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LED CONVERTER WITH LIMITED DUTYCYCLE

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Abstract: *Light emitting diodes (LEDs) can be used for many lightning applications in offices, in homes, and in streets. A special converter with limited duty cycle for driving LEDs is treated. The basic analysis is done resulting in dimensioning equations of the converter. The basic analyses have to be done with idealized components (that means no parasitic resistors, no switching losses) and for the continuous mode in steady (stationary) state. A mathematical model based on state-space description is derived. Some experimental results are shown. The converter is useful for street, home, and automotive lightning applications.*

Keywords: *LED converter; limited duty cycle; peak-current-control; high-power LED*

INTRODUCTION

Light emitting diodes (LEDs) can be used for many lightning applications in offices, in homes, and in streets. There exists a rich literature about converter topologies and control. The [1] shows a classical boost converter used to drive a series connection of LEDs. In [2] a good overview about possible converter topologies is given. Buck, boost, buck-boost, flyback and a resonant converter are treated. Peak current control is used. The control concepts of peak and hysteresis control are discussed in [3]. The voltage controlled non-inverting buck-boost and the Sepic converter are explained in [4] and [5], respectively. A system analysis and a control description for a boost converter are given in [6]. A combined power factor corrector and LED driver based on a flyback converter is explained in [7]. An interesting concept based on a kind of three-level converter is shown in [8]. Deep insight views on power electronics are given in [9, 10].

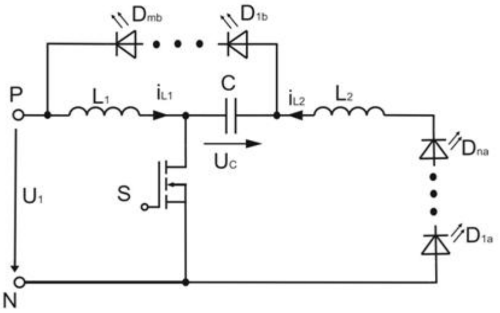

Figure 1 . Converter schematic

The here described converter was first published in the patent literature [12] and is shown in Figure 1. The converter consists of an active switch (S), two inductors (L_1, L_2), one capacitor (C), and two strings of LEDs. The upper one has m diodes (D_{1b} till D_{mb}) and can be replaced by only one diode, working as a freewheel path. The other string has n diodes connected in series (D_{1a} till D_{na}) which is in series to the second inductor and is the main light source. The current through this series connection can be easily controlled by a bang-bang controller. The special feature of the converter is that a duty cycle greater than 0.5 is necessary as will be shown in the following section.

BASIC ANALYSIS

The basic analyses have to be done with idealized components (that means no parasitic resistors, no switching losses) and for the continuous mode in steady (stationary) state. A good way to start is to consider the voltage across the inductors. The duty cycle d is the ratio of the on-time of the active switch related to the switching period.

Since for the stationary case the absolute values of the voltage-time-areas of the inductors have to be equal (the voltage across the inductor has to be zero in the average), we can easily draw the shapes according to Figures 2 and 3. (Here the capacitor is assumed to be so large that the voltage can be regarded constant during a pulse period). The shapes are drawn with a duty cycle of 70%. The forward voltage of an LED is symbolized by V_D.

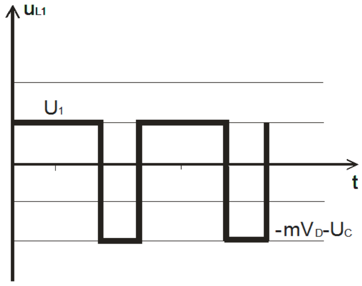

Figure 2. Voltage across inductor L1

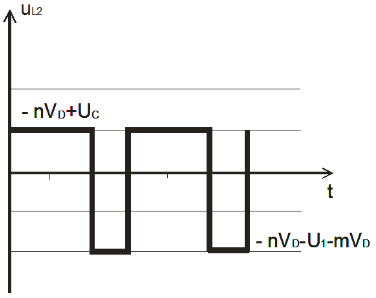

Figure 3. Voltage across inductor L_2

The equal voltage-time-areas of inductor L_1 are

$$U_1 \cdot d \cdot T = (U_C + mV_D) \cdot (1-d) \cdot T \qquad (1)$$

and therefore the capacitor mean voltage in steady-state is

$$U_C = \frac{U_1 \cdot d - mV_D \cdot (1-d)}{(1-d)} \qquad (2)$$

The equal voltage-time-areas of inductor L_2 are

$$(-nV_D + U_C) \cdot d \cdot T = (nV_D + U_1 + mV_D) \cdot (1-d) \cdot T \qquad (3)$$

and therefore the mean voltage across the series connection D_{1a} till D_{na}(output voltage of the converter U_2) in steady-state is

$$U_2 = \frac{U_1 \cdot (1-2d) - mV_D \cdot (1-d)}{(d-1)} \qquad (4)$$

When only one free-wheeling diode is used instead of the series connection D_{1b} till D_{mb}, the idealized voltage transformation rate of the converter is

$$M = \frac{U_2}{U_1} = \frac{1-2d}{(d-1)} \qquad (5)$$

The duty cycle must be greater equal than 0.5 and smaller than one. If the duty cycle is smaller than a half, the output voltage would change its sign. That is impossible due to the used semiconductors. The converter is a step-up-down converter, useful for step-up rates of up to about four. Figure 4 shows the voltage transformation rate of the converter.

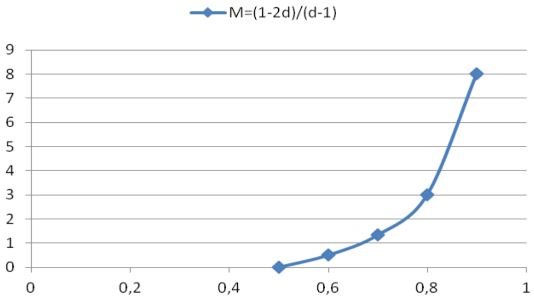

***Figure 4** . Voltage transformation rate in dependence of the dutycycle*

In steady-state the mean-value of the current through a capacitor must be zero. Therefore, the positive and the negative current-time-areas must be equal. With the mean values of the inductor currents, one can write

$$d \cdot \bar{I}_{L2} = (1-d) \cdot \bar{I}_{L1} \qquad (6)$$

The mean value of the current through inductor L_2 is equal to the mean value of the current through the LED string (D_{1a} till D_{na})

$$\bar{I}_{LED} = \bar{I}_{L2} \qquad (7)$$

The current through the inductors has a pronounced current ripple (shown in Figure 5) depending on the voltage and the inductor value.

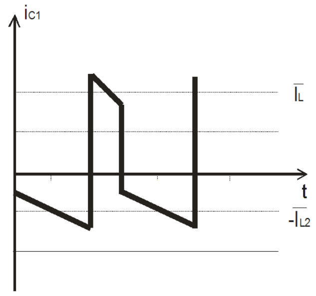

***Figure 5** .Current through the capacitor*

The current through the first inductor depends on the load (LED) current and the duty cycle. The mean value of i_{L1}i s always larger than the current through the load.

DIMENSIONING OF THE COMPONENTS

Capacitor

The change of the capacitor voltage during one period can be described by

$$\Delta u_{C1} = \frac{1}{C} \cdot \int_0^{dT} i_{C1} dt \qquad (8)$$

With $M = \frac{U_2}{U_1} = \frac{1-2d}{(d-1)}$ *the duty cycle can be calculated to*

$$d = \frac{U_2 + U_1}{U_2 + 2U_1} \qquad (9)$$

The capacitor can now be dimensioned by

$$C = \frac{1}{\Delta u_C} \cdot \frac{U_1 + U_2}{2U_1 + U_2} \cdot I_{LED} \cdot \frac{1}{f} \qquad (10)$$

The higher the switching frequency f the lower is the capacitor value.

Inductors

With the chosen current ripple ΔI_{L1} and ΔI_{L2} of the inductors, the inductor values can be calculated out of the basic equation of the inductor to

$$L_1 = \frac{U_1}{\Delta I_{L1}} \cdot \frac{U_1 + U_2}{2U_1 + U_2} \cdot \frac{1}{f} \qquad (11)$$

$$L_2 = \frac{U_1}{\Delta I_{L1}} \cdot \frac{U_1 + U_2}{2U_1 + U_2} \cdot \frac{1}{f} \qquad (12)$$

Voltage stress of the semiconductors

The highest voltage stress of the active switch is during the free-wheeling stage and is

$$U_S = U_C + U_1 + mV_D \qquad (13)$$

which can be converted to

$$U_S = 2U_1 + U_2 + mV_D \qquad (14)$$

Using a free-wheeling diode and ideal devices one gets

$$U_S = 2U_1 + U_2 \qquad (15)$$

The maximum stress across the free-wheeling diode or the LED string D_{1b} till D_{mb} occurs during the on-time of the active switch and its absolute value is the same as in (15).

Current stress of the semiconductors

When the active switch is on, the sum of the inductor currents is flowing through it. Using the mean values one can calculate the mean value of the current through the active switch according to

$$\bar{I}_S = (\bar{I}_1 + \bar{I}_2) \cdot d \qquad (16)$$

The maximum value of the current through the active switch is

$$I_{\max,S} = \bar{I}_1 + \bar{I}_2 + \frac{\Delta I_{L1} + \Delta I_{L2}}{2} \qquad (17)$$

Using the mean values (assuming that the inductor current ripple is low) one can approximately calculate the rms value to

$$I_{rms,S} = (\bar{I}_1 + \bar{I}_2) \cdot \sqrt{d} \qquad (18)$$

When the active switch is off, the sum of the inductor currents is flowing to the freewheeling diode or the LED string D_{1b} till D_{mb}. Using *the mean values one can calculate the mean value of the current through the passive switch or the diode string acting as the free-wheeling path according to*

$$\bar{I}_S = (\bar{I}_1 + \bar{I}_2)\cdot(1-d) \tag{19}$$

The maximum value of the current through the passive switch is equal to the active switch and can be again calculated by (17).

Using the mean values (assuming that the inductor current ripple is low) one can approximately calculate the rms value to

$$I_{rms,S} = (\bar{I}_1 + \bar{I}_2)\cdot\sqrt{(1-d)} \tag{20}$$

STATE SPACE MODEL

The state variables are the inductor currents i_{L1}, i_{L2}, and the capacitor voltage u_C. The input variables are the input voltage u_1 and the fixed forward voltage of the LED strings mV_D and nV_D. The LEDs are modeled as a fixed forward voltage V_D and an additional voltage drop depending on the differential resistor of the LED diodes R_D). The other parasitic resistances are the on-resistance of the active switch R_S, the series resistance of the converter coils R_{L1}, R_{L2}, and the series resistor of the capacitor R_C.

In continuous inductor current mode there are two states. In state one the active switch is turned on and the passive switch or the LED string D_{1b} till D_{mb} is turned off. Figure 6 shows switching state one.

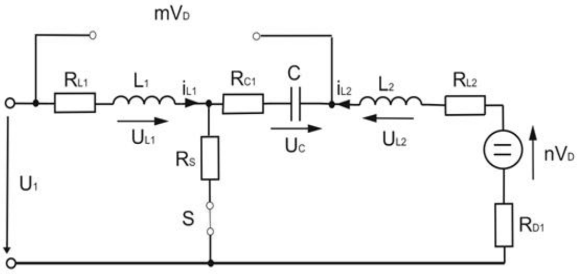

***Figure 6 .** Equivalent circuit for state 1*

The state space equations are now

$$\frac{d_{iL1}}{dt} = \frac{-i_{L1}\cdot(R_{L1}+R_S) - i_{L2}\cdot R_S + u_1}{L_1} \tag{21}$$

$$\frac{d_{iL2}}{dt} = \frac{-i_{L1}\cdot R_S - i_{L2}\cdot(R_{L2}+R_{D1}+R_S+R_{C1}) - nV_D + u_C}{L_2} \tag{22}$$

$$\frac{du_C}{dt} = \frac{-i_{L2}}{C} \tag{23}$$

leading to the state-space matrix description according to

$$\frac{d}{dt}\begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} = \begin{bmatrix} -\frac{(R_{L1}+R_S)}{L_1} & -\frac{R_S}{L_1} & 0 \\ -\frac{R_S}{L_2} & -\frac{(R_{L2}+R_{D1}+R_S+R_{C1})}{L_2} & \frac{1}{L_2} \\ 0 & -\frac{1}{C} & 0 \end{bmatrix} \cdot \begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} + \tag{24}$$

$$+\begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}\cdot(U_1) + \begin{bmatrix} 0 \\ -\frac{1}{L_2} \\ 0 \end{bmatrix}\cdot(nV_D) + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}\cdot(mV_D).$$

In state two the active switch is turned off and the passive switch or the LED string D_{1b} till D_{mb} is turned on. Figure 7 shows this switching state two.

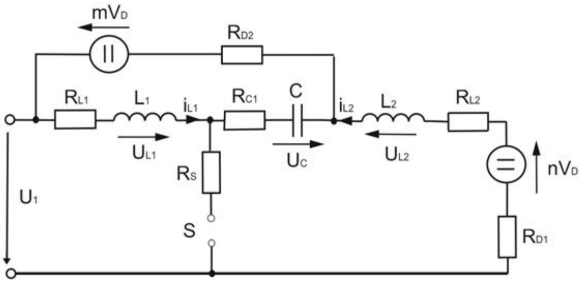

***Figure 7**. Equivalent circuit for state 2*

The describing equations are

$$\frac{d_{iL1}}{dt} = \frac{-i_{L1}\cdot(R_{L1}+R_{D2}+R_{C1}) - i_{L2}\cdot R_{D2} - mV_D - u_{C1}}{L_1} \tag{25}$$

$$\frac{d_{iL2}}{dt} = \frac{-i_{L1}\cdot R_{D2} - i_{L2}\cdot(R_{L2}+R_{D1}+R_{D2}) - mV_D - nV_D - u_1}{L_2} \tag{26}$$

$$\frac{du_C}{dt} = \frac{i_{L1}}{C_1} \tag{27}$$

leading to the state-space matrix description according to

$$\frac{d}{dt}\begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} = \begin{bmatrix} -\frac{(R_{L1}+R_{D2}+R_{C1})}{L_1} & -\frac{R_{D2}}{L_1} & -\frac{1}{L_1} \\ -\frac{R_{D2}}{L_2} & -\frac{(R_{L2}+R_{D1}+R_{D2})}{L_2} & 0 \\ \frac{1}{C} & 0 & 0 \end{bmatrix} \cdot \begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} + \tag{28}$$

$$+\begin{bmatrix} 0 \\ -\frac{1}{L_2} \\ 0 \end{bmatrix}\cdot(U_1) + \begin{bmatrix} 0 \\ -\frac{1}{L_2} \\ 0 \end{bmatrix}\cdot(nV_D) + \begin{bmatrix} -\frac{1}{L_1} \\ -\frac{1}{L_2} \\ 0 \end{bmatrix}\cdot(mV_D).$$

Under the condition that the system time constants are large compared to the switching period, we can combine these two sets of equations (24, 28) to the state-space model

$$\frac{d}{dt}\begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} =$$

$$\begin{bmatrix} -\frac{[d\cdot R_S + (1-d)\cdot(R_{D2}+R_{C1}) + R_{L1})]}{L_1} & -\frac{[d\cdot R_S + (1-d)\cdot R_{D2}]}{L_1} & \frac{(d-1)}{L_1} \\ -\frac{[d\cdot R_S + (1-d)\cdot R_{D2}]}{L_2} & -\frac{[d\cdot(R_S+R_{C1}) + (1-d)\cdot R_{D2} + R_{L2} + R_{D1})]}{L_2} & \frac{d}{L_2} \\ \frac{(1-d)}{C} & -\frac{d}{C} & 0 \end{bmatrix} \cdot \begin{pmatrix} i_{L1} \\ i_{L2} \\ u_C \end{pmatrix} +$$

$$+\begin{bmatrix} \frac{d}{L_1} \\ \frac{(d-1)}{L_2} \\ 0 \end{bmatrix}\cdot(U_1) + \begin{bmatrix} 0 \\ -\frac{1}{L_2} \\ 0 \end{bmatrix}\cdot(nV_D) + \begin{bmatrix} \frac{(d-1)}{L_1} \\ \frac{(d-1)}{L_2} \\ 0 \end{bmatrix}\cdot(mV_D). \tag{29}$$

By this equation the dynamic behavior of the converter is described correctly in the average. The superimposed ripple (which appears very pronounced in the coils) is of no importance for qualifying the dynamic behavior. This model is also appropriate as large-signal model, because no limitations with respect to the signal values have been made.

EXPERIMENTAL MODEL OF THE CONVERTER

In Figure 8 a picture of the experimental converter is shown. The values of the devices are included. Five LUXEON Altilon LED were used. The typical of the forward voltage of one chip is about 6.4 V.

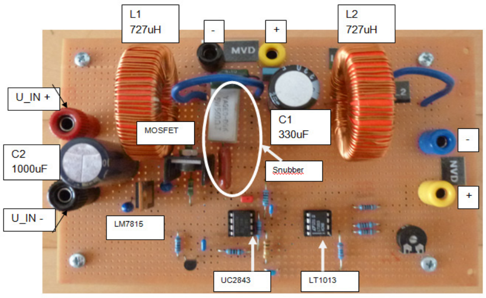

***Figure 8** . Experimental Converter*

In Figure 9 the voltage across the capacitor, the current through the load, and the drain voltage of the active switch are shown. Due to an RCD snubber the spikes at switch-off are minimized.

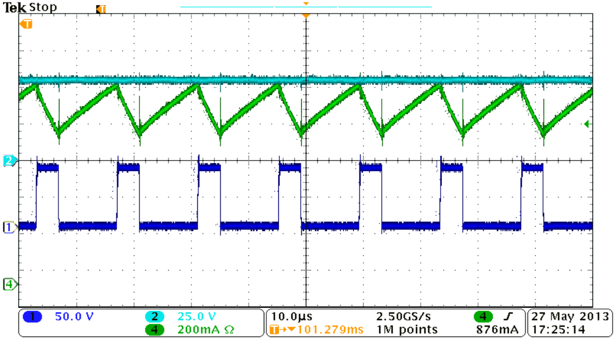

***Figure 9** . Voltage across the capacitor (turquois), the current through the load (green), and the drain voltage of the active switch (blue)*

Figure 10 shows the converter with a series connection of five LED in action.

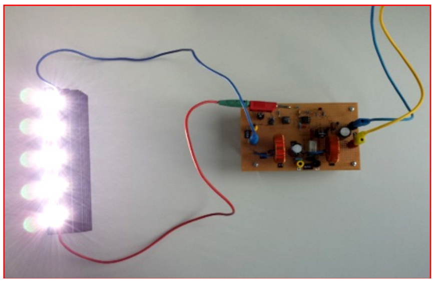

***Figure 10** . Converter in action*

CONCLUSION

A novel LED converter with limited duty cycle was analyzed. The advantage of this converter is its continuous output current and a duty cycle which is always greater than 0.5. If loss-less snubbers are used, more than the half switching period is available to discharge the snubber capacitor. The input and the output have the same reference point (ground) so avoiding common mode disturbance. The current can be controlled with a standard current control IC. The freewheeling path can also be used to drive further LED in series. The converter is easily dimmable.

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