also proportional to the supply voltage V_S.

Converter Control

As can be seen at fig. 5, the flip-flop activates the switch when the inductor current is zero, and turns-OFF the mosfet when the inductor current reaches 2·I_m .This is equivalent to force the average input current to its value, that is I_m . The reference is given by an integrator controller.

Thus, the hysteretic controller has two tasks. By one side assures that the converter operation at DCM-CCM boundary, by other side it assures that the switch be at ON-state, only the minimum time to deliver the expected output power. As higher is the output power P_o, lower will be the switching frequency, thus minimizing the switching losses. Nevertheless, the most important is that any extreme duty-ratio can be done, making feasible very high voltage-gains.

In classical PWM systems, such extreme duty ratios are not possible due to different causes. Common integrated-circuit PWM controllers limit the duty-ratio range internally. Often, switching noise makes the comparison between the control signal and the triangular carrier very unstable or chaotic, loosing progressively more switching cycles as higher is the duty-ratio attempted. Duty ratios over 95% are practicably unfeasible. And finally, sometimes the devices rise-time and fall-time make unfeasible such duty ratios if the switching frequency cannot be reduced.

Control-loop is closed using an integrator controller. At steady-state conditions, the integrator gives the appropriate reference 2·I_m to assure a zero steady-state error between a reference variable X_{ref}, and its measured value X_o. The reference variable X_{ref} can be an either an output voltage reference, or in the case of a LED-based lamp, a 20 mA current reference.

$$2\cdot\overline{I_m} = k\int\left(X_{REF} - X_O\right)\cdot dt \qquad (5)$$

By applying the sliding motion theory to the system presented here, it can be easily proved that the inductor current will track 2·I_m, achieving a zero steady-state error of the output variable, X_{ref}-X_O =0. System stability, as well, can also be proved. Detailed formulas of these processes are not given for paper brevity.

Experimental and Simulation Results

To demonstrate the feasibility of the presented system, some preliminary simulations were carried out by means of PSIM program.

Fig. 9 depicts these results. In -fig. 9c, the expected Inductor current saw-tooth waveform is clearly seen. The steady-state output voltage reaches 650 V (Fig 9b), as expected from an array of 204 standard-size white LEDs. The output current is 20 mA (Fig. 9a), corresponding to the rated current of 5 mmø standard devices. Finally, the nonlinear characteristic of the diodes can be seen, because the output current only begins growing when LED's voltage have reached around 600 V.

Moreover, the proposed converter has been subjected to many test, including different input voltages, reference values, and load conditions. The experiments shown here, were done considering an output current reference adjusted at 20 mA approximately.

During the first test, Fig. 12a the converter is loaded with a resistive load of 10 kΩ ± 10%. From a 12 V car battery (ch.1), the output current is 20 mA (ch.4), and the converter achieve 200 V (ch.3) working in the boundary betwwen DCM-CCM (ch.1). In this case, the converter exhibits a moderately high, voltage gain.

The second test presented here is related to efficient lighting. According to recent stiduies, conventional 12 V 55 W halogen bulbs for car head-lamps could be replaced by 8 W LED spots. Using standard LED's (20 mA, 3.2 V), a matrix with 204 LEDs has been developed. In Fig. 12b, the converter is loaded with a 204 white LEDs matrix. Realize that the output current is kept (ch.4), and the output voltage reaches 643 V, see (ch. 3), as expected.

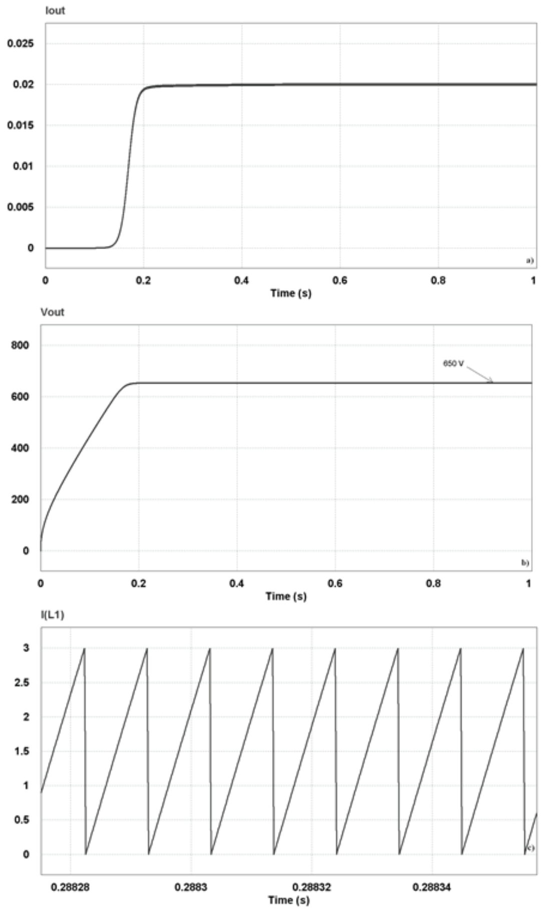

Fig.9. PSIM simulated results

Finally in the experiment of Fig. 12c, the converter is loaded with a 43 kΩ ± 10% resistor, and supplied with a 9 V (ch.1) source. The output gain is 100, and the output voltage (ch.3) achieves 900 V. As expected, this case exhibits the lower switching frequency.

Table 3 shows the converter performance supplied from a 12 V car-battery, with different resistive output loads. Finally, Fig. 10 depicts the converter performance at different input voltages. Realize that for output voltages under 800 V, as lower is the input voltage, better is the efficiency because switching losses decrease.

Table 3. Experimental measurements

Load	Vin(V)	Iin(A)	Vout(V)	Iout(mA)	η(%)
10 kΩ	12.09	0.475	199	20.019	69.37
20 kΩ	12.05	0.878	398	20.003	75.25
30 kΩ	12.02	1.297	597	20.011	76.76
40 kΩ	12.04	1.733	795	20.031	76.90
43 kΩ	12.03	1.884	849	20.008	75.13
43 kΩ	11.99	2.298	920	21.672	72.36

Conclusions

A high voltage-gain single stage-boost converter has been simulated and realized with an extremely voltage gain about 100.As expected, hysteretic control is the key issue to minimize switching losses as well as achieving the extreme duty-ratios required to those voltage gains. The main problem of increasing the voltage gain and the converter power rating comes mainly from the lack of high-performance commercially available devices. The system is protected about the patent P20131281.

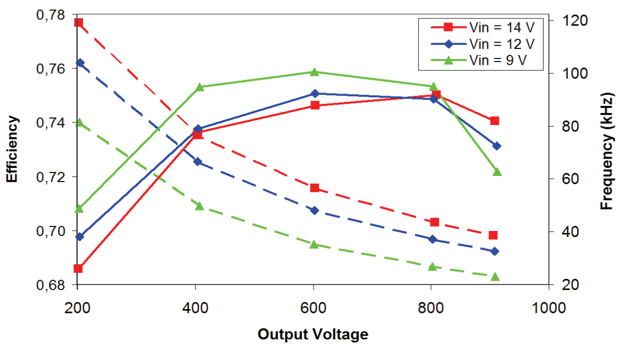

Fig.10. Performance graph at different input voltages

For instance, the mosfet, although probably are very good to operate at high-voltages, has too much resistance to be a good choice to operate at low input voltage, especially if the output power is increased. Similar things happen with bipolar diodes.

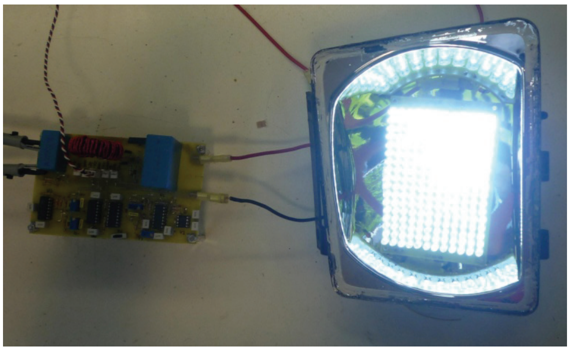

Fig.11. LED-based spot-light and Boost converter

In this sense, recently emerging silicon carbide devices, especially mosfets, and diodes (shottky and JBS), could help to improve the converter efficiency, and even, to increase its power rating and voltage gain.

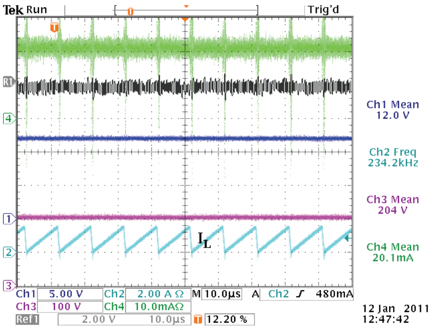

Fig.12a. Performance at low gain

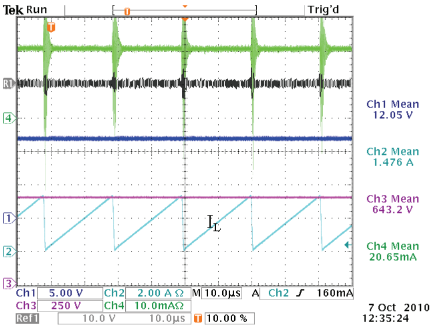

Fig.12b. LED spot-light experiment

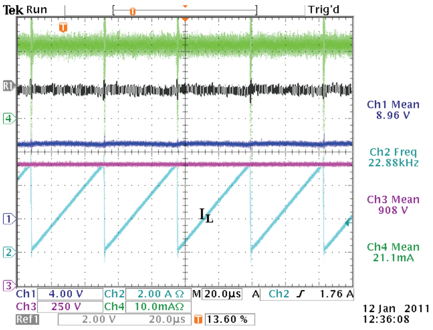

Fig.12c. Extreme voltage-gain

***Acknowledgements**: This work has been partially sponsored by the Spanish Ministry of Research and Science, under grants: DPI2009-14713-C03-02, and Consolider RUE CSD2009-00046.*

REFERENCES

[1] Hu Y., Jovanovic M.Y., "A Novel LED Drive with Adaptative Drive Voltage", Delta Power Electronics Laboratory, Research triangle park, NC 27709

[2] Nishikawa M., Ishizuka Y., Matsuo H., Shigematsu K., An LED Drive Circuit with constant-Output-Current Control and Constant Luminance Control", INTELEC Telecomunications Energy Conference, pp 1-6, December 4, 2006

[3] Ronat O., Green P., Ragona S., "Accurate Current Control to Drive High Power LED strings", IEEE Appec 2006, pp 376-380, March, 19, 2006

[4] Qu X., Wong S.C., Tse C.K., "Non cascading Structure for Electronic Ballast design for Multiple LED Lamps with independent Brightness control" IEEE transactions on Power Electronics, VOL 25, NO. 2, February 2010

[5] Wu C.Y., Wu T.F., Tsai J.R., "Multistring LED backlighting driving system for LCD panels with Color sequential Dysplay and area control" IEEE transactions on Ind. Electron., VOL 55, NO. 10, October 2008

[6] Grant D.A., Darroman Y., Suter J., "Synthesis od Tapped-inductor Switched.mode converters" IEEE transactions on Power Electron., VOL 22, NO. 5, September 2007

[7] Hu Q., Zane R., "Led Driver Circuit with Series-Input-Connected Converter Cells Operating in Continuous Conduction Mode" IEEE transactions on Power Electron., VOL 3, NO. 25, March 2010

[8] Zhao Q., Lee F.C., "High efficiency, high step-up DC-DC converters" IEEE transactions on Power Electron., VOL 18, NO. 1, January 2003

[9] Wai R.J., Lin C.Y., Duan R.Y., Chang Y.R., "High efficiency DC-DC converters with high voltage gain and reduced switch stress" IEEE Trans. INd. Electron., VOL 54, NO. 1, pp 354-364, February 2007

[10] Changchien S.K., Liang T.J., Chen J.F., Yang L.S., "Step-up DC-DC converter by coupled inductor voltage lift tecnique" IET Power. Electron., VOL 3, pp 369-378, 2010

[11] Axelrod B., Berkovich Y., Ioinovici A., "Switched capacitor/inductor for getting transformerless hybrid DC-DC PWM converters" IET Trans. Syst. I, Reg.Paper, VOL 55, NO. 2, pp 687-696, March 2008

[12] He Y., Luo F.L., Analisys of Luo converters with voltage lift technique" Proc. IEEE Elec. Power App., pp. 1239, Sept. 2005

[13] Jovanovic M.M., "A technique for reducing rectifier reverse recovery related losses in high power boost converters" IEEE Trans. On Power Electron. VOL 13, NO. 5, September 1998

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