INVESTIGATION OF ZCS RESONANT-SWITCH DC-DC CONVERTER FOR FULLY MONOLITHIC IC IMPLEMENTATION

Tihomir Sashev Brusev, Petar Trifonov Goranov,
Marin Hristov Hristov

FETT, Technical University of Sofia, 8, Kliment Ohridski St., 1000 Sofia, Bulgaria, phone: 00359-2-965-21-11 fax: 00359-2-868-32-15, e-mail: office_tu@tu-sofia.bg

This paper includes investigations results of monolithic zero-current switching (ZCS) resonant-switch dc-dc converter. Circuit was designed on AMS CMOS 0.35 µm process. Soft-switching control technique was used in the simulations. Efficiency of about 86 % at 1.75 GHz switching frequency is illustrated for voltage conversion from 3 V to 1.2 V. Effects of low Q passive filter components over the converter's behavior are presented.

Keywords: dc-dc converter, fully monolithic design, efficiency, CMOS 0.35 µm technology, ZVS

1. INTRODUCTION

The tendency of the microelectronics is miniaturization. Integrated circuits (IC) become much more sophisticated and their operating voltages decrease. One of major problems is how to use efficiently energy from the battery, of battery powered electronic devises. The dc-dc converters are used for attaining the desired voltage level. Fully monolithic design of dc-dc converter with high efficiency η is very important task. One of the biggest problems is integration of passive components and their low Q factor. To work in a proper manner in the basic switched mode dc-dc converter usually filter's passive components are offchip. Step-down zero-current switching (ZCS) resonant converter designed on CMOS 0.35 µm process is presented in this paper. Due to the characteristics of ZCS technique energy dissipated in the converter should be minimized. A soft-switching regulation is used for decreasing of the switching losses and consequently increasing of the efficiency η.

2. PROBLEM STATEMENT

In Fig. 1 is shown ZCS resonant-switch dc-dc converter.

This is step-down converter with an additional L_r and C_r – inductor and capacitor which form parallel resonant circuit. The diode in the basic circuit is replaced by the transistor *SW2*, which is controlled in appropriate manner. Before turning *SW1* on, the output current I_o flows through *SW2*, and if switches are ideal voltage across C_r equals V_{in}. Switch *SW1* "turns on" at zero current, because of the inductor L_r. Current through the *SW1* i_{SW1} rises. So long as i_{SW1} is less than average output current I_o, *SW2* is closed and voltage across the capacitor C_r stays equal to V_{in}. When i_{SW1} equals I_o, *SW2* is turned "off" and L_r and C_r formed parallel resonant circuit. Current i_{SW1} has sinusoidal shape. When this current reaches zero, switch *SW1* is turned "off". Output current I_o flows through the C_r. When the voltage across the capacitor reaches V_{in}, *SW2* is turning "on" and output current flows through the switch. After certain time switch *SW1* "turns on" again and the next cycle is starting.

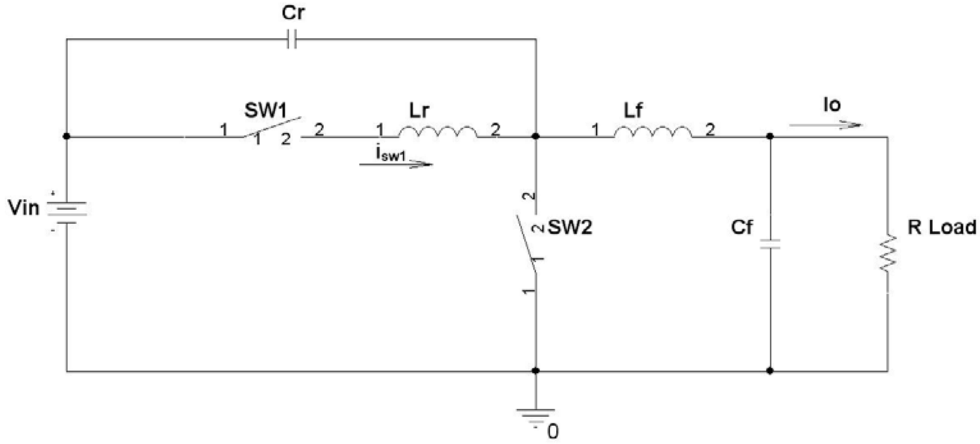

Fig. 1 ZCS resonant-switch dc-dc converter.

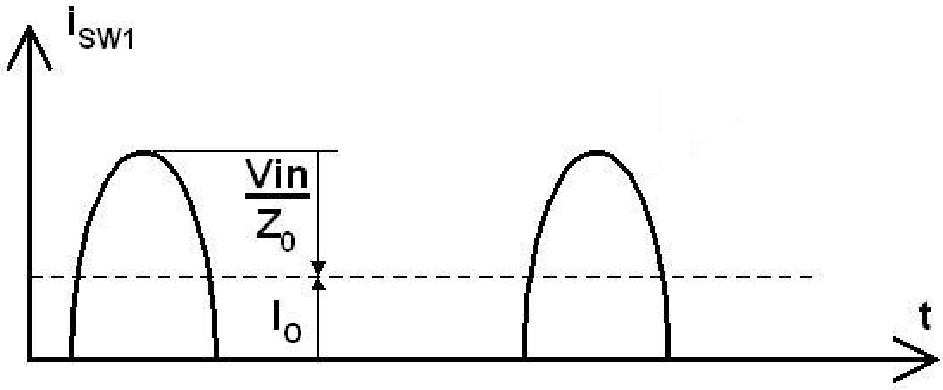

Fig. 2 ZCS - current through the *SW1*.

Forward operating voltage of *SW1* is limited to V_{in}. Output voltage can be controlling by the switching frequency of *SW1*. If $I_o > V_{in}/Z_0$, where Z_0 is equivalent impedance of the parallel resonant circuits, i_{SW1} will not came back to zero naturally and the switch will be forced off. Thus losses in turning "off" of the *SW1* will be appeared. Therefore, if the passive components which form the resonant circuit have low *Q* factor, ZCS can not be achieved.

In the presented step-down dc-dc converter except ZCS for improving the efficiency results, a soft-switching technique is proposed. Regulation of the switching "on" time of the second switch *SW2*, with some delay after the switching "off" of the main switch *SW1*, could leads to switching "off" the main switch at zero voltage. This method combined with ZCS minimized losses in the switches.

3. RESULTS

In Fig. 3 is illustrated investigated circuit of ZCS resonant-switch dc-dc converter converter. Circuit is designed on AMS CMOS 0.35 μm process. Switches *SW1* and *SW2* are realized respectively by PMOS and NMOS transistors. In first approximation inductor's losses are neglected. In order to estimate energy dissipated in the real transistors and behavior of the converter with ideal inductors. In such way ZCS will be achieved, because of the high Q factor of passive components. In circuit shown in Fig. 3 power dissipated in the converter is produced only by the transistors.

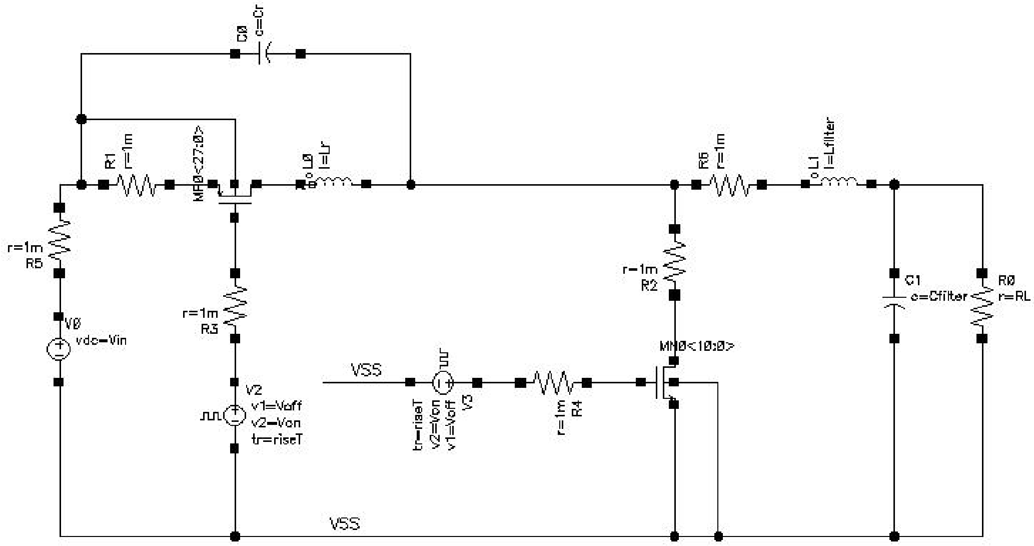

Fig. 3 Simulated circuit on AMS CMOS 0.35 µm process.

Efficiency of the dc-dc converter is:

$$\eta = \frac{P_{OUT}}{P_{IN}} \tag{1}$$

where P_{OUT} is output power of the converter,

$$P_{OUT} = \frac{V_{OUT(av)}{}^{2}}{R_{Load}} \tag{2}$$

and P_{IN} is input power,

$$P_{IN} = I_{IN(av)} \times V_{dd} \tag{3}$$

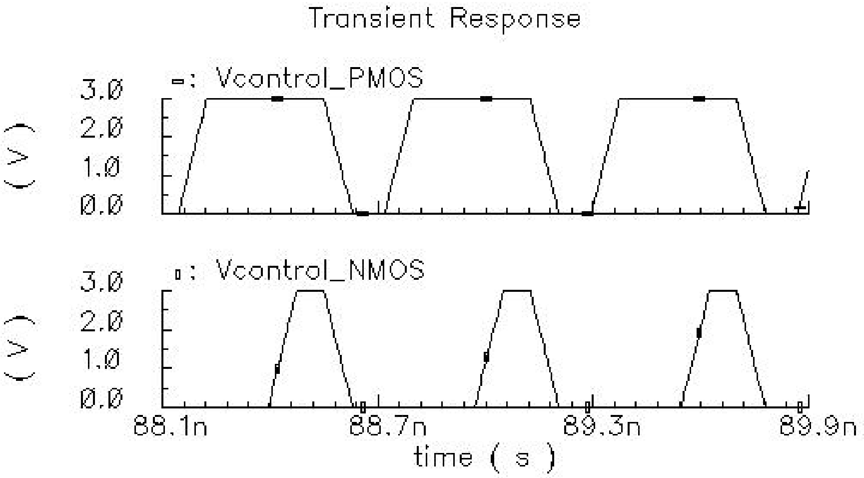

Fig. 4 Control pulses of the PMOS and NMOS transistors.

Control signals of the PMOS and NMOS transistors are shown in Fig. 4.

As can be seen NMOS transistors in this circuit, which perform functions of *SW2* is turned "on" with delay after the switching "off" of PMOS transistors. In such way soft-switching can be realized. The idea is main PMOS transistor to be switched "on" at zero voltage.

In Fig. 5 are presented simulations results of the output voltage and inductor current of the converter.

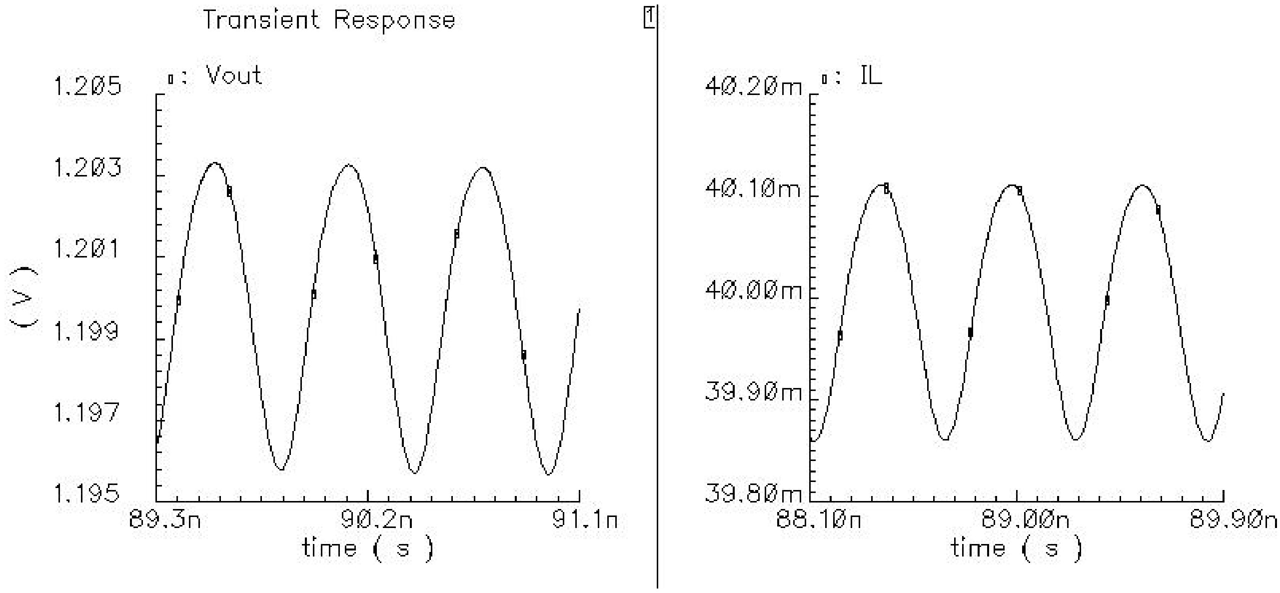

Fig. 5 Simulation results of output voltage and inductor current.

In Table 1 are presented received simulated results, when ideal inductors for simulations are used. Switching frequency *fs* is 1.75 GHz. Input voltage V_{in} is 3 V and output voltage V_O is 1.2 V. In four columns are shown results, when different filter's inductors are used. With small filter inductor – about 10 nH, which could be integrated on chip, are achieved good results. The biggest real inductor in AMS CMOS 0.35 µm process is 10 nH. Second resonance inductor L_r is smaller then the filter inductor.

Table 1

ZCS resonant-switch dc-dc converter	**Lf=10 nH Cf=200 pF**	**Lf=25 nH Cf=200 pF**	**Lf=50 nH Cf=200 pF**	**Lf=100 nH Cf=200 pF**
V_{OUT} (av) [V]	1.2	1.2	1.2	1.2
I_{Load} (av) [mA]	47	40	37	36
f_S [MHz]	1750	1750	1750	1750
P_{IN} [mW]	66.37	54.9	51.7	49
P_{OUT} [mW]	57.11	48	45.3	43
η [%] (P_{OUT}/P_{IN})	86	87.4	87.5	87.6

As can be seen from Table 1 86 % efficiency η could be achieved, if only transistor's losses are considerate. Simulations results shows that ZCS technique combine with soft-switching control helps to reduce dissipated power in the transistors even with small filter inductance with high *Q* factor. Inductors of 10 nH could be integrated and they are available in AMS CMOS 0.35 µm process.

In the Table 2 are illustrated simulations results of ZCS resonant-switch dc-dc converter at different switching frequencies. The filter inductor *Lf* is equal to 10 nH.

Table 2

ZCS resonant-switch dc-dc converter	**Lf=10 nH Cf=200 pF**	**Lf=10 nH Cf=200 pF**
V_{OUT} (av) [V]	1.2	1.2
I_{Load} (av) [mA]	47	35
f_S [MHz]	1750	2000
P_{IN} [mW]	66.37	55.68
P_{OUT} [mW]	57.11	42
η [%] (P_{OUT} /P_{IN})	86	75.5

In Fig. 6 is shown ZCS resonant-switch dc-dc converter simulated with real inductors.

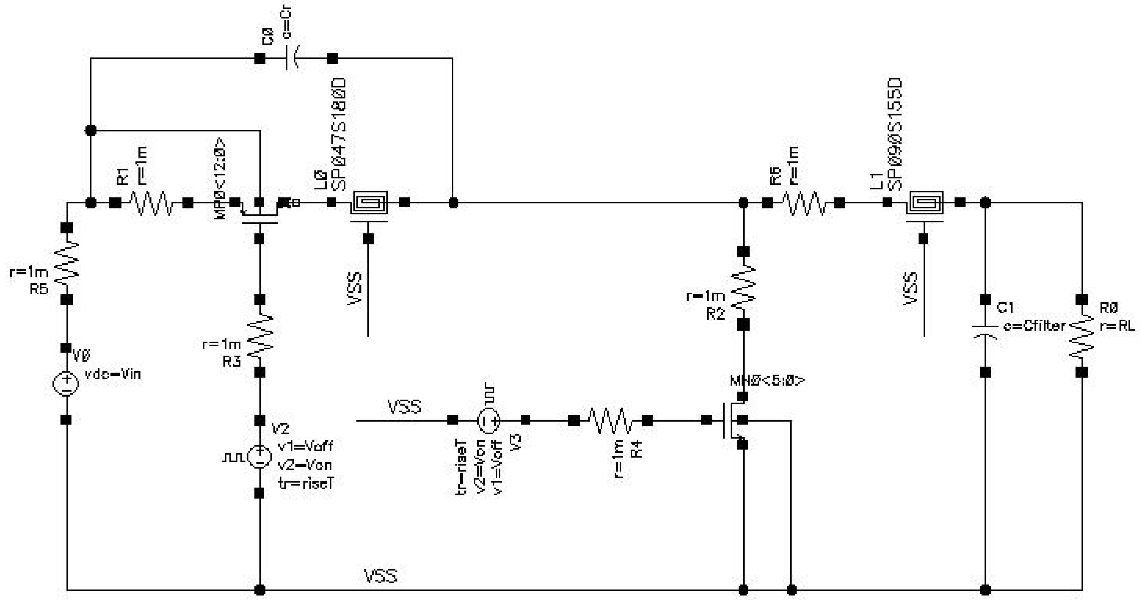

Fig. 6 Simulated circuit on AMS CMOS 0.35 µm process with real inductors.

In Table 3 are shown simulated results of circuit from Fig. 6. Input voltage V_{in} is 3 V and output voltage V_O is 1.2 V. Switching frequency of operations *fs* is 2 GHz.

Table 3

ZCS resonant-switch dc-dc converter	**Lf=10 nH – real inductor Cf=200 pF**	**Lf=10 nH – real inductor Cf=200 pF**
V_{OUT} (av) [V]	1.2	1.2
I_{Load} (av) [mA]	22	20
f_S [MHz]	1750	2000
P_{IN} [mW]	92.38	70.55
P_{OUT} [mW]	26.45	25.18
η [%] (P_{OUT} /P_{IN})	28.6	35

The comparison between efficiency η results from Table 2 and Table 3, shows decreasing from 75.5 to 35 %. Low Q factor of real inductors is reason for unacceptable efficiency η. ZCS can not be achieved because of high equivalent impedance of the parallel resonant circuits.

4. CONCLUSIONS

ZCS resonant-switch dc-dc converter can work at high switching frequency *fs* with good efficiency and reasonable components value. This is proved by the circuit investigation done on AMS CMOS 0.35 μm technology. Inductor with normal for integrated components value and higher *Q* factor then available is needed for realization of suitable dc-dc converter. Simulations shows, that with 10 nH filter inductance, which is possible to be integrated can achieved good efficiency η. Soft switching control help for decreasing of the dissipated power in main switch.

Available inductors in AMS CMOS 0.35 μm can not satisfied requirements for dc-dc converter.

5. ACKNOWLEDGMENTS

The research described in this paper was carried out within the framework of Contract BY-TH-115/2006.

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