18th INTERNATIONAL SYMPOSIUM on POWER ELECTRONICS - Ee 2015

NOVI SAD, SERBIA, October 28th - 30th, 2015

MULTIPHASE BUCK DC-DC CONVERTER WITH ZERO VOLTAGE SWITCHING

Georgi Kunov, Tihomir Brusev*, Elissaveta Gadjeva
Technical University of Sofia, Faculty of Electronic Engineering and Technologies, Sofia, Bulgaria
*Technical University of Sofia, Faculty of Telecommunications, Sofia, Bulgaria

Abstract – *In the present paper, a control algorithm of multiphase buck DC-DC converter with zero voltage switching (ZVS) is proposed. It allows combining the advantages of ZVS and multiphase converters. ZVS allows efficiency increasing of the DC-DC converter. The usage of the multiphase buck DC-DC converter leads to increasing of the value of output current and its frequency of pulsations, as well as to decreasing the amplitude of these pulsations. The problem is solved for ensuring a constant phase shifting when the amplitude of the output current is changing.*

Keywords – *Power Electronics/Switch Mode Power Supply/Multiphase Buck DC-DC Converters/Zero Voltage Switching*

1. INTRODUCTION

In recent years, the development of technology in microelectronics led to a significant increase in operating frequency of the microprocessors in the computers. As a result, a change followed in the requirements to the power supply devices: low supply voltages with a large value of the consumed by them current. This led to the development of Multiphase Switch Mode Power Supply (MPh-SMPS). A number of specialized ICs of leading companies are based on this principle of operation: TPS400090-Texas Instruments, ICL6564-intersil, MAX1887-MAXIM, FAN53168-FAIRCHILD and others. They are built on connected in parallel phase shifted synchronous BUCK DC-DC converters working at continuous conduction mode (CCM) of operation. In this way, minimal conductive losses are achieved.

A number of publications and monographs are devoted to MPh-SMPS [1,2,3]. The reducing of the switching losses in the BUCK power transistors by zero voltage switching (ZVS) is not considered. CCM does not allow switching of the transistors in a ZVS mode.

It can be achieved easily by the BUCK DC-DC converters. For this purpose, a synchronous BUCK converter is used, in which the bottom transistor is turn-on while the current in the filter inductor changed its direction for a short time from the output to the input source [4,5].

In this way an improvement of the efficiency is achieved, as shown in Fig.1 [7].

In this paper, a circuit solution is proposed, which allows working of the Multiphase BUCK DC-DC converter in ZVS mode of operation.

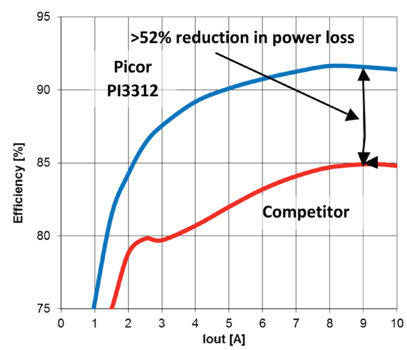

Fig. 1. *Efficiency of ZVS Buck step down 24 V – 2.5 V @ 10A (Picor Semiconductor Solutions, Vicor Corporation)*

2. MULTIPHASE BUCK DC-DC CONVERTER WITH ZVS

2.1. ZVS BUCK DC-DC converter

The circuit of the ZVS BUCK DC-DC converter is shown in Fig. 2. The principle of operation of ZVS is described in [4]. In summary, one can say that it is reduced to hysteresis current mode control. The specific issue here is that the low current level is fixed to a constant minimum value (I_{min}), while the high current level (I_{peak}) is changing depending on the output current value. Consequently, the switching frequency of the transistors is a function of output current (Fig. 3).

The control system of the BUCK DC-DC converter consists of the following elements: comparators U1 and U2; logical elements U3 and U4 (RS flip-flop); logical elements U5 and U6 (Run / Stop gates of pulses for Top and Bottom transistors of the DC-DC converter).

The comparator U2 sets the RS trigger in state U4 = 1 and U3 = 0 when the output current has the value I_{min}, wherein VgT = 1 and the transistor QT is turned on. When the output current reaches the value I_{peak}, the comparator U1 changes the state of the RS trigger (U4 = 0 and U3 = 1). The transistor QT is turned off and the transistor QB is turned on.

The elements of the control system: voltage controlled switch - S1; voltage controlled current source G1 and analog behavior model ABM realize generator of sawtooth voltage whose maximum value V_{tr} remains constant regardless of the frequency of the switching transistors.

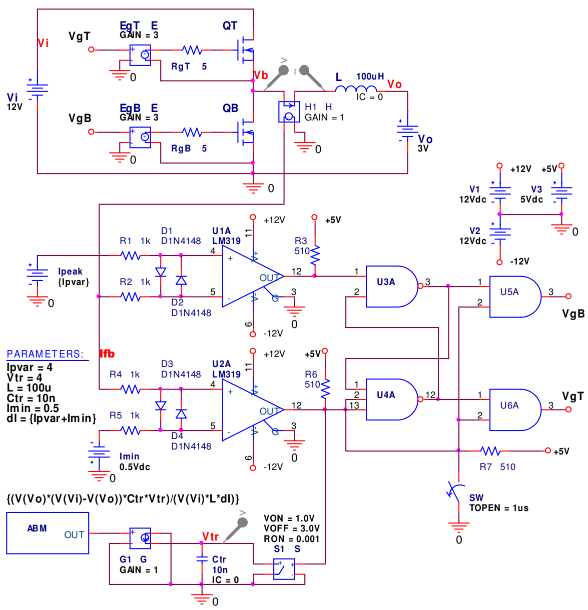

Fig. 2. *BUCK DC-DC Converter with ZVS*

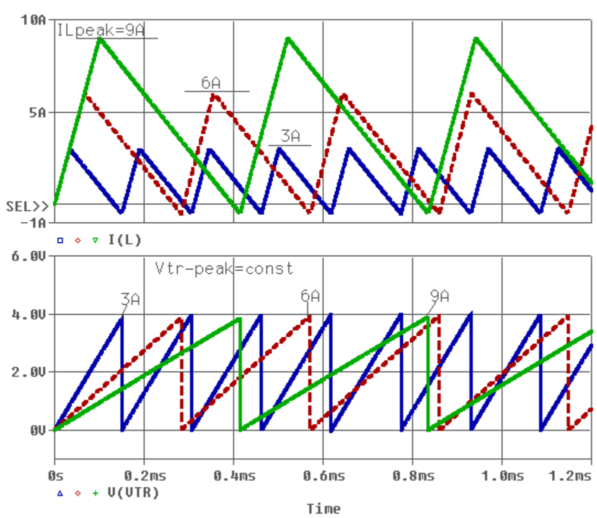

Fig. 3. *Waveforms illustrating the dependence of switching frequency on I_{Lpeak} value*

The generator of line voltage is in phase with the turn-on moment of the transistor QT (start of increase of the output current). The principle of operation of the frequency-independent generator of sawtooth voltage is described below.

In order to implement the circuit of the multiphase BUCK DC-DC converter, it is necessary to form triangular voltage with a period T_{tr} equal to the switching period T_{sw} and with constant amplitude V_{tr}. Such amplitude of the triangular voltage allows constantly phase shifting of the switching between BUCK DC-DC converters, at variable operating frequency (Fig. 3). This can be achieved by appropriate mathematical tools, which will be presented, based on the equality of the switching period and the period of the triangular voltage (Fig. 4).

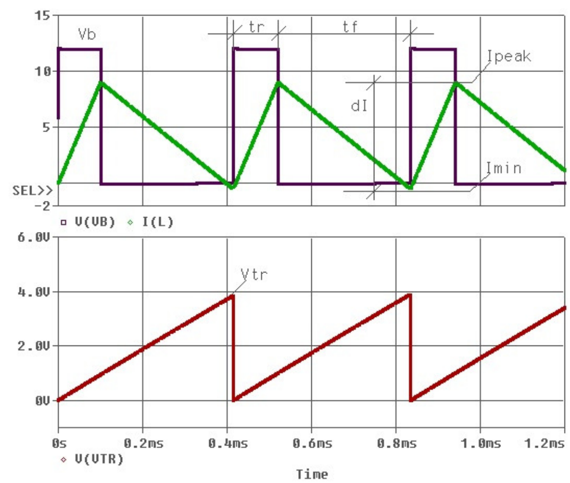

Fig. 4. *Waveforms illustrating the relationship between T_{sw} and T_{tr}*

The switching period is composed of two time intervals: t_r - interval during which the transistor T_{op} is turned on and wherein the current through the inductor increases to the value I_{peak}, and t_f - interval during which the bottom transistor is turned on and the current through the inductor decreases to the value I_{min}.. As a result

$$T_{sw} = t_r + t_f \,, \qquad (1)$$

where

$$t_r = L\frac{\Delta I}{V_i - V_o} \,, \qquad (2)$$

$$t_f = L\frac{\Delta I}{V_o} \,, \qquad (3)$$

$$\Delta I = I_{Lpeak} + I_{min}.$$

The period of the sawtooth voltage is:

$$T_{tr} = \frac{C_{tr} V_{tr}}{I_C} \,, \qquad (4)$$

where: I_C is the charging current for the capacitor, forming the sawtooth voltage.

From (1) - (4) the following relationship is obtained:

$$I_C = \frac{V_o (V_i - V_o) C_{tr} V_{tr}}{V_i L \Delta I} \qquad (5)$$

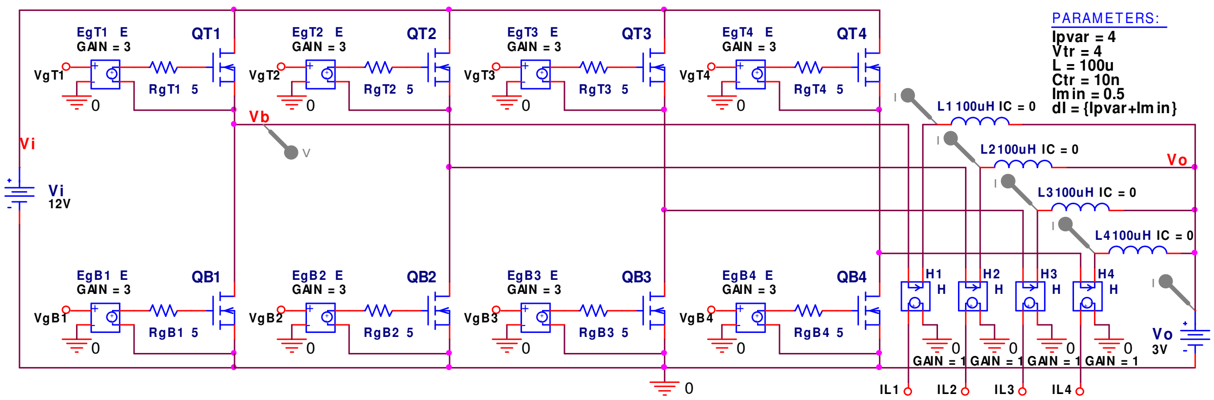

Fig. 5. *Power scheme of Multiphase DC-DC- Converter with ZVS*

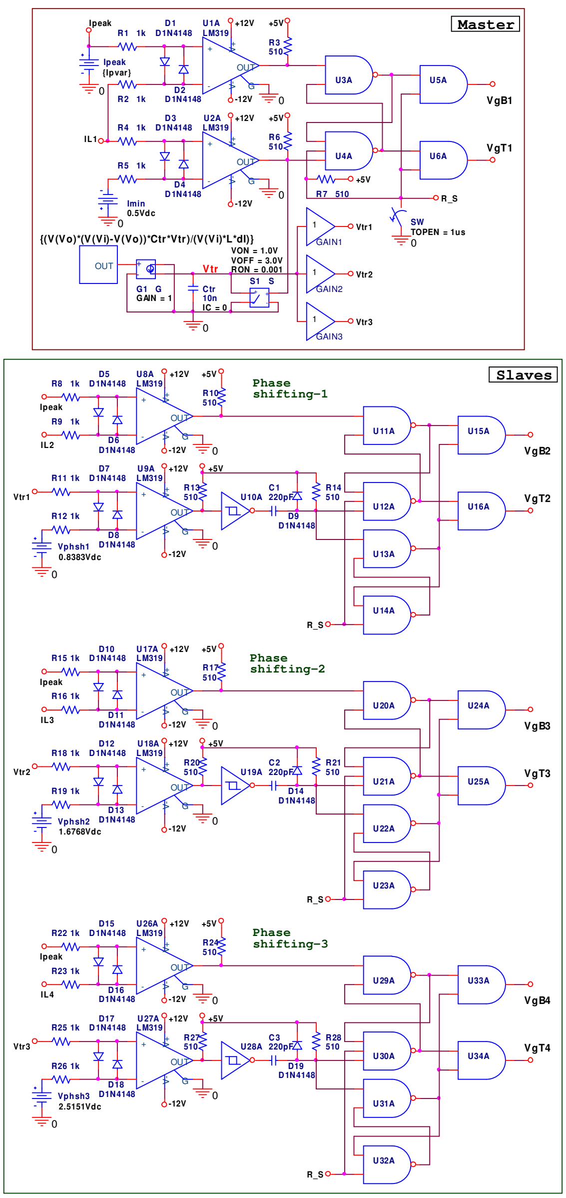

Fig. 6. *Control System of Multiphase DC-DC Converter with ZVS*

Equation (5) is applied to the circuit in Fig. 2 and its validity is confirmed by the stimulation results shown in Fig. 3 and Fig. 4.

2.2. Simulation model and simulation results of Multiphase BUCK DC-DC Converter with ZVS

The circuit of multiphase BUCK DC-DC converter consisting of four DC-DC converters is shown in Fig. 5.

Simulation using *Cadence PSpice* [8] is performed. The control circuit is shown in Fig. 6. It is conditionally divided into two parts. The part named Master repeats the circuit in Fig. 2, except that the triangular voltage is buffered by the elements Gain1-Gain3.

The buffered signals $V_{tr}1$-$V_{tr}3$ are applied at the non-inverter inputs of the comparators U9, U19 and U27 from the second part of the control system named Slaves. There they are compared with the reference phase shifted voltages $V_{phsh}1$, $V_{phsh}2$ and $V_{phsh}3$. The value of $V_{phsh}1$ is equal to one quarter of the maximum value of the sawtooth voltage V_{tr}.

The increment of Vphsh2 and Vphsh3 is equal to the same value. This leads to the same phase shifting between the four BUCK DC-DC converters.

The amplitude of V_{tr} is frequency-independent, as demonstrated above. As a result, a constant phase shifting is obtained when the value of I_{peak} changes.

The RS triggers U13-U14; U22-U23 and U31-U32 realize successive starting (with the same phase shifting) of the second, third and fourth DC-DC converters, by the initial run of the Multiphase converter (Fig. 7). Through the logical elements U5-U6; U15-U16; U24-U25; and U33-U34, a Run/Stop Multiphase BUCK DC-DC converter is realized.

The waveforms, illustrating the operation of Multiphase DC-DC Converter with ZVS, are shown in Fig. 7. It is seen that the currents through the four inductors I_{L1}-I_{L4} have the same phase shifting.

The output current is a sum of the above currents and its frequency of the pulses is four times higher than the frequency of the pulses of its constituent currents.

The proposed principle of control of Multiphase DC-DC Converter with ZVS could be realized on chip [4,7].

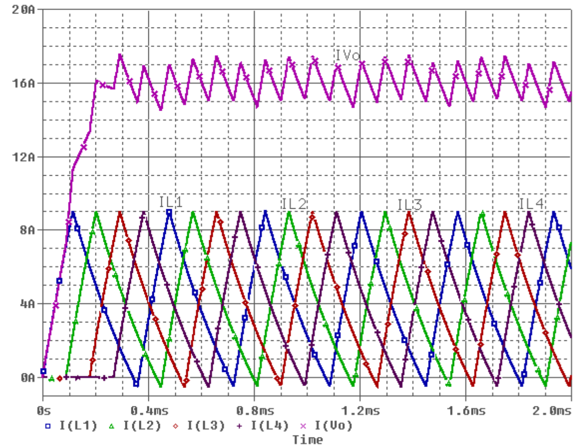

Fig. 7. *Simulation results of Multiphase DC-DC- Converter with ZVS*

3. ACKNOWLEDGEMENT

The investigations are supported by the project FNI E02-85/2014

4. CONCLUSION

A control algorithm of multiphase buck DC-DC converter with zero voltage switching (ZVS) has been developed. The principle of operation of the proposed control system is described in details. The developed approach combines the advantages of ZVS and multiphase converters. Mathematical expressions describing the dependence between the period of the sawtooth voltage and the amplitude of the output current are derived in order to ensure a constant phase shifting. Simulation using *Cadence PSpice* is performed and the waveforms of the sawtooth voltage and output current with different amplitudes are presented. The obtained simulation results confirm the validity of the proposed approach.

5. REFERENCES

[1] H. Nguyen, *Design, analysis and implementation of multiphase synchronous buck DC-DC converter for transportable processor*, PhD Thesis, 2004, https://vtechworks.lib.vt.edu/bitstream/handle/10919/32139/Huy_Nguyen_Thesis_2.pdf ?sequence=1

[2] M. Shi, *Design and analysis of multiphase DC-DC converters with coupled inductors,* PhD Thesis, Texas A&M University, 2007, http://repository.tamu.edu/bitstream/handle/1969.1/5962/ etd-tamu-2007A-ELEN-Shi.pdf?sequence=1&isAllowed=y

[3] M. Cory, *Conventional and ZVT Synchronous Buck Converter Design, Analysis, and Measurement*, PhD Thesis, University of Central Florida Orlando, Florida, 2010, http://etd.fcla.edu/ CF/CFE0003106/ Cory_Mark_A_201005_MS.pdf

[4] S. Chen, O. Trescases, W.T. Ng, *Fast dead-time locked loops for a high-efficiency microprocessor-load ZVS-QSW DC/DC converter,* IEEE Conference on Electron Devices and Solid-State Circuits 2003, EDSSC'03, 2003. pp. 391-394.

[5] P. Amiri, M. Sharafi, "*A High Efficiency Low-Voltage Soft Switching DC–DC Converter for Portable Applications*", Journal of Electrical and Computer Engineering Innovations, JECEI, Vol. 1, No. 2, 2013

[6] M. Alimadadi, S. Sheikhaei, G. Lemieux, P. Palmer, S. Mirabbasi, W. Dunford, *A 660MHz ZVS DC-DC converter using gate-driver charge-recycling in 0.18µm CMOS with an Integrated Output Filter,* Power Electronics Specialists Conference, PESC 2008. IEEE, 2008, pp. 140-146.

[7] C.R. Swartz, *High performance ZVS Buck Regulator removes barriers to increased power throughput in wide input range point-of-load applications*, Picor/wp_HighPerfomanceZVS.pdf ,2012, http://www.vicorpower.com/webdav/site/com.vicor.www/shared/documents/whitepapers/Picor/wp_High PerfomanceZVS.pdf

[8] PSpice User's Guide, Cadence PCB Syst. Division, USA, 2000.