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An Asynchronous-Switched-Capacitor DC-DC Converter Based on GaN and SiC Devices
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Summary
For the state-of-the-art switched-capacitor DC-DC converters at high-voltage low-power levels, switching loss becomes a major concern and challenge. Existing switching schemes operate power semiconductors at a single common frequency, which does not optimally address the switching losses, especially for a high-conversion-ratio design. This paper presents a concept of Asynchronous-Switched-Capacitor (ASC), which is applied to the GaN switches that are combined with the SiC diodes to improve the efficiency and the power density. The ASC operation is named when the switches can be operated with uncorrelated frequencies, with unnecessary phase/clock synchronization of the control signals. A 380 V, 6 W, 4:1 conversion ratio converter experimentally validates the concept. The efficiency is improved by 4% and the peak-to-peak output voltage ripple is reduced by 39%, with the proposed ASC switching, compared to the conventional switching. A peak efficiency of 95.4% is achieved.

Motivation
Switched-capacitor DC-DC converters are commonly implemented on integrated circuits (IC)\(^1\). Theses converters are either limited by the input voltage (\(\leq 12\) V) and/or the output power (\(\leq 2\) W). Recent research demonstrates switched-capacitor converters using discrete components with an input voltage up to 200 V and output powers of 30-53 W\(^2,3\). At higher characteristic impedance (higher-voltage, lower-current) levels, new designs and concepts are anticipated to emerge. This paper presents a 380 V input voltage, 6 W output power, 4:1 conversion ratio switched-capacitor DC-DC converter (see Fig. 1), and proposes the concept of Asynchronous-Switched-Capacitor (ASC). The switching losses of the switches related to charging and discharging the output capacitances are calculated as follows. It shows that the switching losses are not evenly distributed with the conventional switching at a single common frequency. Furthermore, the optimum switching frequencies depend on the current level hence the characteristic impedance level, for a given energy transfer capacitance. This motivates the proposed ASC concept, which mitigates the requirements of the control signals with high tolerance of phase-shifts.

\[
\begin{align*}
P_{sw,cost,total} & \equiv f_{Q1,Q2} \cdot V_{IN} \cdot \int_0^{V_{IN}/2} c_{oss}(V_{DS}) \cdot dV_{DS} + f_{Q3,Q4} \cdot (V_{IN}/2) \cdot \int_0^{V_{IN}/4} c_{oss}(V_{DS}) \cdot dV_{DS}
\end{align*}
\]

Results
A high-voltage low-power switched-capacitor DC-DC converter experimentally validates the proposed ASC switching. The efficiency (see Fig. 2 and Fig. 3), the thermal performance (see Fig. 4) and the output voltage ripple (see Fig. 5) are improved. The measured peak slew rates of the GaN (EPC2012C) and SiC (C3D1P7060Q) devices in the operating converter (see Fig. 6) are about 90 V/ns and 80 V/ns, respectively, which also enhance the performance of the converter, with switching frequencies as low as 1 kHz. All experimental work is finished and will be presented in the final paper.

Figures

Fig. 1: Proposed asynchronous-switched-capacitor DC-DC converter (4:1 conversion ratio). Wide-bandgap devices are highlighted.

Fig. 2: Measured efficiency versus switching frequency of Q3 and Q4, while Q1 and Q2 are operated with a constant frequency of 1 kHz.

Fig. 3: Measured efficiency versus output power. The phase-shift is defined as Q3/Q4 referred to Q1/Q2 when Q1-Q4 have the same frequency. The asynchronous is measured with Q3/Q4 at 4 kHz and Q1/Q2 at 1 kHz (unnecessarily multiple times of each other).

Fig. 4: Thermal image (°) of the prototype asynchronous-switched-capacitor converter. Measured after one hour full-power operation, without heatsink or airflow.

Fig. 5: Waveforms of the output voltage (AC-coupling) versus the asynchronous control signals. The phases/clocks are not necessarily synchronized. The peak-to-peak output voltage ripple is reduced by 39% compared to conventional switching.

Fig. 6: Measured turn-on transients. Peak slew rates of GaN Q2 and SiC D2 are about 90 V/ns and 80 V/ns, respectively. RTO-1024 2 GHz oscilloscope, RT-ZP10 500 MHz probes, and 1 kHz switching frequency.