Integrated DC/DC converter with digital controller

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1. Abstract

A DC/DC converter with integrated digital controller and switches is realized. This DC/DC converter only needs an external coil, diode and capacitor. The main advantages of this type of digital DC/DC converter are the fast response on load variation and the high efficiency over a wide power range. The DC/DC converter uses low resistance CMOS switches and operates in multi mode. The controller uses a small output voltage window as reference for control actions.

2. Introduction

With a DC/DC converter a variable battery supply voltage can be converted to an optimal supply voltage for an application [1]. Integration of the switches and controller on a single chip or embedded in an application chip is very attractive. In this paper the control principles of an integrated boost or step up converter are described, similar principles are valid for buck or step down converters. Fig. 1 shows the circuit of the boost converter.

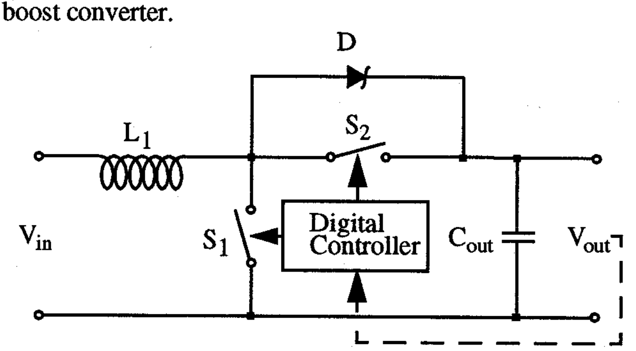

Figure 1: DC/DC boostconverter

The MOS-switches and the digital controller are integrated.

The DC/DC converter has 3 modes, a discontinuous mode for low power or standby operation, a continuous mode for efficient power conversion and a ramp-up mode for fast response on increase of load power.

Instead of a single reference voltage, the controller uses a small output voltage window with levels V_H and V_L as reference for switching between discontinuous, continuous and ramp-up mode. By switching between modes the controller stabilizes the output voltage between the levels V_H and V_L. This combination of use of an output voltage window and switching between the modes gives a fast response on variation of the output load. Compared to existing converters with a single level reference the stability of this converter is very tolerant to component values.

3. Conversion modes

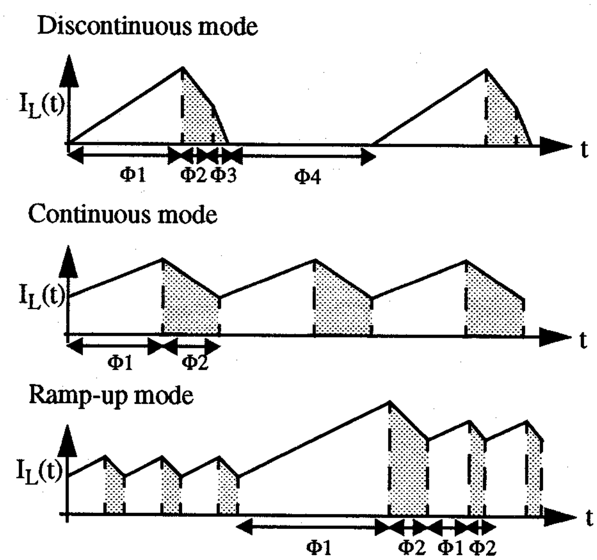

Figure 2: DC/DC conversion modes

Discontinuous mode is used for standby or low power. The output voltage is controlled by pulse frequency modulation. Continuous mode is used for normal power conversion. In this mode a DC-current with ripple flows through the coil. Ramp-up mode is used for a fast response on an increase of

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the output load. In this situation the average current through the coil is too low to keep the output voltage at the required level. An extra long phase 1 is included to give a fast increase of the average current through the coil.

4. Continuous mode model

The analog part of the DC/DC-converter can be modelled by the circuit shown in fig. 3. In this model ideal switches, diode, coil and capacitor are used. The total series resistance of the battery, coil and switches are modelled with series resistor R. The esr resistance of the output capacitor is separately modelled because the voltage drop is relevant for the output voltage ripple.

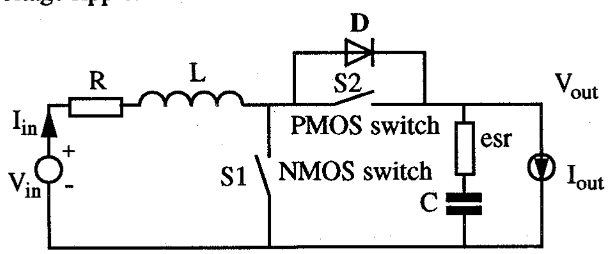

Figure 3: DC/DC converter circuit

The duty cycle D_p in continuous mode is defined as:

$$\text{Duty cycle:} \quad D_p = \frac{t_p}{t_n + t_p} \tag{1}$$

with t_n = the length of phase Φ1 (switch S1 or NMOS on) and t_p = the length of phase Φ2 (switch S2 or PMOS on).

In continuous mode the following average voltage and current relations are valid. The duty cycle D_p determines the ratio between input and output voltage by:

$$\text{Output voltage:} \quad V_{out} = \frac{V_{in}}{D_p} - \frac{R \cdot I_{out}}{D_p^{\;2}} \tag{2}$$

The input current, which equals the average coil current, depends on the output current by:

$$\text{Input current:} \quad I_{in} = \frac{I_{out}}{D_p} \tag{3}$$

This results in the equivalent model of the analog circuit shown in fig. 4.

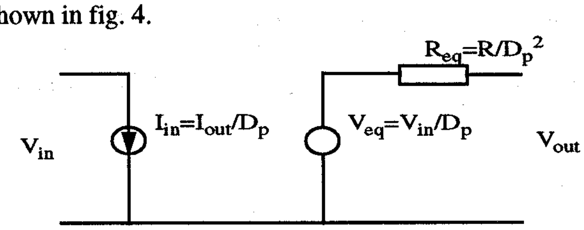

Figure 4: Equivalent circuit

In this model the required duty cycle D_p can be calculated as function of the output load.

$$\text{Duty cycle:} \quad D_p = \frac{V_{in} + \sqrt{V_{in}^2 - 4 \cdot V_{out} \cdot I_{out} \cdot R}}{2 \cdot V_{out}} \tag{4}$$

With this model the relation between the output voltage V_{out} and the output current I_{out} can be determined as a function of the duty cycle D_p. This is shown in fig. 5.

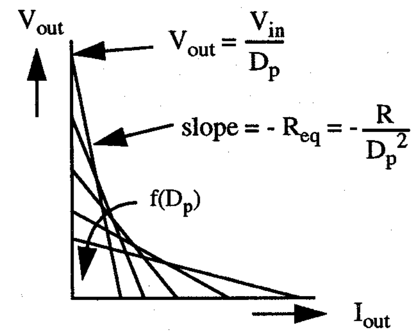

Figure 5: Relation between output current and output voltage as function of the duty cycle D_p

5. Control system

Instead of a single reference voltage, this controller uses a small output voltage window as reference for control actions. The duty cycle is quantized which results in a limited set of lines which repesent the relation between V_{out} and I_{out}. In fig. 6 the resulting output voltage window is shown.

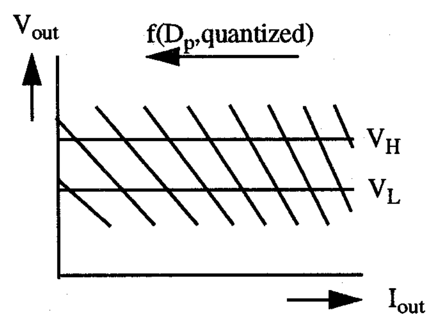

Figure 6: Output voltage window

At the end of each switching cycle the output voltage V_{out} is measured by sampling with two comparators with reference levels V_H and V_L.

In discontinuous mode only one reference level is used, the output voltage stabilizes around level V_H. When the output current increases and the output voltage remains below V_H the controller switches from discontinuous mode to continuous mode.

In continuous mode the controller keeps the output voltage between the levels V_H and V_L. When the output voltage gets above V_H the controller switches back to discontinuous mode and increases the value of duty cycle D_p. The next time the controller gets into continuous mode this new value of duty cycle D_p is used which gives a lower output current than in the previous situation. When the output voltage gets below V_L the controller switches to ramp-up mode and decreases the value of duty cycle D_p. After ramp-up the controller gets back into continuous mode with this new value of duty cycle D_p which gives a higher output current than in the previous situation.

In ramp-up mode the controller tries to get the output voltage above V_L by increasing the current through the coil. When the output voltage gets above V_L the controller switches back to continuous mode. As long as the output voltage remains below V_L the ramp-up cycle is repeated and the value of duty cycle D_p is decreased.

The mode control state diagram in fig. 7 contains the 3 modes of the controller, represented by the states DISC, CONT and RAMP. Transitions are possible between discontinuous mode and continuous mode and between continuous mode and ramp-up mode. Transitions depend on the sampled value of the output voltage and the voltage levels V_H and V_L. With low output power or standby the controller will be in state DISC. In normal output operation the controller will be in state CONT or will temporary be in state DISC or RAMP to adapt the duty cycle for a correct output voltage.

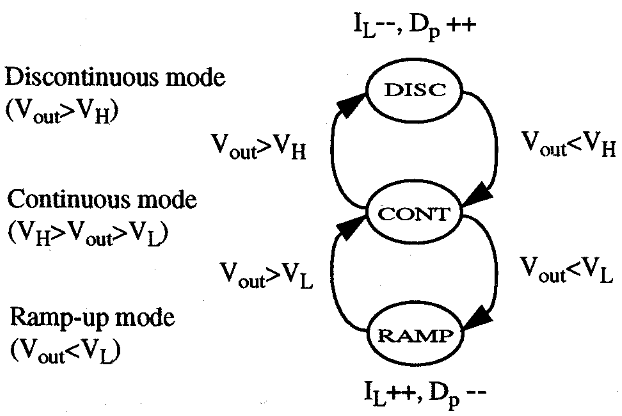

Figure 7: Mode control state diagram

6. Results

In fig. 8 the simulation results for a digital DC/DC boost converter are shown. The input voltage is 1.2V and the output voltage is 2.1V with reference levels V_H=2.15V and V_L=2.05V. The output current is resp. 10µA, 100µA, 3mA and 6mA. During the low output current the converter operates in discontinuous mode. During the normal output power the converter operates in continuous mode and regulates to the correct duty cycle via discontinuous and ramp-up mode. The efficiency of the DC/DC converter depends on the total series resistance of the coil and the switches. Single chip and embedded DC/DC converters with efficiencies of 95% have been realized.

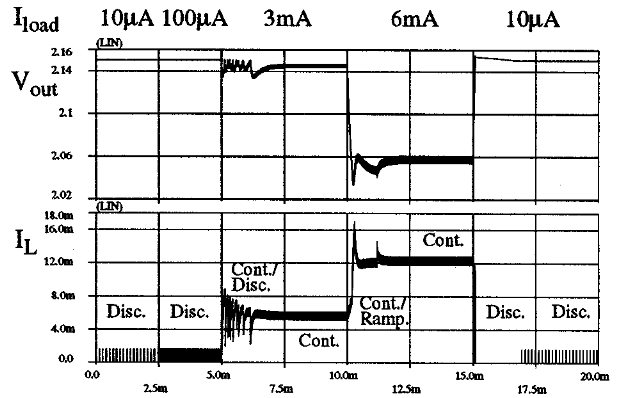

Figure 8: Simulation of transient response

In fig. 9 the chip photograph of an embedded application is shown. The total chip area is 15 mm^2, of which less than 1 mm^2 is used for the DC/DC converter.

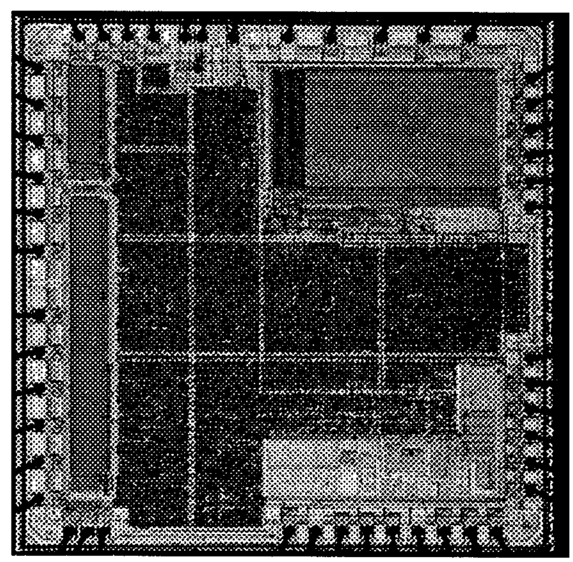

Figure 9: Chip photograph of IC with embedded DC/DC converter

7. Conclusions

With an integrated digital controller a high performance DC/DC converter is realized. The main advantages are the high efficiency over a large power range and the fast response on output load variation. The output voltage window guarantees a stable control operation.

8. References

[1] E.C. Dijkmans, F.J. Sluijs, "DC/DC Conversion, the key to low power consumption", AACD '98 conference, Copenhagen, April 1998.