Third order converters with current output for driving LEDs

FELIX A. HIMMELSTOSS
Faculty of Electronic Engineering and Entrepreneurship
University of Applied Sciences Technikum Wien
Hoechstaedtplatz 6, 1200 Wien
AUSTRIA

Abstract: - Light emitting diodes LEDs are highly efficient in changing electrical energy into light. The applications are lightning, but also medical treatments, and disinfection. After a short discussion of the simplest converter which is based on the Buck converter several third order current converters, which are suitable to drive an LED load, are treated. The Buck converter with input filter, the output current Boost converter, and the output current Cuk converter are shortly treated, but for the other topologies simple control techniques are given. These converters are the current output converter based on the Zeta converter, two converters with a quadratic term of the duty cycle in the voltage transformation ratio, the quadratic step-down converter with current output and the D square divided by one minus d current output converter, which is a step-up-down converter, and two converters which function only for a limited duty cycle, the (2d-1)/d step-down and the (2d-1)/(1-d) step-up-down output current converters. The dynamics of example converters is shown with the help of LTSpice simulations.

Key-Words: - DC/DC converters, current output, Buck-, Boost-, Zeta-, quadratic-, limited duty cycle converter, control, simulation, modelling

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1 Introduction

Beside the main purpose of efficient illumination, LEDs are used also for disinfection (UVC-LEDs cf. [1]), and for medical treatments (IR-LEDs cf. [2]).

Most driver circuits which use switched mode converters have a capacitor in parallel to the output to smooth the current through the load. The characteristics of LEDs are temperature-dependent and change therefore. If the converter controls only the output voltage, the current changes and the light stream decreases, or what is even dangerous the current increases and the light stream and the losses and the temperature of the devices increase, too. This can lead to an overload of the LEDs and to their destruction. In this paper we show converters which have a current output; the output voltage depends therefore on the load and changes by a constant output current. Now it is easy to avoid an overload of the LEDs. The basic converters are extensively treated in the text books [3-5]. A comprehensive review over LED drivers can be found in [6]. Many topologies for DC to DC converters can be found e.g. in [7, 8].

The easiest concept is a first order converter derived from the Buck converter. Fig. 1.a shows a Buck converter without output capacitor. Input and output have the same reference point. A disadvantage is the floating switch. In many LED applications, however, it will not be necessary to have the output referred to the same ground (e.g. in battery applications). Therefore, one can change the position of the active and the passive switches (Fig.1.b). Now the active switch is no more floating and can be easily controlled.

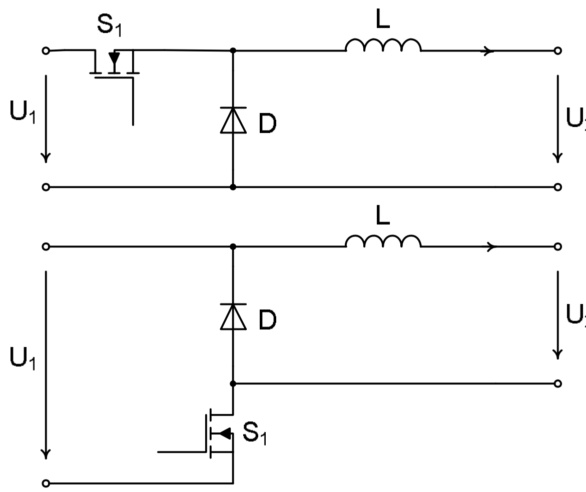


Fig. 1. Buck derived current converter: (a) with floating, (b) with grounded active switch

To control the current a two-level controller with hysteresis is a very effective solution. In [1] the frequency of the controller (and therefore the switching frequency of the converter) is calculated according to

$$f = \frac{(V_{LED} + R_{LED} I_2)\cdot[U_1 - (V_{LED} + R_{LED} I_2)]}{\Delta I \cdot L \cdot U_1} \quad (1)$$

where V_{LED} and R_{LED} describe the load with simple characteristics, U_1 is the input voltage, I_2 the output current in the mean, ΔI the value of the hysteresis, and L the value of the coil. Change of the parameters (temperature dependence of the load, tolerance of the inductor) influence directly the frequency and lead to a very robust control. The basic frequency can be chosen for the working point by the hysteresis ΔI, which directly fixes the current ripple of the load current.

2 Third order converters with current output

In this section an overview about some converters with current output which can be used to drive an LED-load are presented. They are treated with a diode as second semiconductor device. To reduce losses, the diode can be exchanged by a second active switch, which needs, however, an additional driver and a precise control. When the necessary control electronics (and maybe also the active switches) are implemented in an integrated circuit, this leads to a very effective system.

In [9] third order current converters for LED-loads which have also a continuous input current are described. These converters are treated here only shortly. These converters are very useful because the input current is continuous and therefore only a small capacitor is necessary to avoid the influence of the parasitic inductance at the input.

2.1 Output current Buck with input filter

To avoid a pulsating input current, an additional LC input filter can be connected in front of the converter according Fig. 1 as shown in Fig. 2 for the version according to Fig. 1.a.

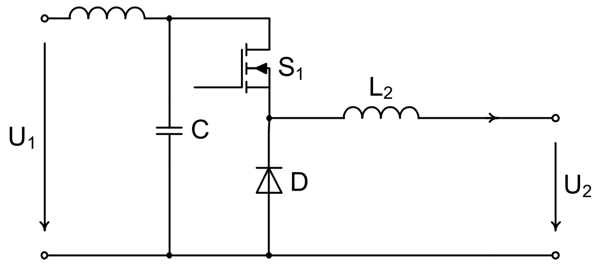


Fig. 2. Buck converter with input filter

When the input voltage is applied, an inrush current occurs to charge the capacitor C. The ringing occurring can be omitted by connecting a diode in series to L_1. The capacitor is in this case charged up to nearly the double of the input voltage. This additional diode increases the loss of the converter and should be applied only when an additional reverse polarity protection is desired. The control can be done again with a two-level controller. More details about the inrush current, the start-up, a state-space model and a calculation of the transfer function between the output current and the duty cycle can be found in [9].

2.2 Output current Boost converter

The Boost converter has a continuous input current and by connecting an additional inductor L2 at the output, the current at the output is also continuous (Fig. 3).

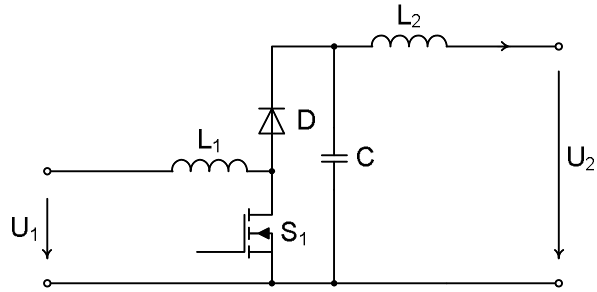


Fig. 3. Output current Boost converter

In [9] the converter is described more in detail (inrush current, soft-start, nonlinear and linear state space model, transfer function of the output current in dependence on the duty cycle). Furthermore, a nonlinear control concept is shown. With this converter loads which need a higher voltage than the input voltage can be supplied.

2.3 Output current Cuk converter

From its basics the Cuk converter has the possibility of a continuous input and output current, one only has to remove the output capacitor to obtain a current converter. With this topology the load can require a higher or a lower voltage than the input voltage available. The inrush current charges the capacitor to a voltage of nearly double the input voltage, when a voltage source is applied to the input connectors, the ringing (compared to the Buck with input filter), however, is omitted by the diode which disables a current in the back direction. In [9] the inrush, the soft-start, a control law, a large and a small signal model and the transfer function are given.

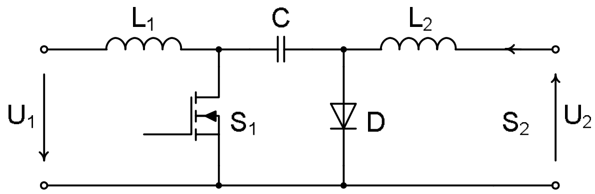


Fig. 4. Output current Cuk converter

2.4 Output current Zeta converter

The advantage of this converter shown in Fig. 5 is the fact that the position of the transistor prevents an inrush current. So the start-up can be done by slowly increasing the duty cycle until it reaches the necessary value. In Fig. 6 the start-up and steps of the duty cycle are shown which result in some pronounced ringing. Fig. 7 depicts the current through the coils, the input and the output voltages and the pwm-signal which controls the active switch. The parameters of the converter can be taken from the appendix Fig. A.1.

a.

b.

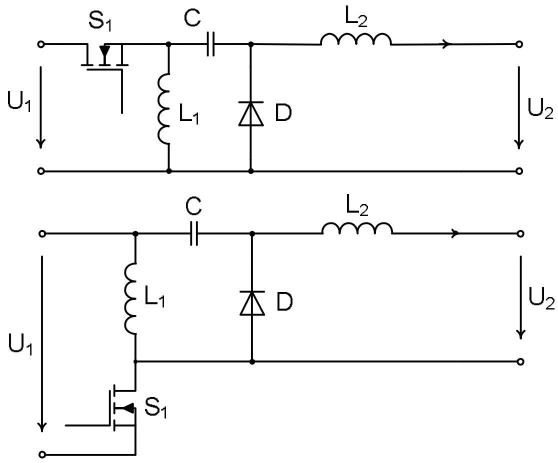


Fig. 5 Output current Zeta converter: (a) with floating switch, (b) with low-side switch

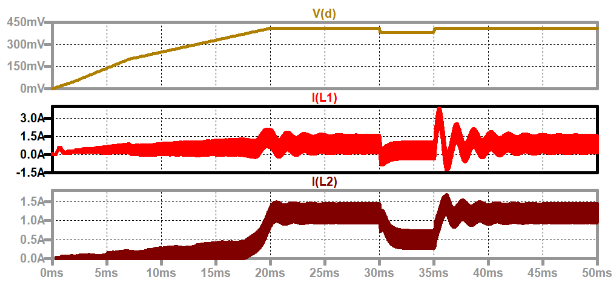


Fig. 6. Output current Zeta converter, start-up and duty-cycle steps: duty cycle (brown), currents through L_1 (red), L_2 (black)

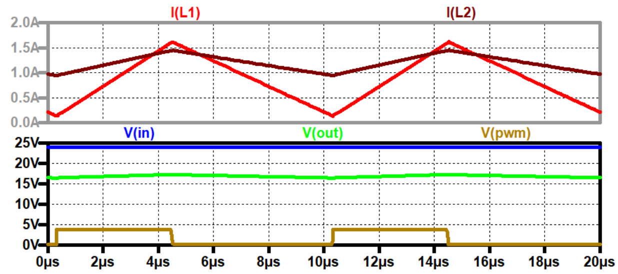


Fig. 7. Output current Zeta converter, steady state: currents through L_1 (red), L_2 (black); input voltage (blue), output voltage (green), control signal (brown)

In the stationary case the output voltage and the voltage across the capacitor are equal. The voltage across the output of the converter can be calculated with the help of the voltage-time balance across L_1

$$U_1 \cdot d = U_C \cdot (1-d) \tag{2}$$

to

$$U_2 = U_C = \frac{d}{1-d} \cdot U_1 \,. \tag{3}$$

The charge balance of the capacitor can be given as

$$\bar{I}_{L2} \cdot d = \bar{I}_{L1} \cdot (1-d) \,. \tag{4}$$

2.4.1 Nonlinear control

The derivation of the control law for the current through L_1 starts from the desired value of the current through the load I_{L2ref} to obtain the reference value for the current through L_1

$$I_{L1,ref} = I_{L2,ref} \cdot \frac{d}{1-d} = I_{L2,ref} \cdot \frac{U_2}{U_1} = I_{L2,ref} \cdot \frac{U_C}{U_1} \;. \tag{5}$$

With a two-level controller the current through the coil L_1 can now be controlled and the current over-shots are limited. Instead of the output voltage, which has a ripple, the smoother voltage across the capacitor is used. The simulation program is shown in the appendix Fig. A.1. The current through the coil L_1 is measured by the current controlled voltage source H1. The two-level controller is realized with the comparator U_2. The control law which produces the desired value for the two-level controller is calculated by the arbitrary voltage source B1. In a practical realization this calculation would be done by a micro-controller. Fig. 8 shows the results. The current through L_1 reacts immediately after steps in the desired output current and also to a step in the input voltage.

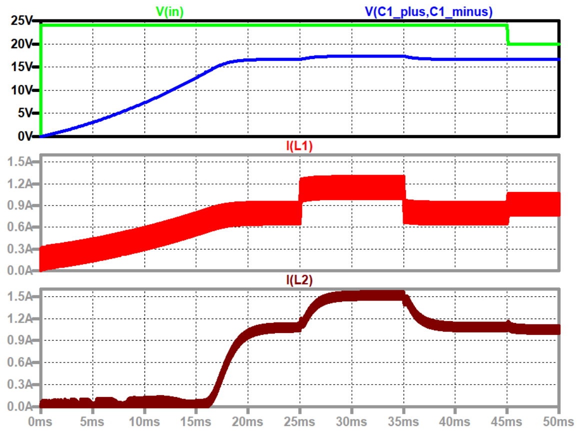


Fig. 8. Output current Zeta converter: input voltage (green), voltage across the capacitor (blue); current through L_1 (red); current through L_2 (load current, black)

Time constant of the system is T=1.8 ms and the gain is one. The system can therefore be described by the PT1 according to

$$\frac{I_{L2}}{I_{L2ref}} = \frac{1}{s \cdot 0.0018 + 1} \quad . \tag{6}$$

2.5 Quadratic step-down converter with current output

When a high gap between the input voltage and the lower load voltage has to be bridged, a series connection of two Buck converters can be used. The first one produces an intermediate voltage and has an output capacitor, and the second one is a current Buck converter according to Fig. 1. The complete converter has therefore two inductors and one capacitor as all converters in this chapter. The output voltage of this converter is equal to the square of the duty cycle (when both switches are controlled with the same duty cycle) multiplied by the input voltage. The converter can be easily controlled by a two-level controller, which leads to a very robust system.

Another possibility to achieve a high step-down ratio of the square of the duty cycle is based on [10]. The converter shown in Fig. 9.a has only one low-side switch. It should be mentioned that the diode D_1 can be exchanged by a second low-side switch which is controlled with the same signal as S_1. If a connection between input and output is desired, the position of diode and transistor has to be exchanged as shown in Fig. 9.b. The duty cycle must start with small pulses which are slowly increased to charge the capacitor and so avoid an inrush current.

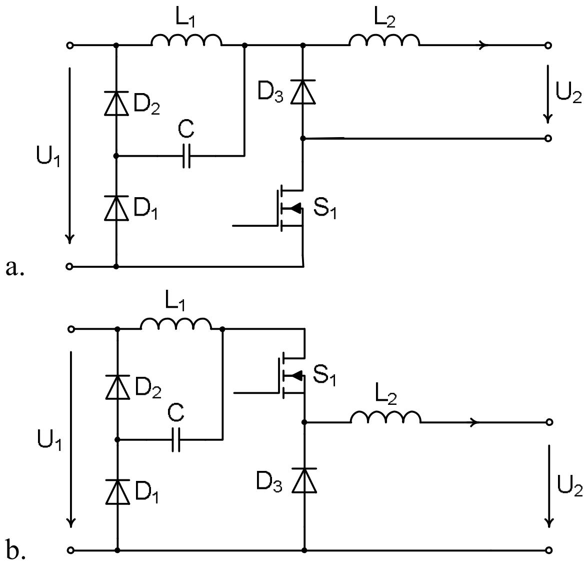


Fig. 9. Quadratic step-down converter with current output: (a) with low-side switch, (b) with high-side switch

The voltage-time balances across L_1 and L_2 can be given by

L_1: $$(U_1 - U_C) \cdot d = U_C \cdot (1-d) \tag{7}$$

L_2: $$(U_C - U_2) \cdot d = U_2 \cdot (1-d) \tag{8}$$

which leads to

$$U_C = d \cdot U_1 \text{ and } U_2 = d^2 \cdot U_1 \quad . \tag{9}$$

The charge balance of the capacitor can be written according to

$$\left| \bar{I}_{L1} - \bar{I}_{L2} \right| \cdot d = \bar{I}_{L1} \cdot (1-d) \, . \tag{10}$$

This leads to the current through L_1 in dependence on the duty cycle and the output current to

$$\bar{I}_{L1} = d \cdot \bar{I}_{L2} \quad . \tag{11}$$

The input current of the converter is pulsating and has the mean value

$$\bar{I}_{IN} = d^2 \cdot \bar{I}_{L2} \quad . \tag{12}$$

To avoid the pulsating input current, an LC filter as in Fig. 2 could be attached. A detailed description of the feedforward control of the d-square converter with output capacitor can be found in [11].

2.6 $d^2/(1-d)$ current output converter

The $d^2/(1-d)$ converter is again based on [10] and is depicted in Fig. 10. For the steady state one gets for the voltage-time balance across L_1

$$U_C \cdot d = U_1 \cdot (1-d) \tag{13}$$

and for the voltage-time balance across L_2

$$(-U_2 + U_C) d = U_2 (1-d) \, . \tag{14}$$

This leads to

$$U_2 = U_C d = \frac{d^2}{1-d} U_1 \quad . \tag{15}$$

The charge balance of the capacitor can be written according to

$$\bar{I}_{L2} \cdot d = \bar{I}_{L1} \cdot (1-d) . \qquad (16)$$

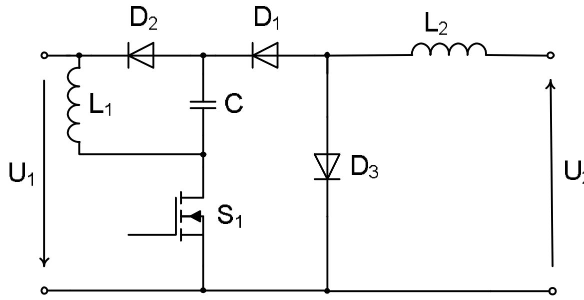


Fig. 10. d²/(1-d) current output converter

2.6.1 Feedforward control

Including the model of the load into (15)

$$U_2 = V_{LED} + R_{LED} \cdot I_{LED} = \frac{d^2}{1-d} U_1 \qquad (17)$$

leads to a quadratic equation of the duty cycle

$$d^2 + \left(\frac{V_{LED} + R_{LED} \cdot I_{LED}}{U_1} \right) d - \frac{V_{LED} + R_{LED} \cdot I_{LED}}{U_1} = 0 \qquad (18)$$

which results with the abbreviation

$$k = \frac{V_{LED} + R_{LED} \cdot I_{LED}}{2U_1} \qquad (19)$$

In (20)

$$d = -k + \sqrt{k^2 + 2k} = -k + \sqrt{k^2 \left(1 + \frac{2}{k} \right)} = k \left(-1 + \sqrt{1 + \frac{2}{k}} \right) .$$

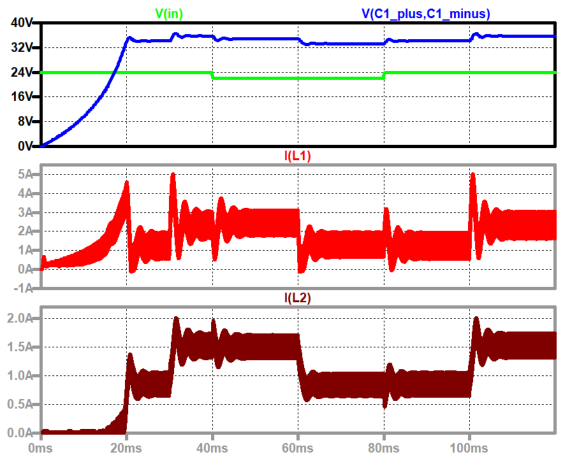


Fig. 11. d²/(1-d) current output converter, up to down: capacitor voltage (blue), input voltage (green); current through L_1 (red); current through L_2 (black)

The used simulation circuit is shown in the appendix Fig. A.2. The comparator U1 transfers the calculated duty cycle with the help of a saw-teeth generator into a pwm signal. The duty cycle is calculated with (20) by the arbitrary voltage source B2. At the beginning the capacitor has to be charged (with the signal soft-start) to avoid overcurrent, because the voltage at the capacitor starts with zero and therefore the demagnetization voltage is too low to avoid the overcurrent. The duty cycle starts with zero and increases slowly. Fig. 11 shows the voltage across the capacitor, the input voltage, and the currents through the inductors. Each change in the input voltage and in the desired load current leads to a ringing. The soft-start happens within the first 20 ms.

2.7 (2 d-1)/d current output converter

The circuit can be obtained from [12] when the second capacitor is deleted and is shown in Fig 12.

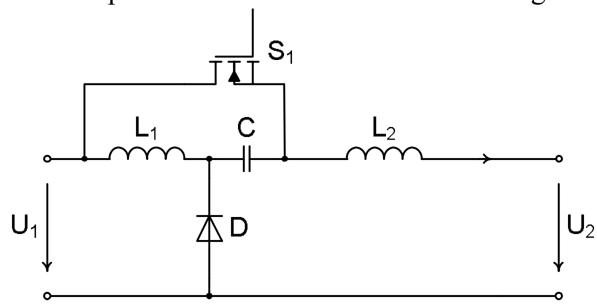


Fig. 12. (2 d-1)/d current output converter

Starting from the voltage-time balance across L_1 one gets

$$U_C \cdot d = U_1 \cdot (1-d) . \qquad (21)$$

The mean value of the voltage across the capacitor must be

$$U_C = U_1 - U_2 . \qquad (22)$$

The mean value of the output voltage can therefore be calculated according to

$$U_2 = \frac{2d-1}{d} U_1 . \qquad (23)$$

From this equation one can recognize that the duty cycle must be greater than 0.5 (the duty cycle is per definition between zero and one), otherwise the voltage would change its direction (this is not possible in this circuit, except when the diode is exchanged by a second MOSFET or current bidirectional switch). The circuit is a step-down converter.

For the capacitor the charge balance is given by

$$\bar{I}_{L1} \cdot d = \bar{I}_{L2} \cdot (1-d) . \qquad (24)$$

When the converter is controlled by a two-level controller for the current through L_1, the reference value for L_1 can be calculated from the desired output current (the current through L_2) and from the measured input voltage and the voltage across the capacitor according to

$$\bar{I}_{L1ref} \cdot d = \bar{I}_{L2ref} \cdot \left(\frac{1-d}{d}\right) = \bar{I}_{L2ref} \cdot \frac{U_C}{U_1} . \qquad (25)$$

Another possibility to control the converter is a feedforward controller. The control law for the duty cycle can be calculated from

$$V_{LED} + R_{LED} I_{LEDref} = \frac{2d-1}{d} U_1 \tag{26}$$

according to

$$d = \frac{U_1}{2 \cdot U_1 - V_{LED} - R_{LED} \cdot \bar{I}_{L2}} \,. \tag{27}$$

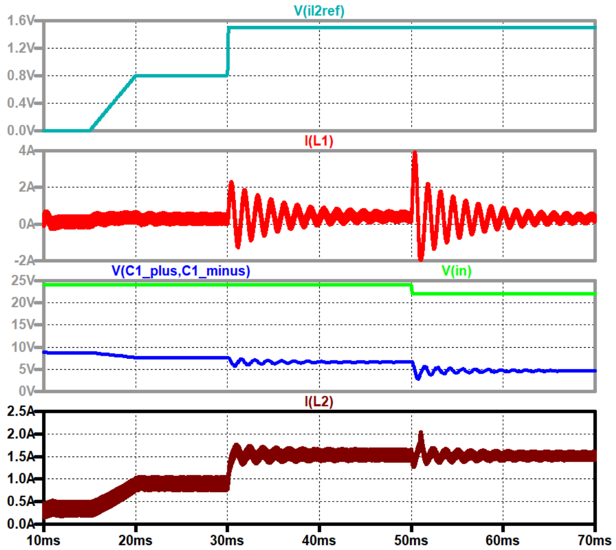


Fig. 13. (2 d-1)/d current output converter feedforward controlled, up to down: desired load current; current through L_1 (red), input voltage (green), voltage across the capacitor (blue); load current (black).

Fig. 13 shows a feedforward controlled converter. The inrush current effect is not shown. Steps in the reference value and of the input voltage lead to ringing especially of the current through L_1. To avoid reference-value-step-ringing, an integrator for the command input can be used.

A disadvantage of this step-down converter is the inrush current, when the input voltage is connected. The inrush current can be described by the integral-differential equation

$$U_1 = (L_1 + L_2) \cdot \frac{di}{dt} + \frac{1}{C} \int_0^t i \cdot dt + V_{LED} + R_{LED} \cdot i \,. \tag{28}$$

Laplace transformation leads to

$$\frac{U_1 - V_{LED}}{s} = (L_1 + L_2) \cdot sI(s) + \frac{1}{C}\frac{1}{s} I(s) + +R_{LED} \cdot I(s) \tag{29}$$

which results in

$$I(s) = \frac{(U_1 - V_{LED})/(L_1 + L_2)}{\left(s + \frac{R_{LED}}{2(L_1 + L_2)}\right)^2 + \frac{1}{C(L_1 + L_2)} - \frac{R_{LED}^2}{4(L_1 + L_2)^2}} \,. \tag{30}$$

The conjugate complex pole pair leads to a damped ringing with the damping factor δ, and the angular frequency ω of

$$\delta = \frac{R_{LED}}{2(L_1 + L_2)} \,, \quad \omega = \sqrt{\frac{1}{C(L_1 + L_2)} - \frac{R_{LED}^2}{4(L_1 + L_2)^2}} \,. \tag{31}$$

Using these abbreviations results and

$$K = \frac{U_1 - V_{LED}}{L_1 + L_2} \tag{32}$$

in (30) leads to

$$I(s) = \frac{K}{(s+\delta)^2 + \omega^2} = K\left[\frac{1}{\omega}\frac{\omega}{(s+\delta)^2 + \omega^2}\right] \tag{33}$$

and in the time domain according to

$$i = \frac{K}{\omega} \exp(-\delta t) \cdot \sin \omega t \,. \tag{34}$$

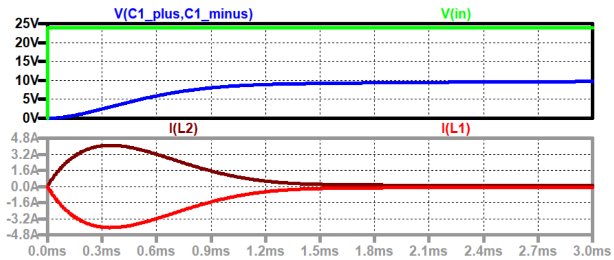
The ringing stops, when the current reaches zero again (the load has a diode characteristics)

$$i(T_{inrush}) = 0 = \sin \omega T_{inrush} \tag{35}$$

which result to

$$T_{inrush} = \frac{1}{\omega} \arcsin 0 = \frac{\pi}{\omega} = = \frac{\pi}{\sqrt{\frac{1}{C(L_1 + L_2)} - \frac{R_{LED}^2}{4(L_1 + L_2)^2}}} = \frac{\pi}{1962} = 1.6 \text{ ms} \,. \tag{36}$$

a.



b.

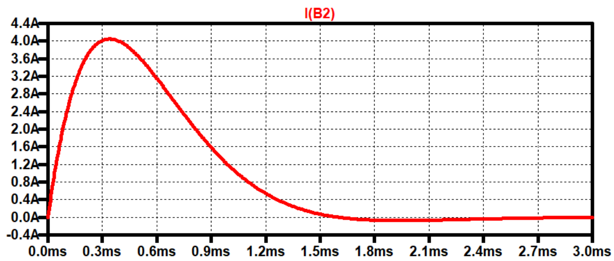


Fig. 14. (2 d-1)/d current output converter, up to down: (a) input voltage (green), voltage across the capacitor (blue); current through L_2 (black), current through L_1 (red); (b) inrush current (red) calculated according to (34)

The simulation shows a good correspondence with the calculated result (Fig. 14). Keep in mind that the parasitic resistances of the inductors and the diode were idealized, but included in the simulation. The results are sufficient. Fig. 14.a depicts the input voltage, the charging of the capacitor, and the current through the coils. Fig. 14.b shows the calculated current (calculated by LTSpice with an arbitrary current source).

2.8 (2 d-1)/(1-d) current output converter

The circuit can again be obtained from [12] when the second capacitor is deleted.

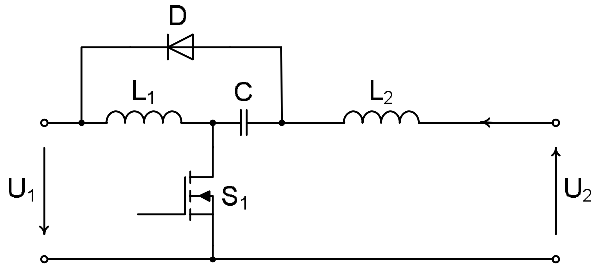


Fig. 15. (2d-1)/(1-d) current output converter

The voltage-time balances are

$$U_1 \cdot d = U_C \cdot (1-d) \quad (37)$$

$$\left(-V_{LED} - R_{LED} \cdot \bar{I}_{L2} + U_C\right) \cdot d = \left|-V_{LED} - R_{LED} \cdot \bar{I}_{L2} - U_1\right| \cdot (1+d) \quad (38)$$

and lead to a voltage transformation ratio for the output voltage (the voltage across the load) and to the capacitor voltage

$$\frac{U_2}{U_1} = \frac{2d-1}{1-d} \qquad \frac{U_C}{U_1} = \frac{d}{1-d}. \quad (39)$$

The converter is a step-up-down converter. In the stationary case the duty cycle must be between 0.5 and 1.

For the capacitor the charge balance is given by

$$\bar{I}_{L2} \cdot d = \bar{I}_{L1} \cdot (1-d). \quad (40)$$

With the desired value of I_{L2} one gets for the current through L_1

$$I_{L1} = I_{L2,ref} \cdot \frac{d}{1-d} = I_{L2,ref} \cdot \frac{U_C}{U_1}. \quad (41)$$

This signal is used as the reference value for a two-level controller.

Fig. 16 shows the load characteristics. The obtained parameters are V_{LED}=15.4 V, R_{LED}=1.6 Ω (linearized around 1.5 A).

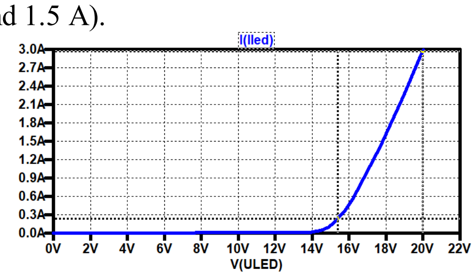


Fig. 16. Characteristics of the load

2.8.1 Feedforward control

From (39) one can calculate the control law for the feedforward controller resulting in

$$d = \frac{U_1 + V_{LED} + R_{LED} \cdot \bar{I}_{L2}}{2 \cdot U_1 + V_{LED} + R_{LED} \cdot \bar{I}_{L2}}. \quad (42)$$

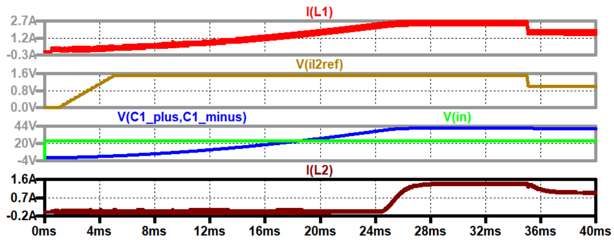


Fig. 17. (2d-1)/(1-d) current output converter, up to down: current through L_1 (red); reference value (brown); input voltage (green), voltage across the capacitor (blue), output current (black)

To avoid the inrush current one has to start the duty cycle from zero, because the capacitor has to be charged slowly. During the on-time the input voltage lies across the coil L_1, and during the off-time the voltage of the capacitor, which is zero at the beginning, lies across the coil, too. Therefore, the demagnetization time must be high at the beginning and the magnetization time short.

Fig. 17 shows the dynamics of the converter with soft-start and reference value step with a two-level converter. No ringing occurs.

3 Conclusion

LEDs are very efficient means to transform electrical energy into light (UV, visible light, and IR). The here treated converters can be controlled with standard linear controllers as shown in the textbooks for control engineering. An example to design linear controllers for a Buck converter with the help of the free simulation tool LTSpice is shown in [13]. Here in this paper feedforward control and a nonlinear control concept with a two-level converter are applied. When the error of a feedforward control is not tolerable, a small linear controller which only has to compensate the small difference between the desired current and the actual value has to be included. The converters 2.1, 2.5, 2.7 can be used for higher input voltages compared to the load voltage, the type 2.3 can be used for lower input voltages and the converters 2.3, 2.4, 2.6 are able to handle lower and higher input voltages compared to the necessary load voltage. The question concerning the inrush current and the soft-start of all types are discussed. It should be mentioned that the current through the capacitor is pulsating. For aerospace, traction and other reliable applications, ceramic or film capacitors should be used instead of electrolytic capacitors [14].

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Appendix

In the appendix two examples of the simulation circuits (LTSpice) are shown. The parameters for the other converters have about the same values.

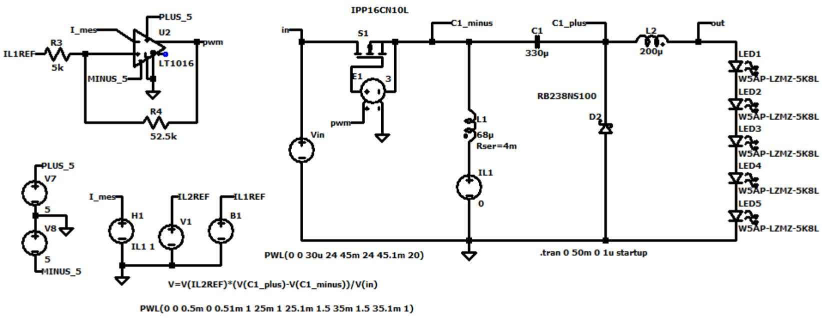

Fig. A.1. Output current Zeta converter: simulation circuit for the nonlinear control

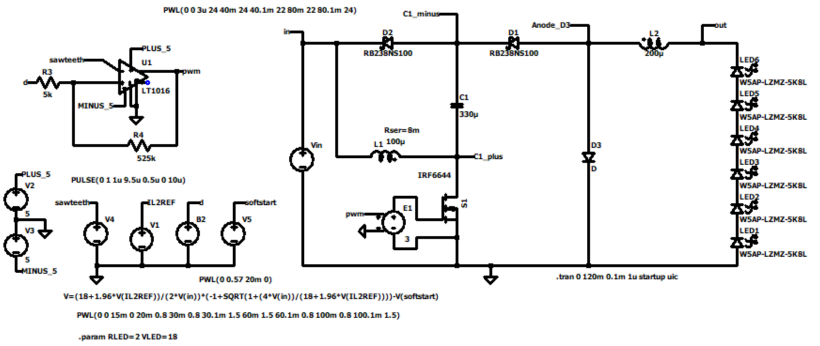

Fig. A.2. $d^2/(1-d)$ current output conrter: simulation circuit for the nonlinear control