Power driver topologies and control schemes for LEDs

Heinz van der Broeck[1], Georg Sauerländer[2], Matthias Wendt[2]
[1] Cologne University of Applied Sciences, Faculty IME, Betzdorfer Str. 2, 50679 Köln, Germany
[2] Philips Research Europe Laboratories, Weisshausstrasse 2, 52066 Aachen, Germany

Abstract - This paper deals with power electronic drivers for LED strings. Due to the enormous progress recently achieved in the technology of light emitting diodes (LEDs) it can be expected that LEDs lighting will replace incandescent and halogen bulbs in general illumination in the near future. A LED light source typically consists of a series connection of single LED cells. It shows a similar behaviour like a zener diode. For efficiency reasons LED strings can not be supplied via series resistors but need switched mode power drivers with current control. Different standard DC-DC converter topologies are discussed which can be adapted to feed a constant current into a LED load. For future LED driver developments it has to be considered that LEDs can also efficiently be supplied by pulsating currents. This simplifies the converter and control design and reduces the number of components. Hence, different converter topologies are studied which are able to stabilise the average value of a pulsating output current. This also includes topologies with galvanic isolation. Resonant operating LED drivers seem to be specially suited for this task. Hence, a series resonant galvanic isolating LED driver is studied in detail. Under certain conditions this converter does not need a current sensor to stabilise the average current in the LED load. Finally, the features of different pulsating current waves are investigated concerning their peak, RMS and high frequency content.

1. INTRODUCTION

Solid state lighting is of growing interest for residential, automotive and medical applications. This is mainly caused by the enormous improvements achieved in the technology of light emitting diodes (LEDs) in the last years [1]. Today, LEDs are available for various colours and they are also suitable for white illumination. New single power LEDs are designed for an input power of 1W, 3W or 5W and their energy efficiency has already surpassed that of incandescent and halogen bulbs. Recent industrial research results [2] claim already LED energy efficiencies above 100 Lumen / Watt. Another important advantage of LEDs is their long life time of up to 100.000 hours. LEDs are already regularly applied in new traffic lights and in rear lights of cars.

In the past LEDs have mainly been used to indicate the state of devices (e.g. on/off, fault, …etc). Since these devices operate with low voltage and current values (e.g. 1.5V, 10mA) they are simply supplied from a constant DC voltage via series resistors (see fig.1).

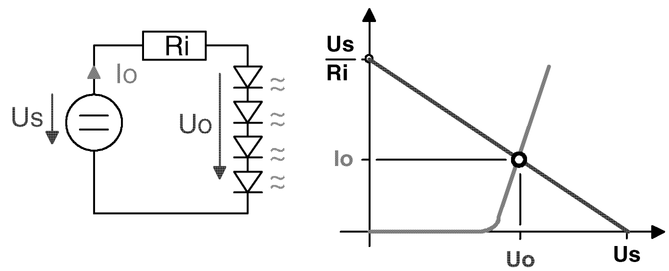


Figure 1 LED current set by a series resistor

New power LEDs are, however, designed for nominal currents of 350mA and more. The forward voltage drop of these devices is about 3V and large manufacturing tolerances have to be taken into account. In new LED lighting applications many single power LEDs are connected in series and form a LED string as shown in figure 2. Thus, the total power consumption and the additional losses in a series resistor can no longer be neglected. Moreover, the LED current has to be controlled. Hence, new LED lighting equipment needs power electronics to avoid additional losses and to control the LED current. This paper thus investigates and compares different possibilities to supply LED strings and to control their output current by power electronic drivers.

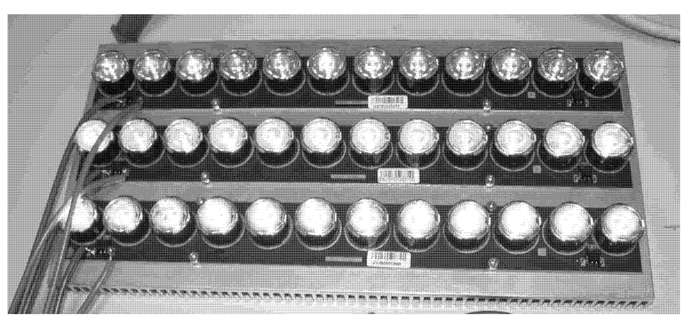


Figure 2 LED strings from Lumileds

1-4244-0714-1/07/$20.00 ©2007 IEEE.

2. USE OF STANDARD DC TO DC POWER SUPPLIES

In order to avoid high losses in a series resistor, power LEDs have to be supplied by switched mode power supplies. These converters are used for all kind of applications today. However, DC to DC converters are typically designed to stabilise their output voltages, while LEDs require a stabilised output current. By adding a shunt resistor Rs in series to the LEDs, the current can be measured via the voltage at the shunt Rs, so that standard circuit topologies and control schemes can be applied [3]. In contrary to standard DC to DC converters the measured voltage has to be very small to avoid additional losses. Thus, both the controller IC and the shunt resistor have to be connected to common ground. This leads to the basic buck, boost and buck-boost converter topologies as shown in figure 3a,b,c.

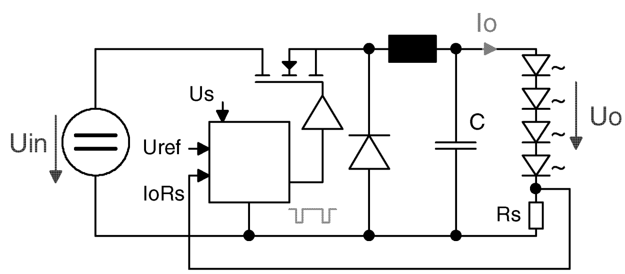


Figure 3a Buck converter

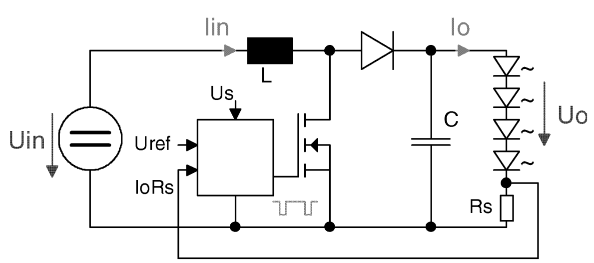


Figure 3b Boost converter

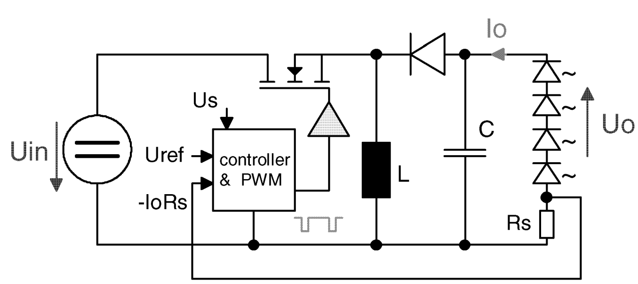


Figure 3c Buck boost converter

Only in case of the boost converter the switching transistor is also connected to ground. For the buck and the buck-boost converter, the gate source terminal of an N-channel FET is floating and requires a special level shifter driver. Alternatively, a P-channel FET may be used, but this is only suitable for lower supply voltages.

In the same way LED strings may also be fed by galvanic isolated converters such as the forward, flyback or push pull converter. In this case the comparison between reference voltage Uref and shunt voltage $Rs \cdot Io$ as well as the error amplifier has to be realised on the secondary side while the PWM controller is needed on the primary side. Both control parts are connected via an opto coupler. From the principle circuit schematic, illustrated in figure 4, it becomes obvious that this control method requires a larger effort. Another problem of this solution is that most low cost error amplifiers contain an internal 2.5V reference voltage (e.g. TL431), which does not meet low voltage drops at the LED shunt resistor.

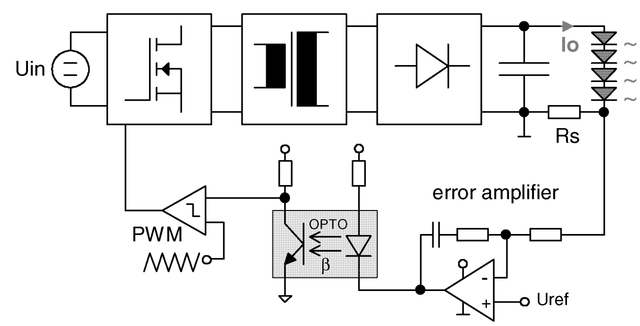


Figure 4 Galvanic isolating LED driver

3. Optimal LED driver design

The LED drivers, reviewed up to now, are all derived from standard DC/DC converters. Future LED lighting sources will however be produced in very high quantities so that the design of their drivers can be optimised considering special features of LEDs and certain application requirements:

- LED drivers are probably subject to low cost requirements. Thus, the component count has to be reduced.

- LEDs show an extreme fast light to current response. Therefore, it is possible to feed LEDs by pulsating currents if the resulting, usually small, colour shift can be neglected [4].

- Another important feature of LEDs is their long life time. Thus, electronic LED drivers have to be designed for long life times as well. Electrolytic capacitors typically used at the output of a SMPS may reduce the lifetime of the driver, especially if located in high ambient temperatures.

All three requirements may be fulfilled by omitting the smoothing capacitor at the output. In this case the LED current becomes pulsating. Depending on the driver topology and the control scheme an almost square, triangular or sinusoidal current pulsation occurs in the LED load. The most important solutions are discussed in the following chapters.

4. None-isolated LED driver topologies

If the output filter capacitor is removed in the basic DC to DC converters shown in figure 3 the current in the LEDs is no longer a pure DC but contains a pulsating part. In case of the boost or the buck-boost converter the LED load is fed by an almost square wave for a sufficiently high filter choke. This concept is illustrated in figure 5 and it is proposed in several application notes of semiconductor manufacturers [5].

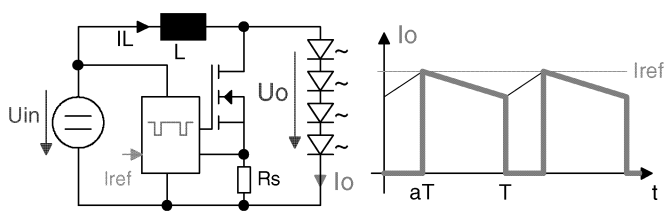


Figure 5 LED feed by a boost converter

For the basic buck converter the resulting LED current is composed of a DC and a triangular wave, which makes an accurate current control more difficult [6]. If, however, the buck converter is operating in the critical conduction mode, a simple peak & zero current control scheme can be applied. This concept is shown in fig. 6.
Apart from the topology the result of a measurement is presented, where three LEDs are fed from a 20V DC. The peak reference current is set to $\hat{I}_{REF} = 700 \cdot mA$, which yields an average LED current of $\overline{I_0} = 350 \cdot mA$.

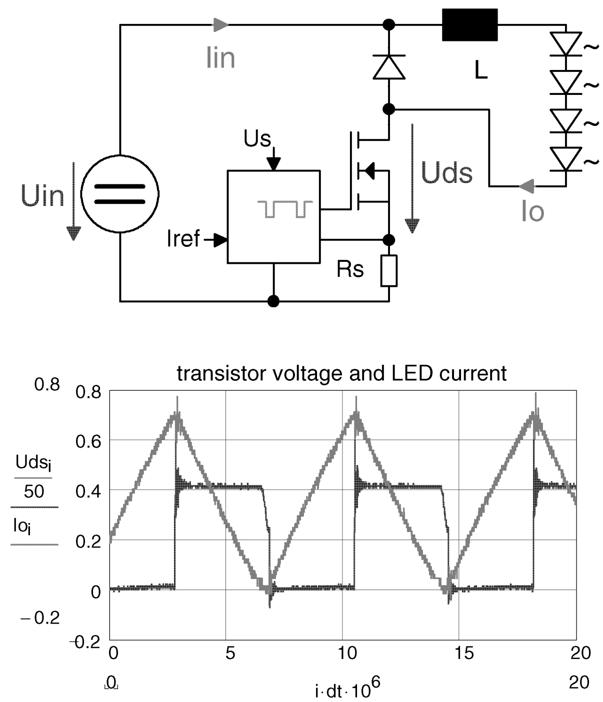


Figure 6 Buck converter with peak current control and critical conduction mode: measurement: 5µs/div

5. Galvanic isolated LED driver

5.1 Flyback converter

For power levels below 100W flyback converter topologies are favorite solutions for all kind of applications and thus also for LED lighting [7]. Flyback converters are typically operating in the discontinuous mode. This operation mode is suitable for employing a current mode controller such as the UC384x IC family. The storage capacitor on the secondary side of the flyback converter can be removed so that the LED is directly supplied from the secondary winding.
Figure 7 shows the topology with control part as well as the characteristic voltage and current waves. Diode D2 prevents a negative voltage across the LEDs.

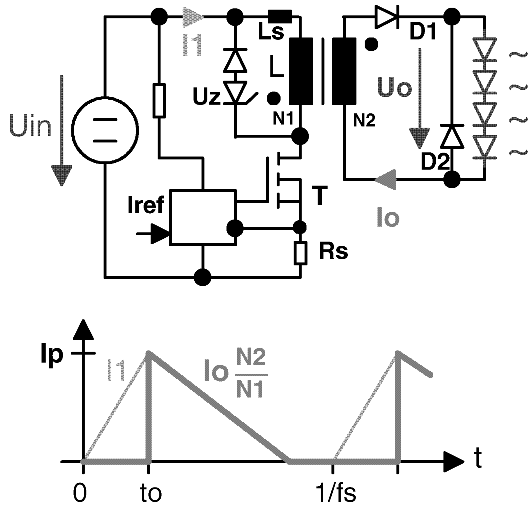


Figure 7 LED supplied by a flyback converter

The current mode controller operates with a constant switching frequency fs and it keeps in the ON-state until the primary current I1(t) exceeds an adjustable reference current value:

I1max = Ip = Iref = Uref / Rs

As a result a constant power is supplied to the secondary side and thus into the LED string :

$$Po = \frac{1}{2} \cdot I_p^2 \cdot L \cdot fs = Uo \cdot \overline{Io}$$

Using this circuit the LED string is fed by a saw-tooth wave current Io(t) as depicted in figure 7.

Within a certain operating range the average current of the LED is not influenced by the input voltage Uin but changes with the load voltage Uo (e.g. with the number of LEDs connected in series) $\overline{Io} = Po / Uo$

This topology requires a minimum number of components, it provides galvanic isolation and allows the combination of an arbitrary number of LEDs to any DC supply voltage by adapting the winding turn ratio of the transformer. However, there are also a few disadvantages:

- The average output current is depending on the number of LEDs connected in series.

-The leakage inductance of the transformer Ls requires a snubber circuit and causes additional losses (e.g. in Uz)

- The current waveform in the LED string may cause EMI problems

5.2 Resonant LED drivers

In the last years, resonant converter topologies have been subject of various power electronics research activities aiming at high power density, low switching losses and low EMI contribution. Therefore, these topologies are also of interest for LED applications. Up to now only little papers have been published concerning resonant operation of LED drivers (e.g. [8]). Thus, the investigation of a resonant LED driver concept will be carried out in more detail.

Figure 8 shows a resonant operating driver which is very suitable for LED supply since it acts as a voltage to current converter without employing a current sensor.

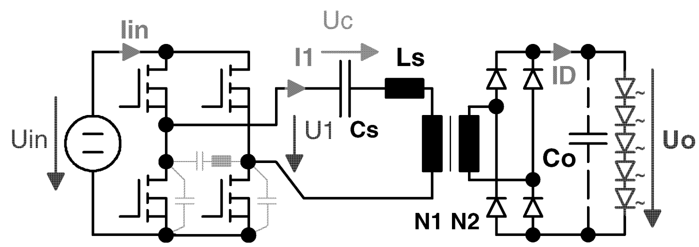


Figure 8 Resonant converter for LEDs

The driver consists of a transistor H-bridge, a controller (not shown), a transformer, a series capacitor Cs, a diode bridge and an optional smoothing output capacitor Co. At the output, a series connection of LEDs can be supplied. The transformer serves for galvanic isolation and adapts the voltage level, e.g. from 300V to 50V. A resonant topology is formed by the stray inductance of the transformer Ls and the series capacitor Cs. Thus, the parasitic leakage inductance of the transformer is part of the driver. The resonant circuit can be characterized by the resonant frequency:

$$fres = \frac{1}{2 \cdot \pi \cdot \sqrt{Ls \cdot Cs}} = \frac{1}{Tres}$$

and by the resonant impedance: $Zres = \sqrt{\frac{Ls}{Cs}}$

The basic operation of the resonant driver can be explained by the simulated voltage and current waves presented in figure 9. The H- bridge alternately generates positive and negative voltage pulses $U1 = \pm Uin$ with a fixed pulse width τ.

Between these voltage pulses the H-bridge generates a free wheel state (U1=0) for an adjustable time (see voltage U1(t) in fig. 8 and 9). Hence, the driver circuit can be controlled by varying the switching frequency fs. If the fixed pulse width τ of the voltage U1(t) is equal to half the resonant period:

$$\tau = \frac{Tres}{2} = \frac{1}{2 \cdot fres} = \pi \cdot \sqrt{Ls \cdot Cs}$$

and if the load voltage ranges between

$$\frac{1}{3} \cdot Uin < Uo \cdot \frac{N1}{N2} < Uin$$

the driver shows the following performance:

For each half period the current in the driver and in the load is composed of two successive sinusoidal current pulses and it is always zero during switching. See current I1(t) in figure 8 and 9.

The peak value of the first current pulse, which is drawn from the input voltage source, can be calculated to

$$\hat{I}_1 = \hat{I}in = \frac{Uo}{Z_{RES}}$$

The peak value of the second current pulse, flowing in the free wheel operation mode (U1=0) can be described by the equation: $\hat{I}_2 = \frac{Uin - Uo}{Z_{RES}}$

There is no further current flowing in the free wheel mode if the output voltage is higher than $Uo > \frac{Uin}{3} \cdot \frac{N2}{N1}$

For the second half period the same current flows in opposite direction.

The LED load is supplied by the rectified wave of all current pulses ID(t) as shown in figure 9.

The average load current can thus be determined by the previous equations and by considering the set switching frequency fs and the resonant frequency fres. It yields: $\bar{I}_D = \frac{Uin}{Z_{RES}} \cdot \frac{2}{\pi} \cdot \frac{N1}{N2} \cdot \frac{f_S}{f_{RES}}$

It is obvious that the average output current is independent of the load voltage Uo in the specified voltage range. The average value of the load current will also not be influenced if a smoothing capacitor Co is inserted. This means the resonant converter acts as a constant current source without using any current sensor. It is thus best suited for LED applications.

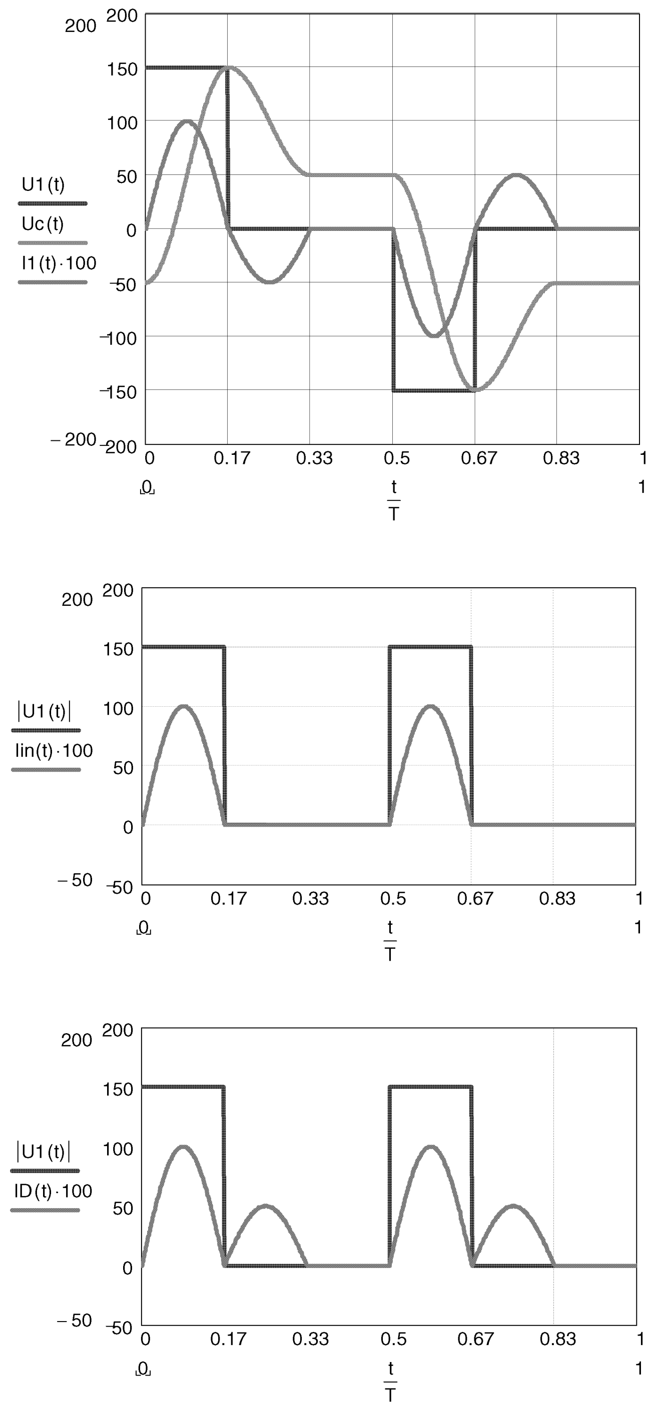


Figure 9 Characteristic voltage and current wave of the resonant LED driver (fig. 8) simulated for $fs = f_{res}/3$ and $Uo = \frac{2}{3} \cdot \frac{N2}{N1} \cdot Uin$ with N1 = N2

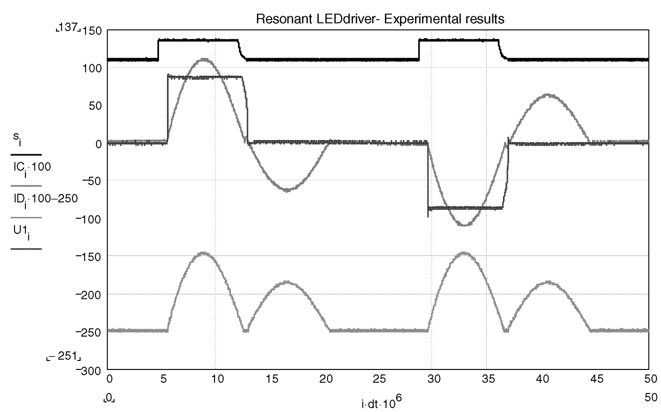
The average current in the LEDs is proportional to the DC input voltage of the driver and to the operating frequency while the resonant impedance Zres serves as an additional parameter.

It is thus possible to provide a dimming function by decreasing the switching frequency: $\bar{I}_D \sim fs$. The frequency must not be higher than half the resonant frequency. This leads to a frequency operation range of $0 < fs \leq \frac{1}{2} \cdot fres$.

The circuit is also able to stabilise the average output current for a varying input voltage Uin. In this case the product of Uin and fs has to be kept constant.

In the special case of fs = fres/2 = constant the average output current remains also constant for lower load voltages down to zero.

Since a fixed pulse time τ is used the transistor bridge can be extended by a ZVS snubber as depicted in fig. 8.



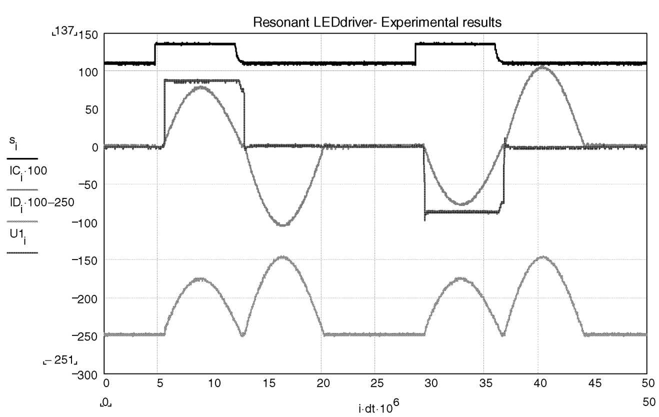


Figure 10 Measurement of the voltage and currents in a prototype of the resonant LED driver (fig. 8)
Uin = 80V $fs = \frac{3}{10} \cdot fres \approx 20kHz$
voltage: 50V/div current: 0.5A/div time: 5µs/div
top: 18 LEDs bottom: 12 LEDs supplied

The performance of the resonant LED driver has been investigated experimentally. Based on the topology shown in figure 8 different numbers of LEDs connected in series have been supplied.

The results are presented in figure 10. All measurements are taken for an input voltage of Uin = 80V. Apart from the inner control signal s(t), the H-bridge voltage U1(t), the primary current I1(t) and the rectified secondary current ID(t) are shown.

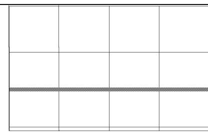
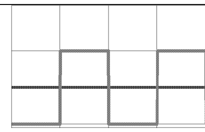
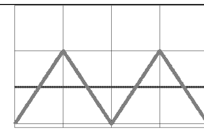
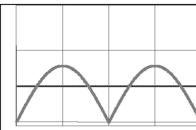
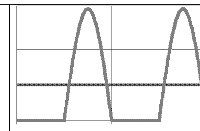
Since no smoothing capacitor is used (Co = 0) the LEDs are fed by a sinusoidal half-wave current ID(t) .

Both measurements are taken for the same conditions, but with a different number of LEDs connected in series. In the upper case 18 LEDs are supplied and in the lower case only 12. This changes the peak values of the current pulses but it has no influence on the average current, which is $\bar{I}_D \approx 320mA$ in both cases.

As can be also seen in measurement the peak value of the first current pulse is proportional to the load voltage drop.

6. Analysis of Pulsating Current Wave Forms

As has been shown in the previous chapters LEDs may also be supplied by pulsating currents. Compared to a pure DC this increases the peak and RMS value of the LED current. Moreover, a pulsating LED current contains high frequency components. Apart from the basic repetition frequency *fp* higher harmonics occur $f = \nu \cdot fp$ where $\nu = 2,3,4,5,...$ denotes the order of the harmonics. These harmonics may cause EMI problems if the LEDs are separated from the power driver. It is thus of general interest to quantify the increase of the peak and RMS values and the generation of harmonics. This has been carried out for 4 characteristic current waves shown in the first row of table 1. In all cases analytical equations have been found which are normalised to the average output current Io. From the comparison of these equations it becomes obvious that step free current waves should be preferred since their harmonics decrease by the square of the frequency.

Table 1 Analysis of pulsating currents in LEDs						
Average DC	$\frac{\bar{I}}{Io}$	1	1	1	1	1
Peak	$\frac{\hat{I}}{Io}$	1	2	2	$\frac{\pi}{2}$	π
RMS	$\frac{\tilde{I}}{Io}$	1	$\sqrt{2}$	$\frac{2}{\sqrt{3}}$	$\frac{\pi}{2}\cdot\frac{1}{\sqrt{2}}$	$\frac{\pi}{2}$
RMS of the first harmonic	$\frac{{}^{1}\tilde{I}}{Io}$	0	$\frac{4}{\pi}\cdot\frac{1}{\sqrt{2}}$	$\frac{8}{\pi^2}\cdot\frac{1}{\sqrt{2}}$	$\frac{2}{3}\cdot\frac{1}{\sqrt{2}}$	$\frac{\pi}{2}\cdot\frac{1}{\sqrt{2}}$
RMS of higher harmonics	$\frac{{}^{\nu}\tilde{I}}{Io}$	0	$\frac{4}{\pi}\cdot\frac{1}{\nu}\cdot\frac{1}{\sqrt{2}}$	$\frac{8}{\pi^2}\cdot\frac{1}{\nu^2}\cdot\frac{1}{\sqrt{2}}$	$\frac{2}{4\cdot\nu^2-1}\cdot\frac{1}{\sqrt{2}}$	$\frac{2}{\nu^2-1}\cdot\frac{1}{\sqrt{2}}$
Order of harmonics	$\nu \geq 2$		odd only	odd only	odd and even	even only

7. Conclusion

It has been shown that LEDs or LED strings can not only be supplied by pure DC currents but also by pulsating currents. This can be applied to almost all converter topologies like the buck, boost or flyback converter. This method reduces the component count in LED drivers and eliminates the use of an output filter electrolytic capacitor which may limit the life time of the driver. Resonant operating drivers are also suitable for LED supplies without smoothing capacitor.

They even allow to keep the average output current constant without using a current sensor or feed back control circuit. Resonant drivers are also favourable concerning EMI contribution and switching losses.

8. References

[1] Steigerwald, D.A.; Bhat, J.C.; Collins, D.; Fletcher, R.M.; Holcomb, M.O.;Ludowise, M.J.; Martin, P.S.; Rudaz, Illumination with solid state lighting technology IEEE Journal of Selected Topics in Quantum Electronics Vol. 8, Issue 2, March-April 2002 Pages: 310 - 320

[2] "Focus on LED lighting - Japanese pioneer breaks through LED barrier " Global Watch Magazine February 2006

[3] Ned Mohan; Tore M. Underland; William P. Robbins Power electronics: Converters, applications, and design New York : John Wiley & Sons , 1989

[4] B. Ackermann, V. Schulz, C. Martiny, A. Hilgers, X. Zhu „Control of LEDs" IAS Conference, 2006. 41th IAS Annual Meeting. Conf. Rec. of the 2006 IEEE Oct. 2006

[5] Design of a non-isolated flyback LED Driver Circuit Appl. Note 3639 Dallas Semiconductor Maxim Sept. 2005

[6] Odile Ronat, Peter Green, Scott Ragona Accurate current control to drive high power LED strings IEEE Publication 0-7803-9547-6/06/2006

[7] Rico-Secades, M.; Calleja, A.J.; Cardesin, J.; Ribas, J.; Corominas, E.L.; Alonso, J.M.; Garcia, J.; "Driver for high efficiency LED based on flyback stage with current mode control for emergency lighting system" IEEE IAS Conference, 2004. 39th IAS Annual Meeting. Conf. Rec. Vol. 3, 3-7 Oct. 2004 Pages: 1655 - 1659

[8] Baddela, S.M.; Zinger, D.S.; "Parallel connected LEDs operated at high to improve current sharing" IAS Conference, 2004. 39th IAS Annual Meeting. Conf. Rec. of the 2004 IEEE Vol. 3, 3-7 Oct. 2004 Pages: 1677 - 1681