12V to 5V Switched Capacitor DC-to-DC Converter With N-channel Power MOS Switches

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Abstract *- A solution to the problem of using only N-channel power MOS-switches for a inductorless switched capacitor 12V-to-5V dc-to-dc converter is proposed. Also, a simple model of the output stage of ICL7667 power MOS driver is proposed. The characteristics of the two converter configurations are investigated and compared using PSPICE simulation. The results show negligible differences of the performances of both converter configurations and thus justify the proposed solution.*

I. INTRODUCTION

Switched capacitor power converters recently attract more attention due to new advances in capacitor technology. Commercially available multilayer capacitors [1] exhibit very high capacitance (up to 1500F) and very low ESR (down to 5mOhm) with very high energy densities (more than 5J/cm^3). Their main disadvantage - low voltage (3-5V) can be overcome by connecting more capacitors in series, but it is to be expected that commercially available capacitors will be rated at higher voltages soon.

Increased implementation of microcontroller circuits in vehicles, that operate at 5V or less, makes high efficiency 12V-to-5V converters with high power densities specially interesting. On the other hand this voltage ratio is very suitable for switched capacitor converters because the switches that connect the capacitor batteries for charging and discharging should operate at low voltage drop to maintain high efficiency.

The circuit diagram of such converter and the timing diagrams of the switches are shown in Fig 1. [2]. The basic principle of operation is as following: two capacitors (C1 and C2) are charged in series at the source (through S1) and then discharged in parallel at the load Ro (through S2). A filtering capacitor (Co) connected in parallel to the load delivers power to the load during the charging interval of the capacitor battery (Ton). If another group of capacitors (C3, C4) and switches (S3, S4) are used in anti-phase with the first one, than better characteristics can be achieved. The regulation of the output voltage is achieved by changing the duty cycle D=Ton/Ts.

In [2] the switches S_1 and S_3 has been chosen to be p-channel MOS-transistors and the switches S_2 and S_4 n-channel MOS-transistors, because the authors have met some problems in driving the switches S_1 and S_3 in four n-channel MOS switch configuration (the potentials of theirs source terminals are not constant). But, the use of different channel MOS transistors bring other problems. There are no p-channel and n-channel MOS transistors with exactly same parameters. The n-channel MOS transistors have better static and dynamic characteristics than p-channel devices. Also, it is important to point out that the production of such converters, with different channel power MOS transistors, in IC technology would not be very convenient. So, as a practical challenge, the realization of the proposed converter with the same type channel devices can be considered.

The aim of this article is to propose some modifications in the driver circuits for the switches S_1 and S_3 in the manner that they can be realized with n-channel MOSFET's. The basic structure of the converter is not to be changed and the main characteristic of the circuit should not be changed.

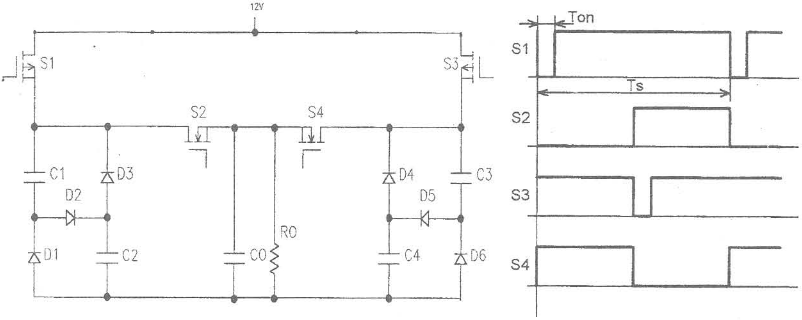


Fig. 1 Circuit Diagram and Timing Diagrams of a 12V-to-5V converter [2]

II. THE MODIFIED CONVERTER

Concerning the driving of the switches S_1 and S_3 (Fig. 1) the authors [2] have pointed out that the driving of the n-channel switches using the boot-strap capacitor based circuit would be power demanding and inefficient.

If a bootstrap capacitor was used for powering another switch, or driver, that would turn on and off the power switch, it would be power demanding and complicated circuit indeed. But, if a capacitor in a clamping configuration is used, the level shifting of the gate drive voltage will be very simple and power efficient (Fig. 2). We have found the 7667 chip [3] as a very convenient for driving purposes.

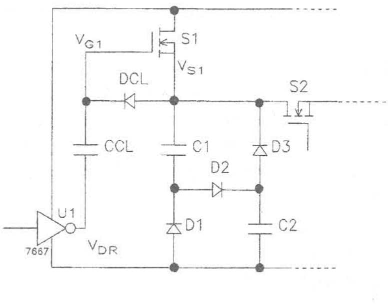


Fig. 2 The Modified Driving Circuit

The operation of the clamper is straight forward (provided that the clamping capacitance C_{CL} is much grater than the gate-to-source capacitance C_{GS1} of the switch S_1). When the driver voltage V_{DR} is low (0V) the gate voltage is $V_{G1} = V_{C2} - 2V_D = V_{S1} - V_D$ and the switch S_1 will be in the OFF state. The voltage of the clamping capacitor is $V_{CL} = V_{C2} - 2V_D$ that is at least 4V.

When the driver voltage is high ($V_{DR} \geq V_{S1}$) the gate voltage will be $V_{G1} = V_{DR} + V_{CL}$, while the source voltage is lower than V_{DR} so that $V_{GS1} \geq V_{CL}$ and the switch will be in the ON state.

The characteristics of the proposed converter were examined and compared with those of the original circuit using the PSPICE evaluation package. The simulated circuit with all n-channel MOS-transistors is shown in Fig. 3.

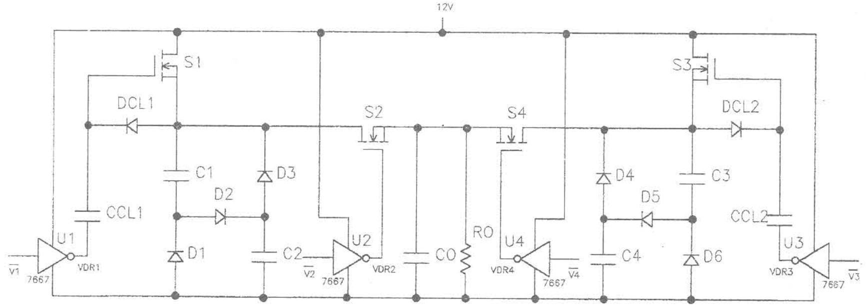


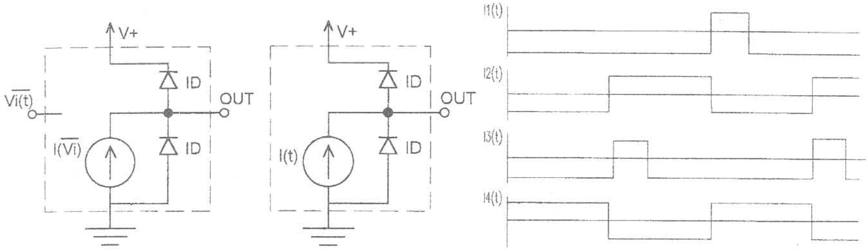
Fig. 3 Complete Modified Converter

III. THE PSPICE SIMULATION

SPICE simulators are proven tools for circuit analysis that give highly accurate results provided that the models and the analysis conditions are correct. The Student version of PSPICE that was used offered models for the n-channel (IRF9140) and p-channel (IRF150) power MOS switches and 1N4148 diode model (DCL1 and DCL2). Schottky diodes (D1-D6) were modeled according to the characteristics of SB830. A detailed model of the ICL7667 power MOS driver would not only exceed the limits of the Student version but also unnecessary complicates the circuit.

Therefore a simple model of ICL7667 was constructed based on its current driving and up-to-rail voltage driving capabilities. These are the main features that determine the transient and steady-state characteristics when driving the power MOS switch gate. The basic idea is represented in Fig. 4-a where the ID denotes an "Ideal Diode" and $I(V_I)$ a voltage dependent current generator whose current is +0.4A or -0.4A depending on the logic state of the input voltage V_I. The "Ideal Diode" is simply a diode with negligible voltage drop at current of 0.4A that is achieved by denoting its parameter N=0.01. This is further simplified (Fig. 4-b) by "integrating" the input time-dependent voltage generator and the voltage-dependent current generator into a time-dependent current generator that generates the appropriate waveforms

(Fig. 4-c). The waveforms shown are the start-up waveforms of the modified converter--for the basic converter, I1(t) and I3(t) should be inverted and the clamping circuits removed.



a) Basic Idea b) "Integrated" Model c) Modified-Converter Timing Diagrams

Fig. 4 The ICL7667 Model

The capacitor batteries (C1, C2 and C3, C4) consist of 47uF capacitance and 20mOhm series resistance while the output filter capacitor Co is 100uF capacitance and 10mOhm series resistance. The switching frequency is 87kHz. The 12V power supply includes 10mOhm internal resistance.

Transient analysis has been performed for both converters to investigate their efficiency, regulation domain (duty cycle D) and output ripple voltage with variable load and variable power supply voltage (Fig. 5, 6 and 7).

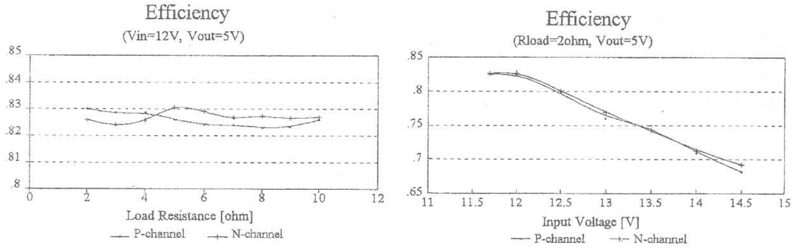


Fig. 5 Efficiency Comparative Diagrams

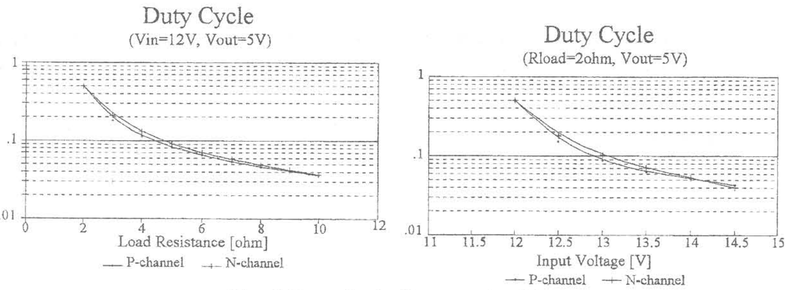


Fig. 6 Duty Cycle Comparative Diagrams

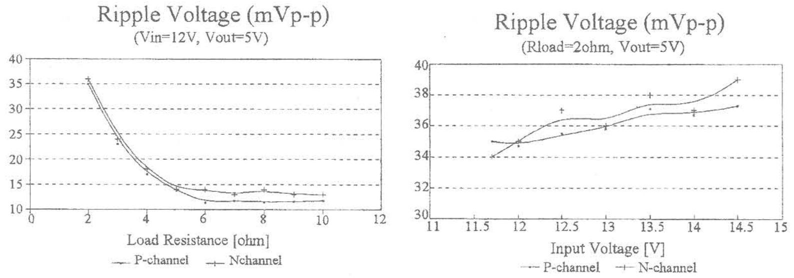


Fig. 7 Ripple Voltage Comparative Diagrams

It is obvious that the differences between the characteristics of the two configurations are negligible (within the calculation tolerances) which proves the validity of the proposed solution.

IV. CONCLUSIONS

New capacitor technologies promise wider range of implementations of switched capacitor power converters. Therefore new configurations of these converters and solutions of the problems within the existing ones are subject of scientific and engineering research and investigation. This article presents a modification of an existing configuration together with the solution of the N-channel MOS-switch driving problem. It also investigates the characteristics of the modified and the original configurations and proves the validity of the proposed solution using the widely accepted SPICE simulator.

V. REFERENCES

[1] *Technical Guide of Electric Double Layer Capacitors,* Matsushita Electronic Components Co. Ltd., Capacitor Division 1992

[2] S.V. Cheong, H. Chung, A. Ionovici, *Inductorless DC-to-DC Converter with High Power Density,* IEEE Transactions on Industrial Electronics, VOL.41, No.2, APRIL 1994, pp. 208-215

[3] *INTERSIL Component Data Catalog 1987*