Multiphase ZVS BUCK DC-DC Converter with Voltage Mode Peak Current Control

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***Abstract*—Multiphase ZVS BUCK DC-DC Converter with Voltage Mode Peak Current Control is proposed in the present paper. In this way, the advantages of Multiphase Converters and Zero Voltage Switching (ZVS) Converters are combined. The proposed Control System provides constant phase shifting between individual DC-DC converters when the peak value of the current varies, as a result of which the switching frequency also changes. The transient process at the start of the converter is simulated, as well as the response of the voltage regulator to a sudden change in load. Using parametric analysis, the optimal parameter values of the compensating circuit elements of the voltage regulator are determined.**

Keywords—power electronics, switch mode power supply, multiphase buck DC-DC converters, zero voltage switching

I. Introduction

Recently, many of the publications concerning BUCK DC-DC converters, are related to power supplies for PCs and laptops. The modern technologies allow to increase the microprocessor operating frequency, which leads to a decrease in the supply voltage (1.5V and lower) and to a significant increase in the current consumption (over 100A) [1]. At the same time, the requirements for efficiency are increasing. This is due to the limited possibility for dissipation of heat from power losses (mostly in laptops because of the small volume).

To achieve high output current, Multiphase Switch Mode Power Supply (MPh-SMPS) is used in modern computer power supplies. As an example, a number of specialized ICs manufacturers can be listed: TPS400090-Texas Instruments, ICL6564-intersil, MAX1887-MAXIM, FAN53168-FAIRCHILD and others. Improvement of efficiency is achieved by reducing the free wheeling diode losses (the circuit of synchronous BUCK DC-DC) and reducing the switching lossess in the transistors (by using zero voltage switching - ZVS). The above-mentioned specialized ICs provide a continuous current mode of operation for the BUCK converter. In this mode, ZVS can only be provided for the top transistor. ZVS for the bottom transistor can be provided if the bottom transistor is turned on while the current through the filter inductor changes its direction [2-4]. Changing the direction of current through the filter inductor, though for a short time, changes the mode of operating. Current regulation is similar to hysteresis current mode of operation, where the switching frequency becomes variable. The variable switching frequency hinders the multiphase mode of operation of the converter.

A method for multiphase operation of BUCK DC-DC is proposed in [5,6]. The present paper is a continuation of the research done. Multiphase ZVS BUCK DC-DC Converter with Voltage Mode Peak Current Control is proposed which combines the advantages of Multiphase Converters and Zero Voltage Switching (ZVS).

II. Multiphase ZVS Buck DC-DC Converter with Voltage Mode Peak Current Control

A. Description of Power and Control Circuits

The power circuit of the investigated Multiphase ZVS BUCK DC-DC converter is shown in Fig. 1. Transistors BSC010NE2LS of the company Infineon are used [7]. For the design of the power circuit, the following initial data are defined: input voltage V_{in} = 9V, output voltage V_{out} = 1.5V, maximum pulsation of the current amplitude over each filter inductor (L_1-L_4): ΔI_L=25A; minimum desired pulsation of the output voltage: ΔV_{out}=13mV. The pulsation of the current amplitude is chosen in such a way that the total output average current is I_{ch}=100A. The minimum switching frequency corresponds to this current for each one power stage: F_{sw}=100kHz. According to [8-10], the following values are obtained for the filter inductors and the filter capacitor: L_f=0.2μH, C_f=3300μF. We select an inductor with R_{DC}=0.2 mΩ and a capacitor with R_{ESR}=3mΩ.

The Control System of Multiphase DC-DC Converter is presented in Fig. 2. It consists of two parts: Master Control System (producing control pulses for the main power stage: QT1, QB1 and L_1), and Slaves Control System (producing control pulses for the rest three stages). The principle of operation and the way of interaction are considered in [6]. The PI Voltage Regulator with slow start is shown in Fig. 3. The compensator elements are optimized during the transient analyses.

The Master Control System (Fig. 2a) is based on hysteresis mode control and produces control pulses for the first unit (QT1 and QB1).

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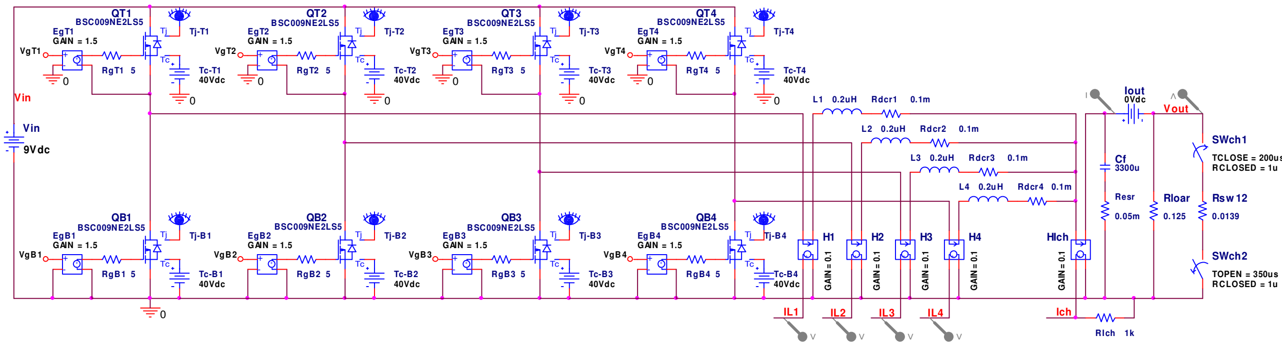
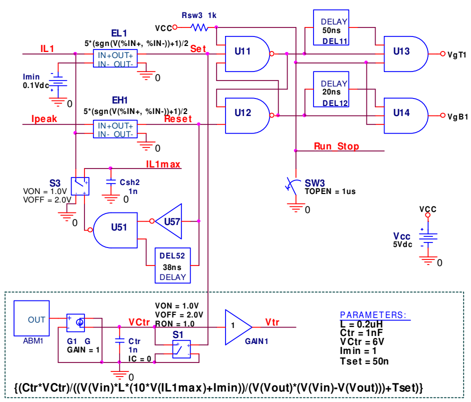
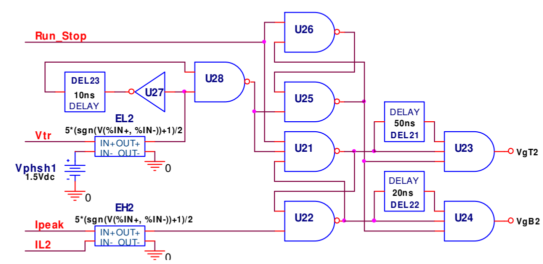


Fig. 1. Power circuit of the investigated Multiphase ZVS BUCK DC-DC Converter with ZVS.



a)



b)

Fig. 2. The Control System of Multiphase DC-DC Converter a) Master Control System b) Slaves Control System.

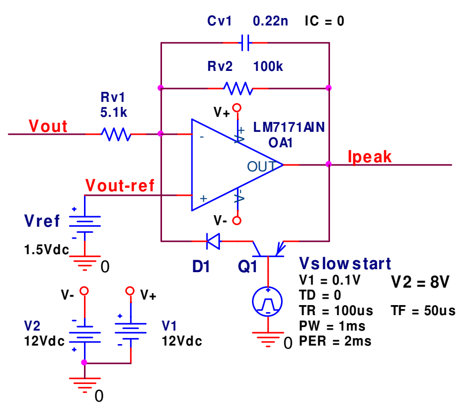


Fig. 3. The PI Voltage Regulator with slow start.

The part of the circuit in the dashed box in Fig. 2a produces frequency-independent triangular voltage. This voltage serves for phase shifting of the transistors control impulses of the next three DC-DC Converters (QT2 - QB2; QT3 - QB3 and QT4 - QB4).

The phase shifting circuit for one of the units is shown in Fig. 2b. The rest phase shifting circuits are realized in the same way. Using the circuit simulator *Cadence PSpice* [11], the transient responses of the Multiphase DC-DC Converter with ZVS are obtained. The simulation results are shown in Fig. 4.

The jump change of the output current I_{out} as a result of switching SW_{ch1} and SW_{ch2} switches is presented in Fig. 4a. The variation of the current I_{out} leads to change of the switching frequency F_{sw}. As a result, the period of the triangular voltage changes, its peak value remaining constant [6] (Fig. 4b). The phase shifting voltages are: V_{phsh1}=1/4V_{TRpeak}, V_{phsh2}=1/2V_{TRpeak} and V_{phsh3}=3/4V_{TRpeak}. In this way, a constant phase shifting is provided between the power stages.

The voltage $V_{out\text{-}reference}$, the V_{out} state, depending on the regulator response, and the voltage at the output of the V_{Ipeak} regulator (divided into two for a better visibility) are presented in Fig. 4c. V_{Ipeak} is a reference for the peak values of the I_{L1}-I_{L4} currents (V_{Ipeak} specifies the value of the hysteresis and hence the switching frequency). The currents I_{L1}-I_{L4} and the sum I_{ch} current are shown in Fig. 4d.

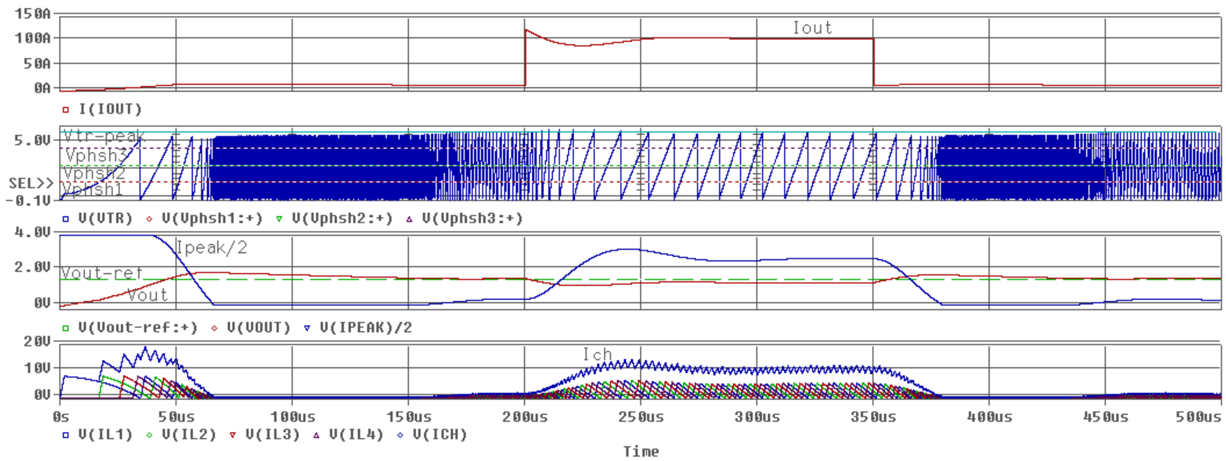


Fig. 4. Simulation results for the transient responses of Multiphase DC-DC Converter with ZVS.

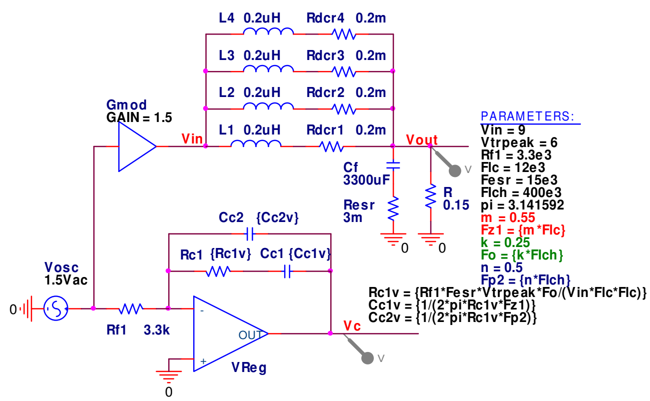


Fig. 5. Equivalent circuit for stability investigation.

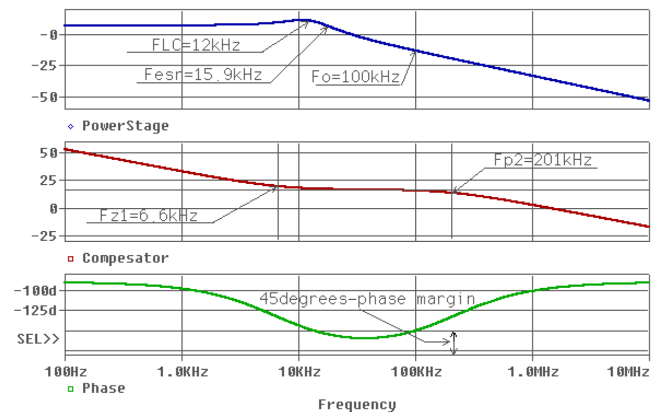


Fig. 6. Simulation results for the magnitude-vs. frequency responses.

B. Equivalent circuit for stability investigation

The equivalent circuit for stability investigation is shown in Fig. 5. The methodology [8-10] is used for zero and pole determination of the power stage.

The pole of the power stage is F_{LC}=12 kHz ($L=L_f/4$ and $C=C_f$). The zero crossover frequency is F_{ESR}=15 kHz. The gain of the modulator is G_{mod}=1.5 (V_{in}=9V, V_{TRpeak}=6V).

The coefficients m, k and n are introduced for determination the desired location of zeros F_{Z1}, bandwidth of the system F_0 and poles F_{P2}. It is taken into account that the frequency pulsation of the total current I_{ch} is four times greater than the switching frequency ($F_{Ich}=4F_{sw}$, F_{Z1}=6.6 kHz, F_0=100 kHz, F_{P2}=200 kHz).

The values of the compensator elements are calculated automatically from the parametric analysis.

The simulation results for the frequency response of the open loop compensator are shown in Fig. 6.

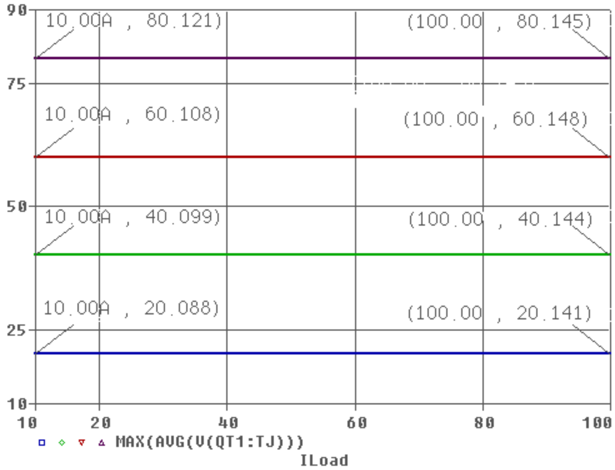
It is necessary to remark that because of the variable switching frequency, the compensator elements are optimized manually in the parametric analysis.

C. Simulation of the temperature, losses and efficiency dependencies

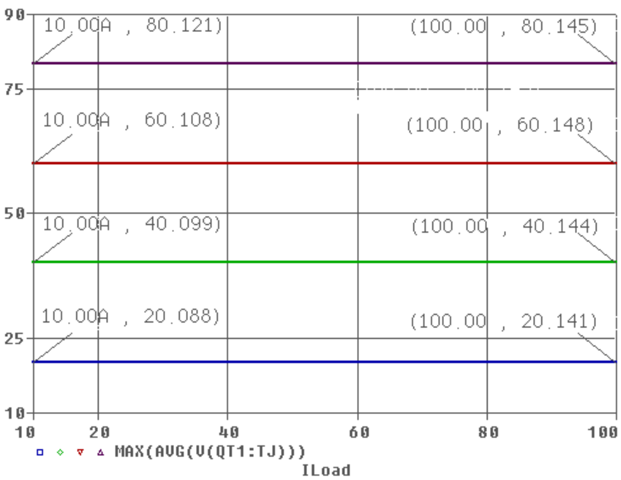
Simulation results for the dependence $T_j(I_d)$ of the transistors QT1 and QB1, for different values of the case temperature, are shown in Fig. 7.

Due to the small switching losses (the presence of ZVS) and the small R_{DS} value of the BSC009NE2LS5 transistors, an increase of the junction temperature, with the increase of the current through them, is not noticeable. T_j is directly dependent on the losses in the transistor. The temperature of the junction depends only on the temperature of the case (i.e., the ambient temperature) and is almost independent of the load current.

The $P_{DS}(I_d)$ dependence of the transistors QT1 and QB1 for different temperature values of the case is shown in Fig. 8.



a)



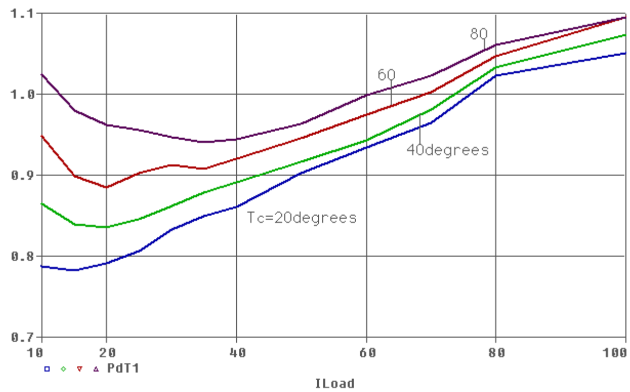
b)

Fig. 7. Simulation results for the dependence $T_j(I_d)$ for T_c=20°C, 40°C, 60°C and 80°C a) for the transistor QT1 ; b) for the transistor QB1.

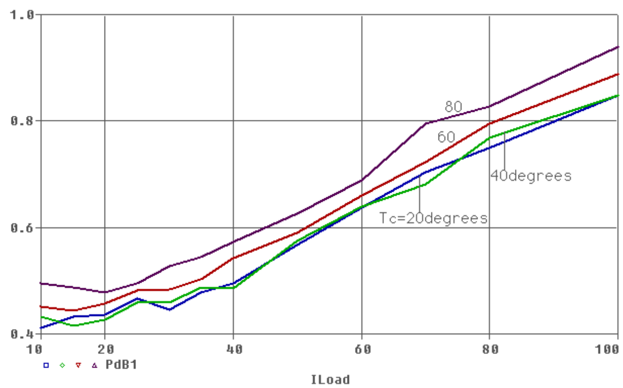
The losses in all transistors of the power circuit are shown in Fig. 9 and the losses in the passive elements P_{Rdc} , P_{Resr} and their sum P_R are presented in Fig.10.

The following macros are used to determine the losses in the individual transistors of the power circuit and their sum:

PdB1=max(S(M(W(QB1)))/199us),
PdT1=max(S(M(W(QT1)))/199us)
PdB2=max(S(M(W(QB2)))/199us)
PdT2=max(S(M(W(QT2)))/199us)
PdB3=max(S(M(W(QB3)))/199us)
PdT3=max(S(M(W(QT3)))/199us)
PdB4=max(S(M(W(QB4)))/199us)
PdT4=max(S(M(W(QT4)))/199us)
Pds=PdB1+PdT1+PdB2+PdT2+PdB3+PdT3+PdB4+PdT4



a)



b)

Fig. 8. Simulation results for the dependence $P_{DS}(I_d)$, for T_c=20°C, 40°C, 60°C and 80°C for the transistor QT1 ; b) for the transistor QB1.

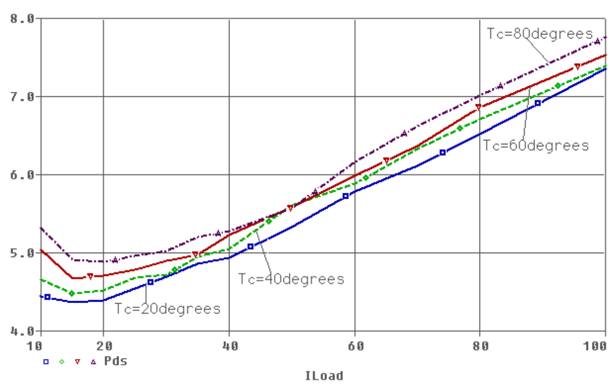


Fig. 9. The total losses $P_{DS}(I_{Load})$ in all transistors.

The following macros are used for determination of the losses in the passive elements P_{Rdc}, P_{Resr} and their sum P_R:

PRdcr1=max(S(M(W(Rdcr1)))/199us)
PRdcr2=max(S(M(W(Rdcr2)))/199us)
PRdcr3=max(S(M(W(Rdcr3)))/199us)
PRdcr4=max(S(M(W(Rdcr4)))/199us)

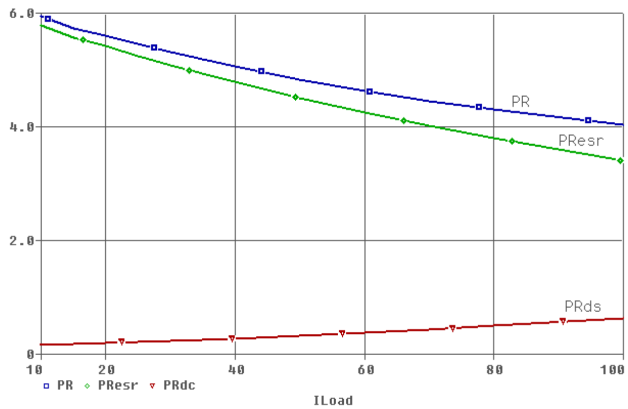


Fig. 10. The powers P_R, P_{Resr} and P_{Rdc} as a function of the current I_{Load}.

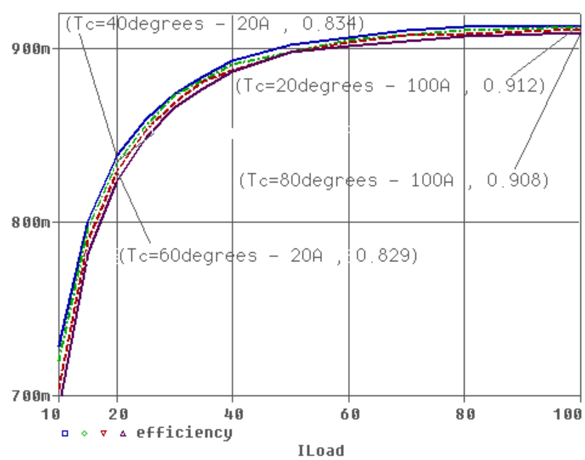


Fig. 11. Efficiency of the Power stage as a function of the current I_{Load}.

PRdc=PRdcr1+PRdcr2+PRdcr3+PRdcr4

PResr=max(S(M(W(Resr)))/199us)

PR=PRdc+Presr

The dependence of the efficiency on the load current I_{Load} is shown in Fig. 11. The following macros are used for its determination:

Pout=max(S(M(W(Rload)))/199us)

efficiency=Pout/(Pout+Pds+PR).

III. Conclusions

Multiphase ZVS BUCK DC-DC Converter with Voltage Mode Peak Current Control has been proposed combining the advantages of Multiphase Converters and Zero Voltage Switching (ZVS) Converters. The proposed Control System provides constant phase shifting between individual DC-DC converters when the peak value of the current varies, as a result of which the switching frequency also changes. Using computer simulation with *Cadence PSpice* circuit simulator, the transient process at the start of the converter and the response of the voltage regulator to a sudden change in load are investigated. Stability analysis is also performed. The losses in the transistors of the power circuit and in the passive elements, as well as the efficiency dependence on the load current are investigated.

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