42/5 V SWITCHED-CAPACITOR DC/DC CONVERTER*

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Summary *– The inductorless switched capacitor DC/DC converter from 42 V to 5 V suitable for the 42-volt system vehicles is proposed. The classical step-down structure has been modified in a manner to overpass the main drawbacks of these converters: significantly lower efficiency when the transfer voltage ratio is quite different from the ideal voltage ratio imposed by the converter structure. The regulation of the output voltage is achieved by the control of the current through the input switches resulting in the continuous input current and minimized conducted electromagnetic interference are. The extensive simulations performed, on the symmetrical 42/5 V SC-converter, using the PSpice and PowerSim simulation programs show very good behaviour of the converter, small ripple of the output voltage, and the efficiency above 80% when the input voltage is equal to 42 V, or 36 V.*

I. INTRODUCTION

The automotive industry today is facing electrical power demands that are stretching the capabilities of present on-board power supplies. The increasing use of electrical and electronics features to enhance customer confort convenience and safety contributes not only to exponential growth in power demand, but also to size and complexity of wiring harness as well. The typical 14V electrical system in a mid-range or luxury car today is rated at approximately 800 W – 1500 W continuous load which is equivalent to a continuous current rating of 60 A – 110 A. The average annual consumption is around 550 W, with maximum static loads of 2500 W (180 A) being quite feasible [1], [2]. If all the electrical loads were to be activated simultaneously, this would represent a power demand of the order of 10 kW. The typical luxury class vehicle today has about 2500 m of wire in the harness and a subset of some 350 connectors. The continuous electrical power which will be needed in the year 2005 is estimated to be in the range of 3000 W – 7000 W, with an annual average of 2220 W. The dynamic aggregate electrical power demand will then be at least 30 – 40 kW [1].

As the maximum static currents which can safely be handled by today's cables, batteries and generators can be considered to be of the order of 150 A – 200 A, it soon becomes clear that the automotive electrical system in its present form has reached the

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limit of its capacity. The global attention has recently focused on 42 V system as the best choice for the nominal voltage of a vehicle [1], [2], [3].

This would imply the need of DC/DC conversion from 42 V to 5 V to assure the proper power supply for the low power electronic systems used in all modern vehicles.

In this paper we are proposing one possibility for 42 V to 5 V conversion using inductorless switched–capacitor (*SC*) converter topology.

II. INDUCTORLESS SWITCHED-CAPACITOR DC/DC CONVERTERS

In recent years, different types of switched-capacitor (*SC*) DC/DC converters that use only switches and capacitors to perform the power conversion have been proposed [4] – [7]. Today some of them are commercially available (*Maxim*, *National Semiconductor*, *Linear Technology*) [8] – [10]. As these circuits do not use any inductive elements the possibilities of integrated circuit fabrication and high power density are very promising. One of the fundamental drawbacks of these converters is the fact that the efficiency is very dependent of the relative value of the wanted output voltage. In fact the efficiency can be calculated by [6]:

$$\eta = P_{Odc} / P_{Isr} = K_i^{-1} \cdot V_{Odc} / V_I \qquad (1)$$

where: K_i is the ideal voltage conversion ratio, V_{Odc} is the actual output voltage, V_I is the input voltage.

This means that: even the regulation of the output voltage is possible the efficiency will depend of the range of possible variation of the input or output voltage. The classical step–down structure has been analyzed in detail in [4] and [6]. This topology has been used to perform different voltage conversion ratios. The 12 V to 5 V *SC*–converter has been proposed in [4], while the step–down SC converter 48/12 V has been presented in [5] (fig. 1). The realized converter is composed of two cells (shown in fig. 1) connected in parallel and operated in antiphase. The switches S_1 and S_2 were realized using the N-channel MOS-transistors. The circuit operates in two cycles. The charging cycle is accomplish by closing the switch S_1 (with S_2 open) which will result in charging the capacitors C_1, C_2 and C_3 (connected in series) each up to $V_E/3$. The discharging cycle is performed by closing the switch S_2 (with S_1 open). This results in a parallel connection of C_1, C_2, C_3, and C_O. The output voltage can be regulated by controlling the operation of the switch S_1.

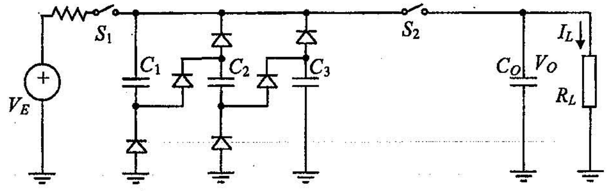


Fig. 1 Circuit structure of the 48/12 V switched-capacitor DC/DC converter cell [5]

Changing the number of capacitor stages in the converter cell given in fig. 1 the voltage transfer ratio can be changed. This imposes that the same structure can be used for converting 42 V to 5V for the future automotive electrical systems. The main problem to solve is the efficiency of the conversion process as the input voltage will change in the range between 36 V and 42 V, depending on the engine operating status.

In fact, from the results given in [5] it can be seen that the efficiency vary from 85% if the input voltage is 40 V, down to 65% for input voltage of 55 V. This means that in the case of converting 42 V to 5 V the circuit will operate with the lowest efficiency when the engine is running and the alternator output voltage is 42 V, while the highest efficiency will be achieved at 36 V (the battery voltage when the engine is not running).

III. 42/5 V SC DC/DC CONVERTER WITH IMPROVED EFFICIENCY

One idea how to achieve better efficiency at 42 volts is presented and analyzed below. The circuit diagram of the proposed topology is given in fig. 2. Using the additional switch S_3 the circuit can change its configuration from the ideal conversion ratio of 6 to ideal conversion ratio of 7.

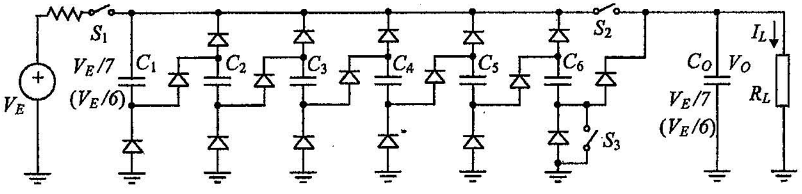


Fig. 2 Circuit structure of the 42/5 V switched-capacitor DC/DC converter cell

When the input voltage is between 36 and 40 volts the switch S_3 is closed and the converter operates with the ideal conversion ratio of 6. The theoretical efficiency, calculated according the eq. (1) will change from 83% to 75%. When the input voltage is between 40 and 42 volts the switch S_3 is open and the converter behave as it has the ideal conversion ratio of 7. The theoretical efficiency changes from 83.3% to 87.5%. To minimize the conducted EMI with the supply network the switch S_1 is operated as a voltage-controlled current source rather than as a PWM controlled switch [5].

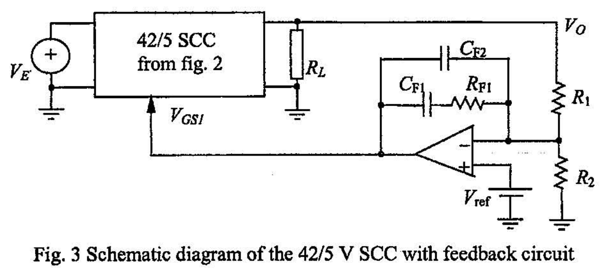


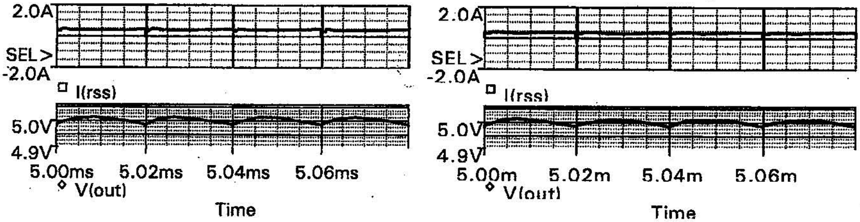
Fig. 3 Schematic diagram of the 42/5 V SCC with feedback circuit

This way, S_3 is kept in the conducting state during the whole half-period, i.e. during the charging cycle, but its current is controlled by using feedback circuit (fig. 3). As the input and output voltage of the converter does not change the expected conversion efficiency will be slightly lower than the values shown above [6].

IV. SIMULATION RESULTS

The extensive simulations were performed, on the symmetrical 42/5 V SC–converter (one cell is shown in fig. 2), using the PSpice and PowerSim simulation programs. The results obtained by both programs were similar. For the PSpice simulations the switches were simulated by the PSpice models for the MOSFETs IRF9140 (S_1) and IRF150 (S_2 and S_3), the diodes were modeled as dsb830 (is=1e-15 vj=0.3 n=0.35 rs=15m cjo=3.5n), the capacitors C_1 to C_6 had C=40 μF and ESR=10 mΩ, while the output capacitor had C=160 μF with ESR=2.5 mΩ. The OrCad PSpice evaluation version 9 was used. The switching frequency was chosen to be 25kHz, and the 12.5 W DC power was delivered to the resistive load. The feedback circuit was realized using the following components: $R_1 = 6$ kΩ, $R_2 = 4$ kΩ, $R_{F1} = 5.6$ kΩ, C_{F1} =58 nF and C_{F2} =146 pF.

The diagrams of the input current and the output voltage for input voltage of 36 V and 42 V are presented in Fig. 4. The shapes are very similar with nearly constant input current with very small spikes. Most probably the reason of these spikes is the computational error as they are not present in the simulation results obtained by PowerSim.

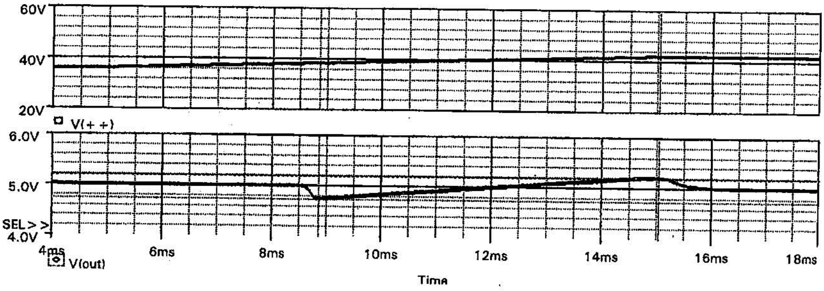


(a) (b)

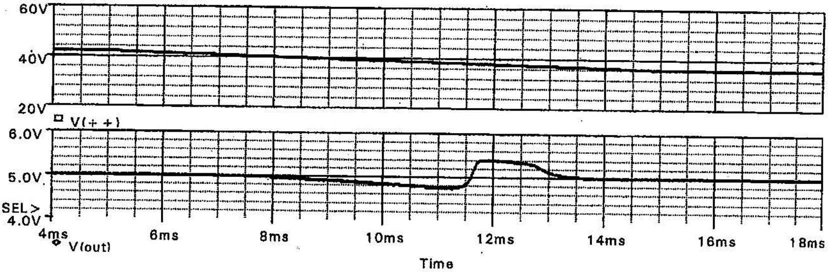
Fig. 4 Input current and output voltage obtained by OrCad PSpice: a) for V_{in}=36V; b) for V_{in}=42V

The transient characteristic of the converter has been investigated for two cases: *a*) increasing the voltage from 36 V to 42 V, and *b*) decreasing the input voltage from 42 V to 36 V. The simulation results are given in Fig. 5. For faster changes of the input voltage the voltage distortion during the transient interval are smaller.

The diagrams showing the efficiency versus input voltage for constant output voltage and current, the efficiency versus output current for constant output voltage and the output voltage versus output current for constant input voltage are shown in fig 6. It can be seen that the output voltage is starting to go below 5 V for output currents higher than 5 A. This is mainly caused by the high resistance of the output MOS-switch. Paralleling two MOS-switches the output current can be increased above 5A without changes of the output voltage.

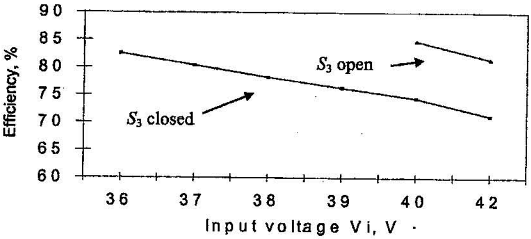


(a)

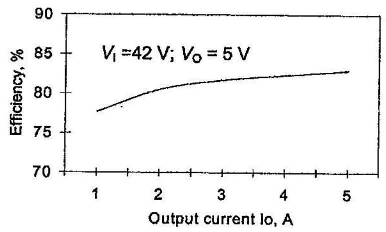


(b)

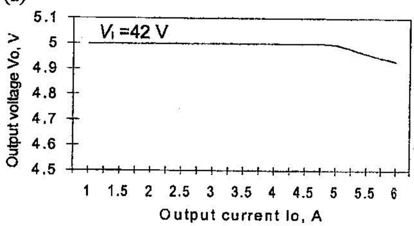
Fig. 5 Diagrams showing the dependence of the output voltage when the input voltage changes: a) from 36 V to 42 V; b) from 42 V to 36 V



(a)



(b)



(c)

Fig. 6 a) Efficiency versus input voltage; b) Efficiency versus output current; c) Output voltage versus output current

V. CONCLUSION

The inductorless switched capacitor DC/DC converter from 42 V to 5 V suitable for the 42-volt system vehicles is proposed. In order to minimize the conducted EMI and the current stress on the switching devices the current control scheme in the charging process [5] has been used.

The simulation results show very good behaviour of the converter, small ripple of the output voltage, nearly constant input current, and the efficiency above 80% when the input voltage is equal to 42 V, or 36 V. These results are very close to the theoretical predictions.

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