Analysis of Continuously Scalable-Conversion-Ratio Switched-Capacitor DC-DC Converters

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Introduction

Conventional switched-capacitor (SC) dc-dc converters have limited voltage swing across capacitor terminals to reduce inherently charge sharing losses. Therefore, conventional SC converters have a specific capacitor voltage corresponding to the ideal voltage conversion ratio (VCR). Since VCR is closely related to efficiency, their output voltage ranges are limited. For a wide output voltage range, SC converters with multiple topologies are widely used, but there exists a low efficiency range between the optimal VCRs.

To overcome this disadvantage, a continuously scalable-conversion-ratio (CSCR) SC converter using the soft-charging method [1] has been proposed for buck conversion to reduce charge sharing losses. It maintains high efficiency over the wide range of VCRs. This work analyzes the unconventional current-source-like behavior of this new type of SC topology. The analysis is confirmed by the simulation of a CSCR SC converter of which the input voltage is 2V with different output voltage ranges.

Working Principle and Analysis

The flying capacitor is gradually charged and discharged through the soft charging per one cycle and this cycle is repeated to transfer the charge from the input node to the output node. Also, the soft charging is realized by adding intermediate M and N nodes for top side and bottom side, respectively. As more intermediate nodes are added, the converter behaves more like a current source [1]. The concept of CSCR SC converters of which each top and bottom side has 3 nodes (M=N=3) is depicted in Fig. 1, and the simulated result of voltage across a flying capacitor during a cycle is also represented in Fig. 2.

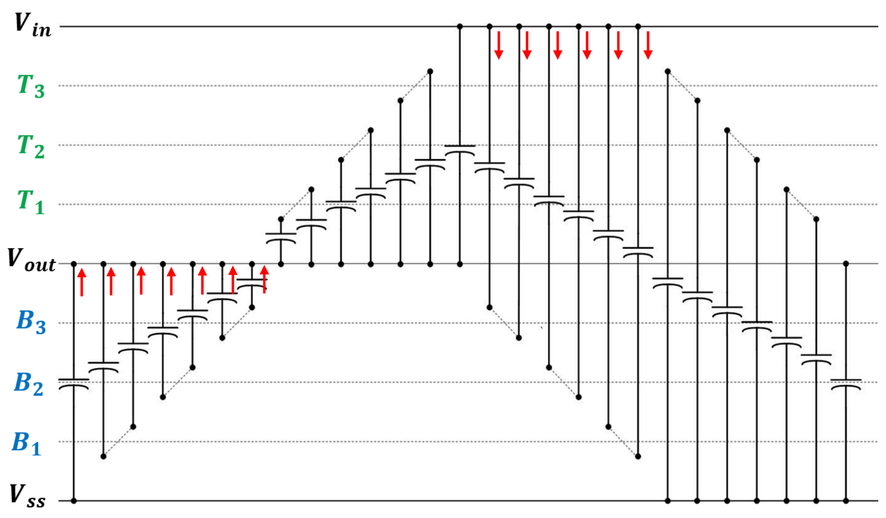

Fig. 1. Voltage versus phase diagram of a topology for buck conversion.

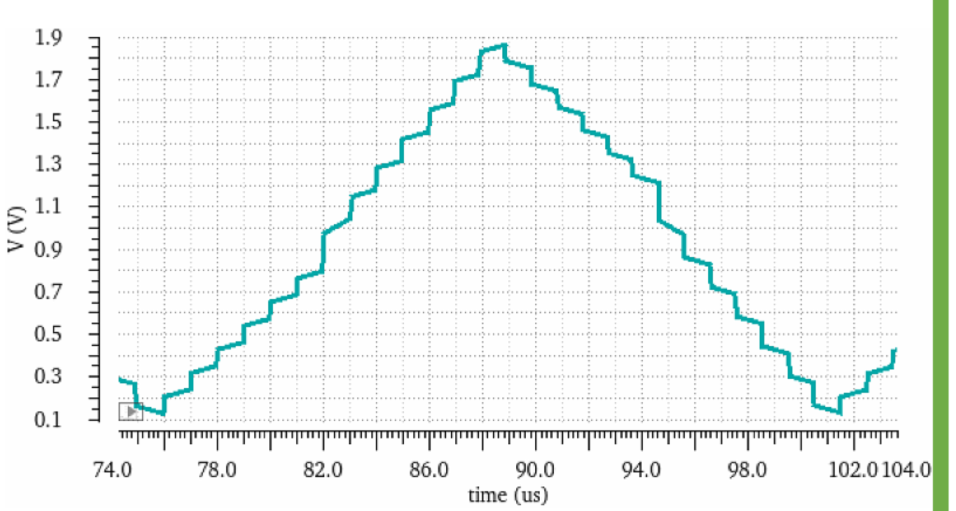

Fig. 2. Voltage across a flying capacitor for 2:1 VCR. (M=N=3)

As can be seen in Fig .1, the charge is continuously transferred to the output in one direction for buck conversion. Therefore, more charges are delivered into the output as the switching frequency increases, which means that output voltage increases when the load is connected as shown in Fig.3. However, regardless of the switching frequency, output voltage is saturated to a certain level when there is no load to the converter as illustrated in Fig. 4. This is because the polarity of a flying capacitor is reversed when intermediate node voltages are higher than V_{in}, so output current flows in both directions for one cycle as shown in Fig. 5. There is a steady-state point where the output voltage is no longer increasing. This result is in contrast with the previous result in Fig. 1. In Fig. 5, each top and bottom intermediate node voltage shares the same voltage level. It is attributed to using outphasing technique shown in [2]. Thus, to obtain proper output voltage as depicted in Fig. 6, feedback control is required.

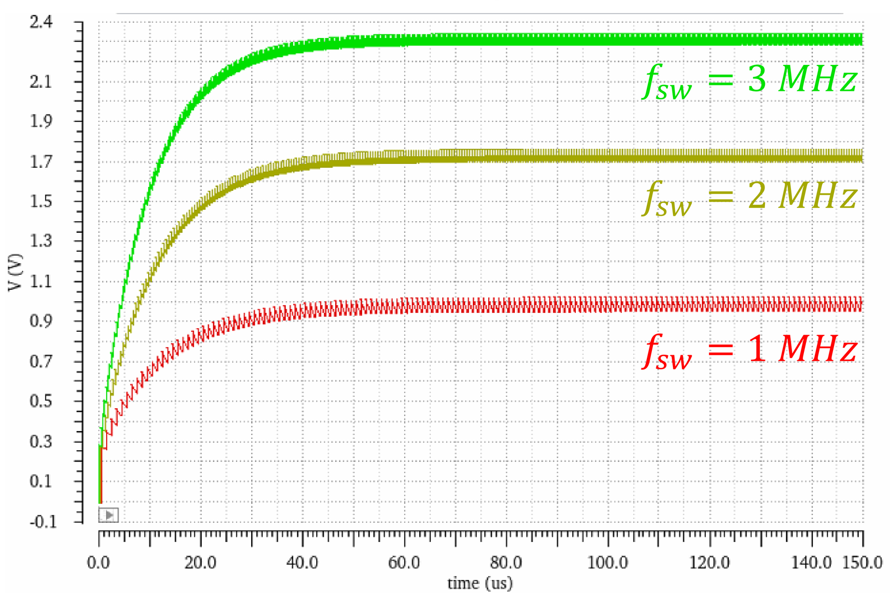

Fig. 3. Output voltage according to switching frequency (f_{sw}) when the load is 10 $k\Omega$. (M=N=3)

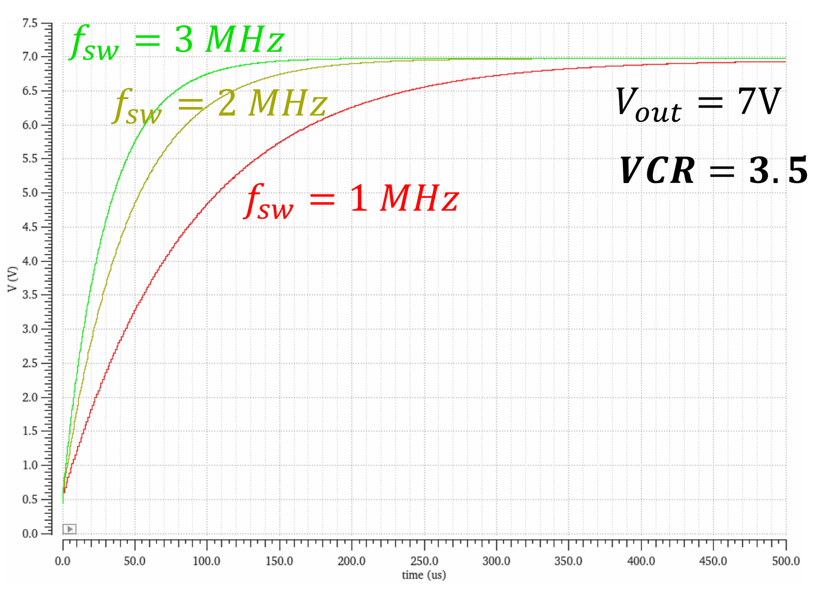

Fig. 4. Output voltage according to switching frequency (f_{sw}) without the load (M=N=3)

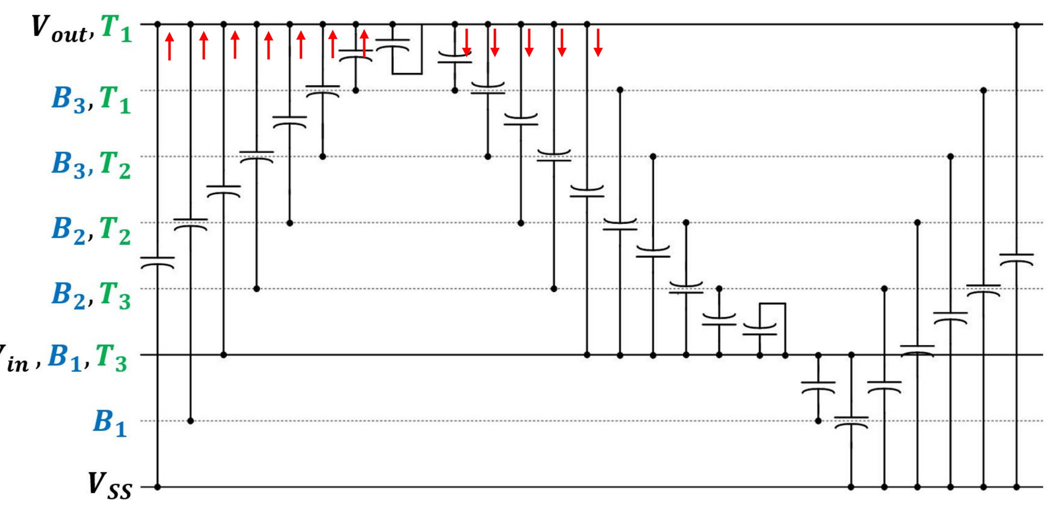

Fig. 5. Voltage versus phase diagram of a topology for boost conversion

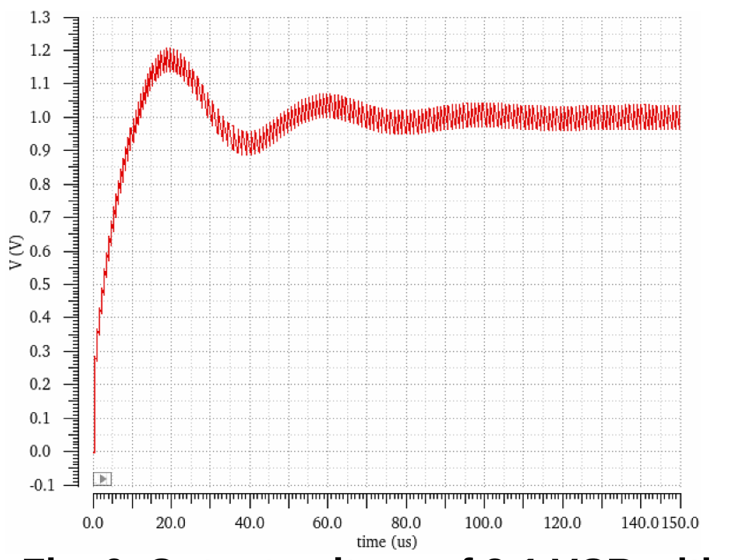

Fig. 6. Output voltage of 2:1 VCR with feedback control.

The simulated result for more intermediate nodes (M=N=5) is also presented in Fig. 7 and Fig. 8. In this case, the output saturation voltage is higher than the previous result (M=N=3). Especially, it is much higher when the load is disconnected. This characteristic can be interpreted as follows.

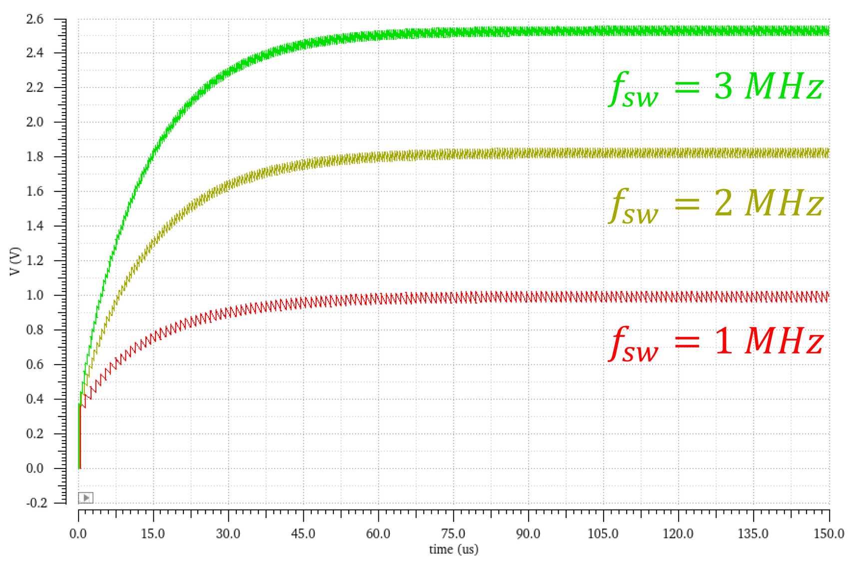

Fig. 7. Output voltage according to switching frequency when the load is 10 $k\Omega$. (M=N=5)

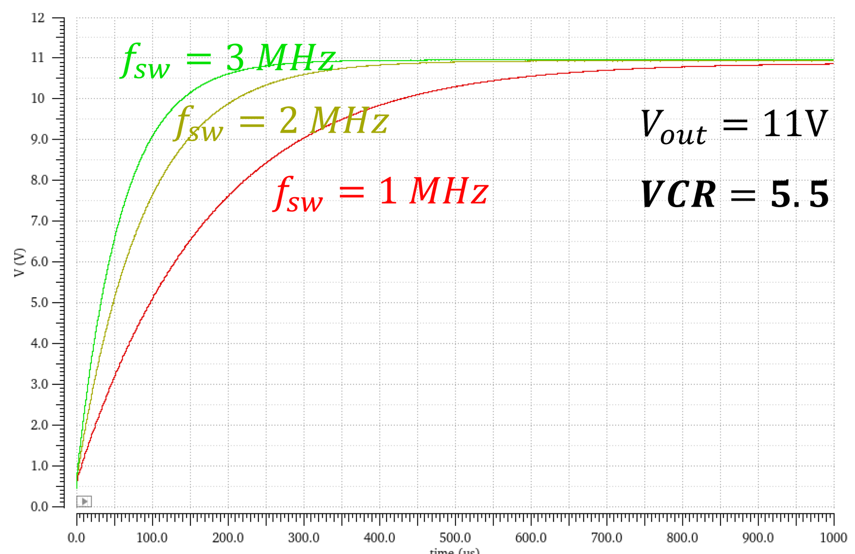

Fig. 8. Output voltage according to switching frequency without the load (M=N=5)

Fig. 9. shows the relationship between VCR and load current. The slope of graph corresponds to the reciprocal of the output impedance. The larger number of intermediate nodes (M, N) is, the larger value of output impedance is. It can be confirmed by comparing the magnitude of slope in Fig. 9. (a) and (b). It means that a large number of intermediate node converters behave more like a current source as explained in [1]. On top of that, zero-crossing points in Fig. 9. correspond to the maximum VCR in Fig. 4 and Fig. 8, respectively because the output voltage is maximum when there is no load. The output impedance of the converter is infinite in this analysis, so the output voltage is saturated to a specific value under no-load condition regardless of switching frequency.

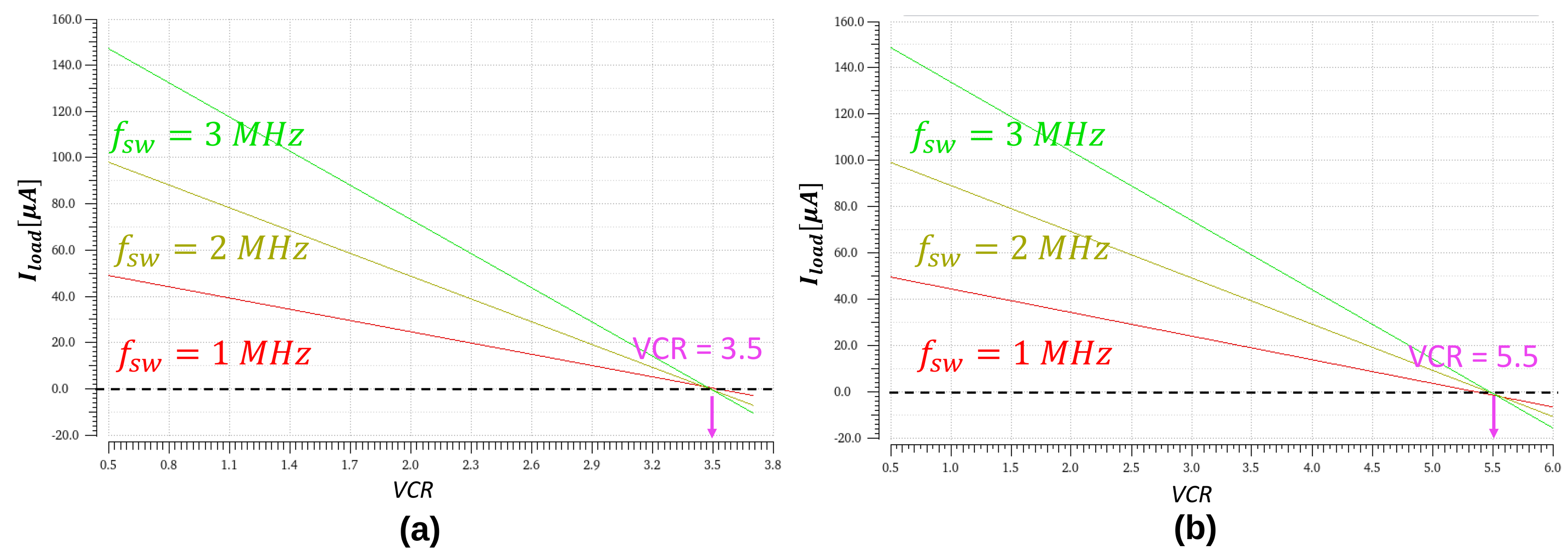

Fig. 9. Output current versus VCR for scaling switching frequency (f_{sw}) (a) M=N=3 (b) M=N=5 .

Conclusion

This poster reviews the characteristics of CSCR SC converter topology. Its working principle and current source behavior are analyzed. In particular, its current source behavior is verified by transient simulation of the converter with and without the load over the wide range of VCRs.

References

[1] N. Butzen and M. Steyaert, "Design of Single-Topology Continuously Scalable-Conversion-Ratio Switched- Capacitor DC–DC Converters," in IEEE Journal of Solid-State Circuits, vol. 54, no. 4, pp. 1039-1047, April 2019

[2] N. Butzen and M. S. J. Steyaert, "Design of Soft-Charging Switched-Capacitor DC–DC Converters Using Stage Outphasing and Multiphase Soft-Charging," in IEEE Journal of Solid-State Circuits, vol. 52, no. 12, pp. 3132-3141, Dec. 2017

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