

A High Step-Down Hybrid Switched-Capacitor DC-DC Converter for High Voltage Space Applications

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Abstract—Future space power systems require advancements in power conversion to overcome mass and efficiency constraints in harsh operating environments. Applications including lunar power distribution and extreme planetary exploration seek to transmit power at high DC voltages to minimize resistive losses and cable mass over extended distances. This distribution architecture requires compact DC-DC converters capable of high step-down conversion ratios. This paper presents a light-weight hybrid switched-capacitor (HSC) DC-DC converter tailored to this application space. The proposed converter topology stacks Dickson switched-capacitor cells to process an 800 V input bus while keeping per-device voltage stress at a fraction of the bus voltage. A subsequent multi-phase buck stage provides output voltage regulation and acts to soft-charge the preceding Dickson stage. Both buck and Dickson stages are synchronized so as to enable assistive resonant-charge-redistribution (RCR) circuitry which imposes zero-voltage switching (ZVS) across all switches within the Dickson stage, improving conversion efficiency and reducing overshoot and ringing. The use of Gallium Nitride devices further improves susceptibility to radiation effects. To validate the proposed topology, we present a discrete hardware prototype weighing 128 g and achieving an output power of 420 W while performing 800 V to 28 V conversion at a 250 kHz switching frequency and yielding a measured power density of 3.28 kW/kg.

Index Terms—hybrid switched-capacitor converter, Dickson converter, zero-voltage switching, resonant charge redistribution, gallium nitride, space power systems, high step-down conversion

I. INTRODUCTION

High voltage, large step-down power converters are a key enabling technology for a range of proposed space missions, including DC tether systems for the robotic exploration of extreme planetary terrains, such as vertical lunar pits, permanently shadowed craters, and steep Martian slopes. Here, electrical power is delivered over a lightweight cable which serves as a dual-use anchor system, simultaneously providing mechanical support for descent and retrieval while acting as the sole energy conduit to the mobile platform. Since resistive cable losses scale with the square of the transmitted current, higher-voltage transmission greatly lowers conduction losses and allows the use of a much thinner, lighter cable

for a given delivered power. For a fixed power budget, a tenfold increase in distribution voltage reduces conductor cross-section by approximately two orders of magnitude at equivalent loss, a scaling relationship that becomes decisive when tether mass dominates the deployable system budget. This architecture, demonstrated by NASA's Moon Diver concept and the TYMPO project, enables efficient power delivery over distances ranging from hundreds of meters to several kilometers while keeping the tether spoolable and mass-minimal [1], [2]. However, it places the full power-conversion burden on the rover, which must step down the high-voltage tether bus to load-compatible levels within strict mass and volume constraints, and must do so while surviving the thermal cycling, vacuum, and radiation conditions characteristic of the destination environment.

Designing such systems for space radiation environments introduces fundamental semiconductor constraints that distinguish them from their terrestrial counterparts. Single-event burnout (SEB), triggered by heavy-ion strikes within the depletion region of a blocking device, is the dominant failure mechanism in power transistors, with susceptibility increasing significantly at higher device voltage stress [3], [4]. Unlike total ionizing dose (TID) effects, which manifest as gradual parametric drift and can be budgeted over mission life, SEB is a destructive single-shot failure, so mitigation must be structural rather than statistical. GaN HEMTs offer inherent radiation advantages over silicon, with reduced TID and SEE susceptibility owing to the wider bandgap and the absence of a gate oxide, making them attractive for space power electronics [5], [6]. However, even space-grade GaN devices must be operated well below their rated voltage to maintain acceptable SEB margins [2], with derating factors of two or more commonly imposed. This requirement poses a direct challenge for conventional high-voltage isolated topologies, such as LLC-resonant and full-bridge converters, in which the blocking devices see the full bus voltage and therefore require switch voltage ratings unavailable in flight-qualified, radiation-hardened form [7].

Hybrid switched-capacitor (HSC) converters offer a struc-

tural solution to this constraint. In particular, ladder and Dickson-type HSC architectures [8], [9], [10] distribute the high-side voltage across a multilevel switch stack, ensuring per-device stress remains a fixed fraction of the bus voltage set by the conversion ratio rather than by the bus voltage itself. This yields a natural derating compatible with radiation requirements and permits the use of mature, low-voltage GaN devices whose SEB behavior is comparatively well characterized. Moreover, this architectural approach enables substantial reductions in passive-component volume and mass, which is especially beneficial for weight-constrained hardware. Here, capacitors are used as the primary passive energy-storage element, where capacitors have energy densities that can be more than $1000\times$ greater than that of comparably rated magnetics [11]. To maintain voltage regulation and efficient soft-charging operation [12], some magnetic elements are still required, but these may now be greatly reduced in size since the switched-capacitor network assumes the majority of the energy conversion burden. Section II presents a new HSC converter topology comprising a stacked Dickson stage merged with a multi-phase buck converter, tailored for light-weight high voltage DC power distribution (Fig. 1). Section III describes an assistive resonant charge redistribution (RCR) technique which exploits the free-wheeling intervals of the buck stage to enable coordinated zero-voltage-switching (ZVS) throughout the Dickson stage at negligible mass cost. Section IV validates the proposed topology in hardware and compares it with prior art. Section V concludes this work.

II. PROPOSED TOPOLOGY

This work proposes a new hybrid switched-capacitor power converter topology for high-ratio step-down voltage conversion, with relevance to systems interfacing high-voltage distribution buses with regulated 48 V or 28 V loads. Depicted in Fig. 1, it comprises an initial Dickson-type switched-capacitor stage, merged with a subsequent multi-phase buck converter. The Dickson stage performs the bulk of the voltage transformation at a fixed ratio, allowing the following buck stage to operate across a narrow conversion range where its inductor volt-second product, and hence its magnetic volume, remains small. The Dickson stage is drawn segmented into an upper and lower half, with the Dickson and buck grounds loosely coupled by a high impedance path to accommodate a split-rail $\pm HV$ input. This partitioning halves the peak potential appearing at either extremity of the capacitor stack relative to the buck ground, reducing overall capacitor voltage stress and permitting the use of smaller, lower-rated ceramic devices whose effective capacitance degrades less severely under DC bias.

For an even N^{th} order switched-capacitor network, flying capacitors within the upper half store approximate voltages of

$$V_{C,i}^{\text{upper}} = \frac{(N - 2i + 1)V_{\text{IN}}}{2N}, \quad i = 1, 2, \dots, \frac{N}{2} \quad (1)$$

while capacitors in the lower half store approximately

$$V_{C,i}^{\text{lower}} = \frac{-(2i - 1)V_{\text{IN}}}{2N}, \quad i = 1, 2, \dots, \frac{N}{2} \quad (2)$$

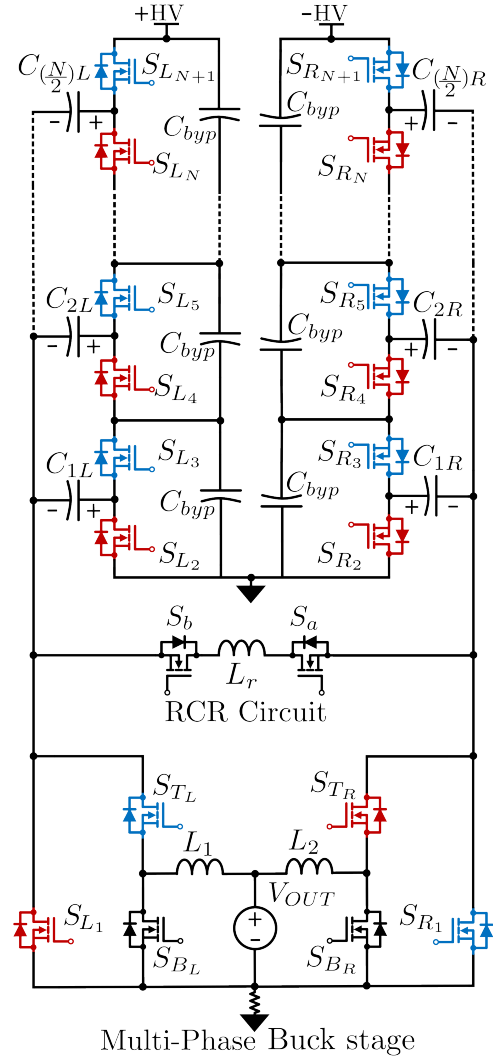


Fig. 1: Schematic of the proposed Dickson HSC converter with merged multi-phase buck stage. Added RCR circuitry enables ZVS operation of the Dickson during the buck's freewheeling intervals.

Under these distributions, the voltage difference imposed across any single switch is bounded by V_{IN}/N , so that increasing the network order proportionally relaxes the per-device blocking requirement and provides the derating margin sought in Section I. In practice, capacitor voltages shift in accordance with amp- and volt-second balance constraints arising from the decoupling of a common ground (analysis omitted here).

The proposed converter's phase progression is depicted in Fig. 2. The Dickson stage is active during phases 1 and 3, which are set equal in duration for uniform charge flow through its switched-capacitor network (charge flow direction annotated). The buck converter comprising inductor L_1 is driven high during phase 1, whereas L_2 is driven during phase 3, providing 180° interleaved outputs and a maximum allowable duty cycle of 50% to avoid phase overlapping

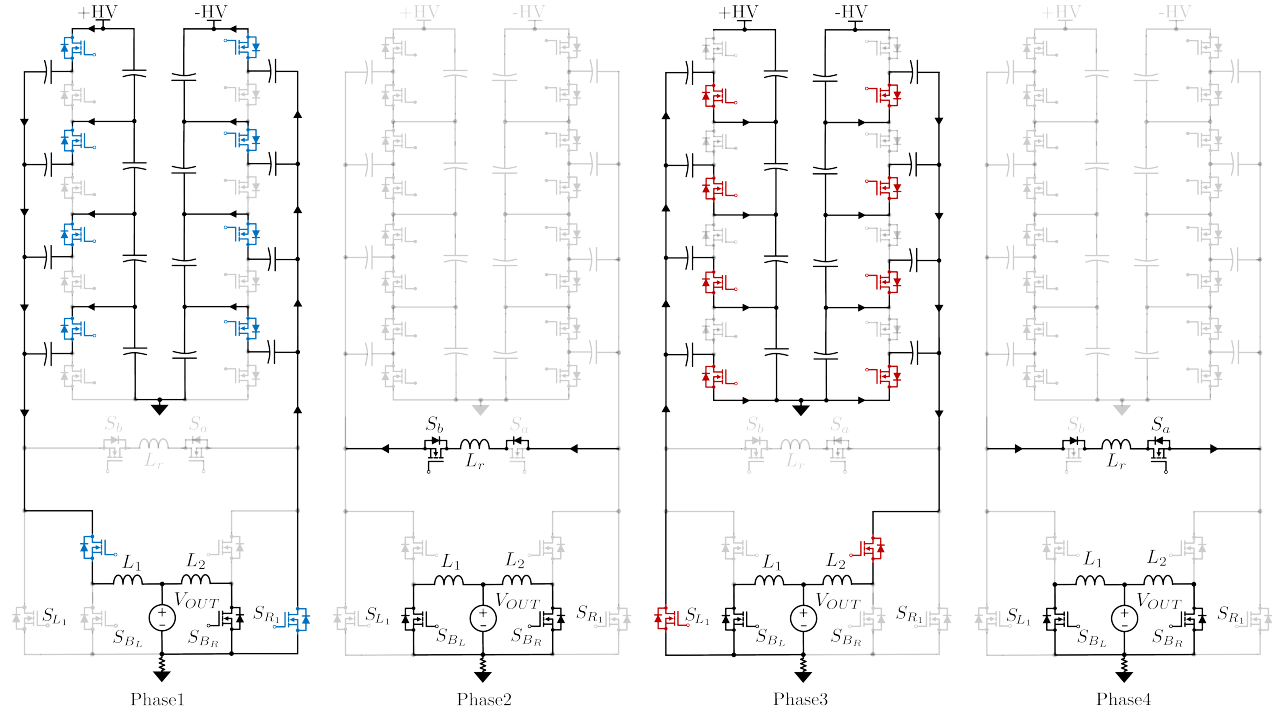


Fig. 2: Phase progression of the proposed HSC Dickson topology with merged multi-phase buck stage. The Dickson stage is active during phases 1 and 3 and enters a high impedance state during phases 2 and 4. Two interleaved buck converters both free-wheel during phases 2 and 4, whose relative phase durations may be adjusted to affect PWM voltage regulation. The RCR inductor L_R resonates with the net $C_{OSS,eq}$ output capacitance of all switches within the Dickson network during free-wheeling phases 2 and 4 to pre-condition them for ZVS (discussed in Section III).

within the Dickson stage. Because each buck phase draws its input current directly through the switched-capacitor network while that network is active, the inductors additionally serve to soft-charge the flying capacitors, suppressing the charge-sharing losses that otherwise dominate conventional switched-capacitor operation in the slow-switching-limit (SSL). Both buck converters free-wheel during phases 2 and 4, where the relative duration of these phases can be varied relative to the phases 1 and 3, for conventional PWM voltage regulation. These intervals leave the Dickson stage electrically idle, a condition that Section III exploits for zero-voltage switching.

III. RESONANT CHARGE REDISTRIBUTION (RCR) FOR ZERO-VOLTAGE-SWITCHING

Noting that the Dickson stage enters a high-impedance state during phases 2 and 4, an auxiliary resonant charge redistribution (RCR) circuit may be used to adiabatically (dis)charge the net C_{OSS} switch capacitance of all switches within the Dickson stage, resulting in zero-voltage switching (ZVS) of Dickson switches come the start of phases 1 and 3. As exemplified in [13], [14], this technique significantly reduces switching losses and associated voltage overshoot and ringing.

Fig. 3 depicts the parasitic circuit model relevant for RCR interactions during phases 2 and 4. In order to achieve ZVS operation, switches S_a and S_b , and inductor L_r are added as shown. Here, inductor L_r serves to adiabatically redistribute

the charge stored on switch C_{OSS} capacitances during free-wheeling phases 2 and 4, eliminating the hard-charged CV^2f switching losses within the Dickson stage. Since L_r interacts only with switch parasitics rather than the main power path, it can be kept very small while maintaining a high Q-factor, occupying a near-negligible fraction of total converter volume [13]. The equivalent capacitance, $C_{OSS,eq}$, presented to L_R is deduced by the series-parallel combining of surrounding C_{OSS} switch capacitance, where the flying capacitors present negligible impedance ($C_{L/R} \gg C_{OSS}$) and may be treated as AC short circuits:

$$C_{OSS,eq} = \frac{10 C_{OSS} \times 10 C_{OSS}}{10 C_{OSS} + 10 C_{OSS}} = 5 C_{OSS} \quad (3)$$

Consequently, when activated, L_r resonates with half-period $t_r = \pi \sqrt{L_r C_{OSS,eq}}$, establishing the minimum required duration of phases 2 and 4 to achieve full ZVS. Fig. 4 depicts measured waveforms illustrating the drain-to-source voltages of S_{L1} , S_{B_L} , S_{B_R} and S_{R1} , both with and without RCR enabled.

IV. HARDWARE PROTOTYPE AND EXPERIMENTAL RESULTS

Fig. 5 depicts an 800 V-to-28 V hardware prototype constructed to validate the proposed topology, and Table I summarizes the primary hardware components. Despite an 800 V

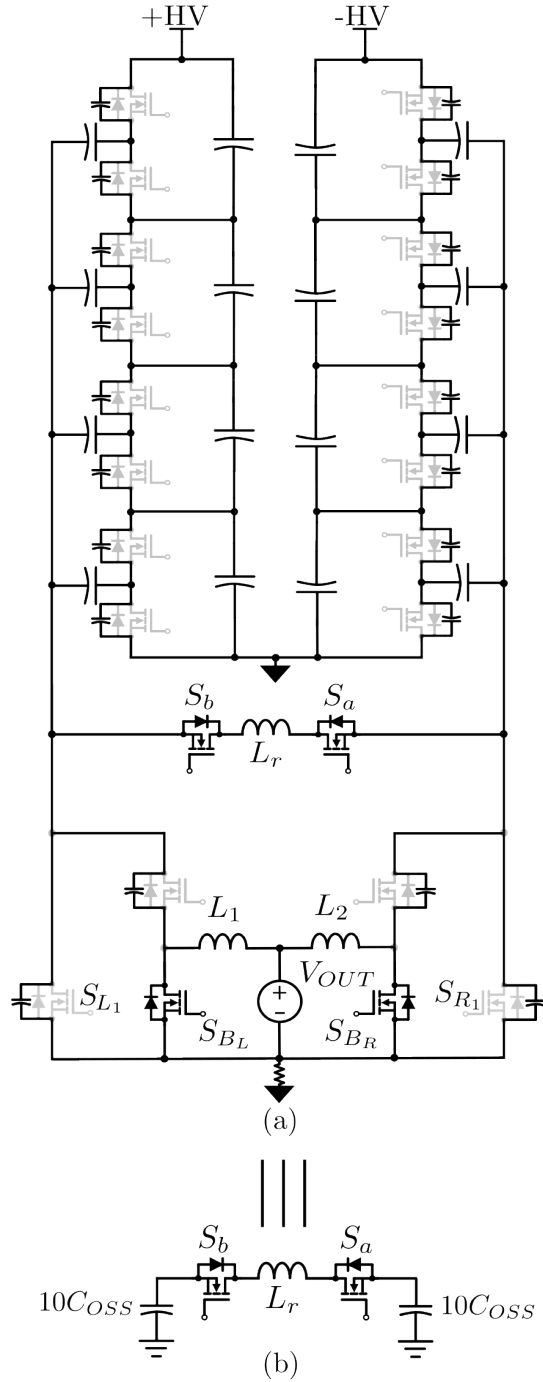
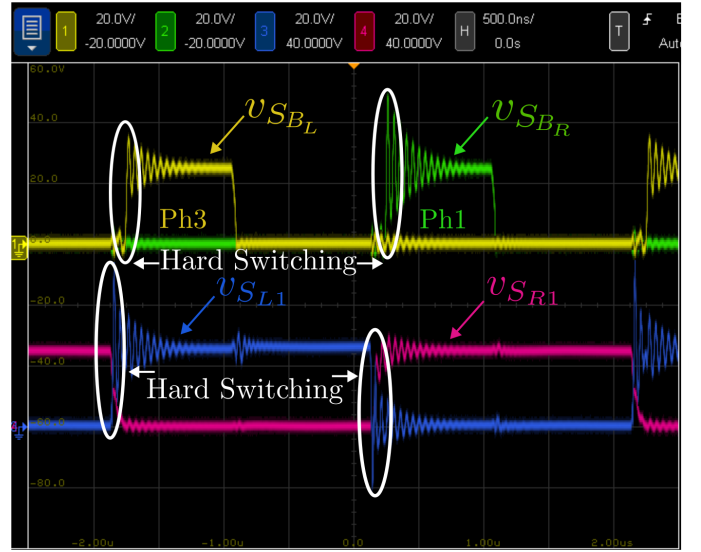
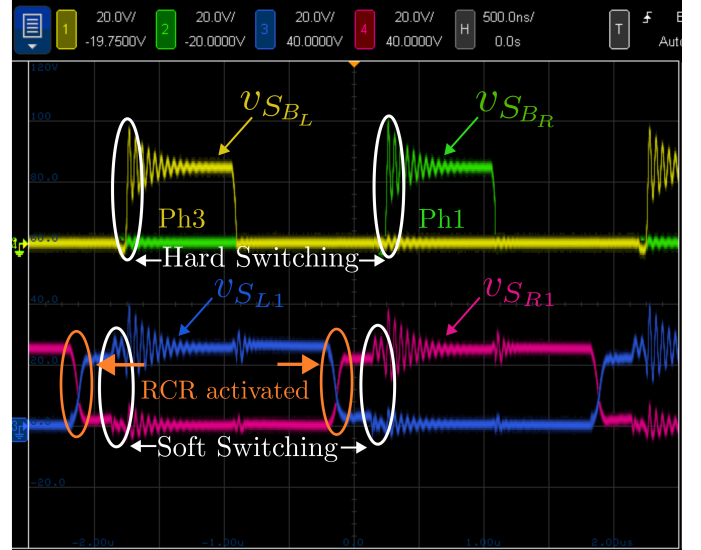


Fig. 3: (a) Parasitic circuit model during phases 2 and 4. (b) Simplified AC equivalent model.

input bus, the power stage is implemented entirely with 150 V-rated EPC2305 GaN devices, where each switch is required to block only a fraction of the input voltage—consistent with the stress distribution indicated by (1) and (2). This confines every device to a blocking voltage well within the derating margins discussed in Section I. Flying capacitance is realized using class II ceramic devices selected with substantial voltage headroom above their nominal operating point, since the effective



(a) Without RCR



(b) With RCR

Fig. 4: Measured waveforms comparing switch voltages (a) without resonant charge redistribution (RCR) and (b) with RCR, illustrating pre-(dis)charging of switch C_{OSS} capacitance for ZVS at, $V_{IN} = 200$ V, $V_{OUT} = 5$ V, $I_{OUT} = 2.5$ A.

capacitance of such dielectrics falls appreciably under DC bias. The overall converter weighs 128 grams, corresponding to a gravimetric power density of 3.28 kW/kg when operating at a maximum power output of 420 W.

Fig. 6 presents a thermal image of the prototype at the same operating point, captured once the converter had reached thermal steady state. Fig. 7 presents measured results obtained from this prototype at $V_{IN} = 800$ V, $V_{OUT} = 28$ V, and $I_{OUT} = 10$ A. In Fig. 7(a), each flying capacitor settles at a distinct steady-state level corresponding to its position within the stack, confirming that the network maintains the in-

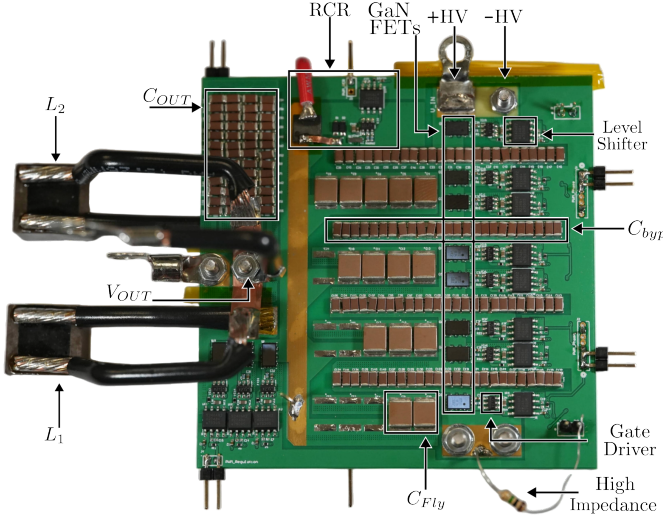


Fig. 5: Photograph of the fabricated 420 W prototype of the proposed 800 V-to-28 V Dickson HSC converter with merged multi-phase buck regulation stage.

TABLE I: Primary Component Details

Component	Details	Part Number
C_{fly}	2.2 μ F, 450 V	28 $\times$ C5750X6S2W225K250KA
C_{bypass}	10 μ F, 100 V	200 $\times$ C3216X6S2A106K160AC
C_{OUT}	10 μ F, 100 V	104 $\times$ C3216X6S2A106K160AC
Dickson & Buck FETs	150 V, 20 m Ω	22 $\times$ EPC2305
L_1, L_2	10 μ H, 20 A	2 $\times$ Coilcraft XAL1513-153MED
Gate Driver	5 V, 5/0.83 Ω source/sink	LM5114
Isolated Level Shifter	5 V, 2.5 kV isolation	ADUM5240
L_R (RCR)	100 nH, 10 A	Coilcraft SLR1065-121KEC
RCR FETs	200 V, 22 m Ω	2 $\times$ EPC2207
RCR Diodes	120 V, 2 A	4 $\times$ V2PM12HM3

tended voltage distribution without active balancing circuitry. Fig. 7(b) shows the buck and Dickson switch-node voltages together with both buck inductor currents; are displaced by 180°, confirming correct interleaved operation. Fig. 7(c) reports measured efficiency with RCR enabled, evaluated both with and without gate-driver losses. The distinction matters for this converter class, since the large number of series-stacked devices imposes a gate-drive burden that is largely fixed with respect to load; a peak power-stage efficiency of 92.96% and a peak system efficiency of 90.66% are measured, the gap between them quantifying this overhead.

Table II compares the constructed prototype with similar recent high step-down converter demonstrations targeting space applications. The proposed converter operates at 250 kHz, appreciably higher than the comparison designs, which is what permits the reduction in magnetic volume underlying its

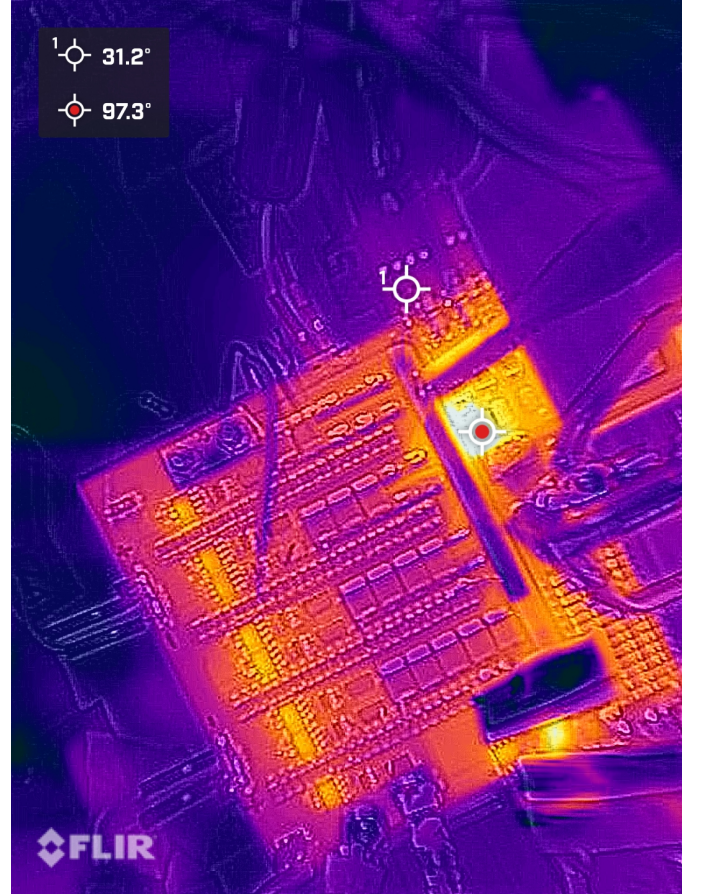


Fig. 6: Thermal image of the prototype at thermal steady state, at $V_{IN} = 800$ V, $V_{OUT} = 28$ V, $I_{OUT} = 10$ A.

mass advantage. It achieves a gravimetric power density of 3.28 kW/kg, more than three times that of the closest reported figure, while supporting the largest conversion ratio among the surveyed works.

V. CONCLUSION

This work presents a hybrid switched-capacitor converter topology with large step-down voltage conversion ratios for high voltage space applications. It features a fixed-ratio Dickson stage merged with a multi-phase buck stage for soft-charging operation and PWM voltage regulation. Auxiliary resonant charge redistribution (RCR) is employed to enable zero-voltage switching (ZVS) throughout the Dickson stage, further alleviating switch stress. A hardware prototype implemented with low voltage Gallium Nitride switches demonstrates effective operation with 800 V input and 28 V output while driving 420 W and achieving a high gravimetric power density of 3.28 kW/kg.

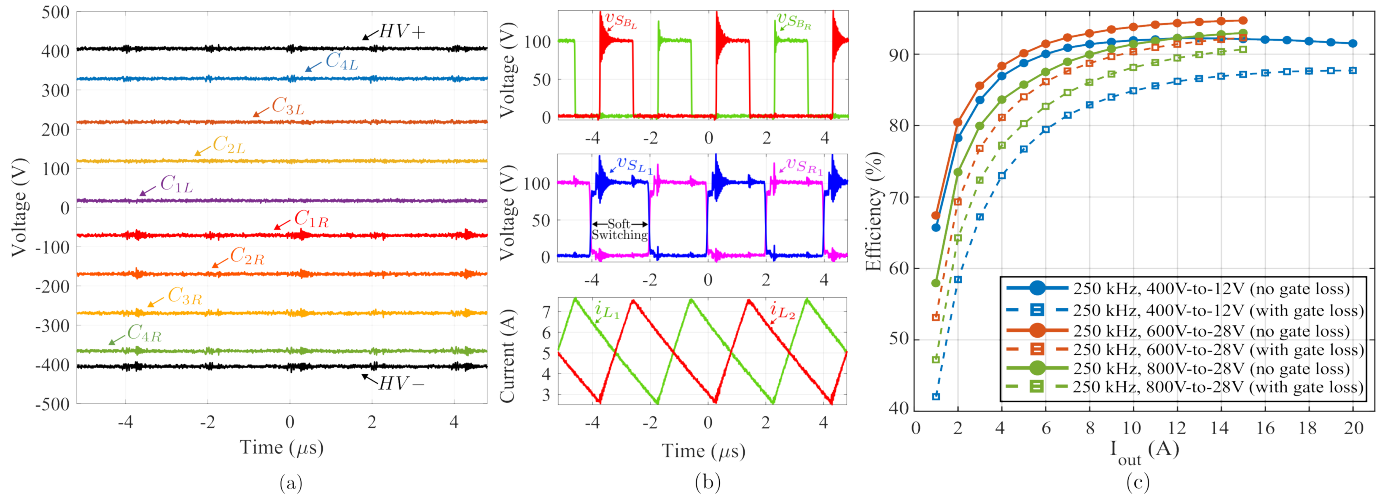


Fig. 7: Experimental hardware measurements of the proposed high-voltage Dickson converter prototype: (a) measured flying capacitor voltages for $V_{IN} = 800$ V, $V_{OUT} = 28$ V, $I_{OUT} = 10$ A, (b) measured buck and Dickson switch-node voltage waveforms along with both buck inductor currents for $V_{IN} = 800$ V, $V_{OUT} = 28$ V, $I_{OUT} = 10$ A, and (c) measured efficiency at different operating points with resonant charge redistribution (RCR) enabled, evaluated both with and without gate-driver losses.

TABLE II: Comparison With State-of-the-Art High Step-Down Converters for Space Applications

Year	Topology	f_{sw}	V_{IN}	V_{OUT}	$I_{OUT,MAX}$	Power Density	Power Stage Efficiency	System Efficiency
2024 [15]	T-type LLC	83 kHz	650–950 V	48 V	11 A	–	–	Peak: 96.5%
2025 [7]	Full Bridge	100 kHz	350–450 V	28 V	14 A	–	–	Peak: 90.2%
2025 [9]	Composite FCML + Rez-Dickson	107 kHz	750 V	50 V	6.5 A	1.02 kW/kg	–	Peak: 96.7%
This Work	ZVS-Dickson + Multi-phase Buck	250 kHz	800 V	28 V	15 A	3.28 kW/kg	Peak: 92.96%	Peak: 90.66%

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