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Miniaturized Solid-State Battery-Based DC-DC Switched Converter

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Abstract— Designing efficient, compact DC-DC converters for ultra-low power applications (below mW) is challenging, primarily due to significant switching losses. In contrast to switched-capacitor converters, switched-battery converters (SBCs) have recently emerged as a solution capable of maintaining high efficiency even at ultra-low frequencies (in the Hz range), while still achieving reasonable power density. However, initial SBC demonstrations relied on button cell batteries, which limited practical adoption in compact systems. This paper presents the first experimental demonstration of an SBC utilizing a solid-state battery, resulting in a reduced footprint. We achieve a power density of $0.34\text{mW}/\text{mm}^3$ with 95% peak efficiency using a 0.33mm^3 battery while maintaining less than 3.1% output relative ripple without any output capacitor. Furthermore, the paper highlights the favorable scaling laws governing SBCs, suggesting a promising design space for IoT power management.

Keywords— switched-battery converter, solid-state battery, ultra-low switching frequency, low power

I. INTRODUCTION

Power management in IoT devices is challenging due to a limited power budget encompassing switching losses, conduction losses, and quiescent control-circuitry consumption. In milli-watt power range, switched capacitor converters (SCC) are common for their good compromise between power-density and efficiency [1], [2], [3]. Using SCC, one viable approach to meet the efficiency requirements is reducing the switching frequency f_{sw} to minimize switching losses. An examination of existing literature on fully-integrated SCC (blue dots in Fig. 1) reveals a correlation between switching frequency and output power.

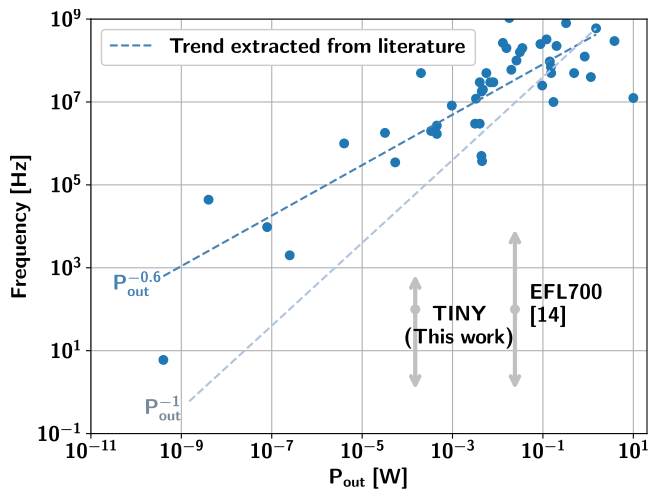


Figure 1 : Operating frequency versus output power practical tradeoff

However, SCC power density is primarily associated with the capacitance density σ_C offered by the silicon technology and the switching frequency for a targeted output impedance [4]. As shown in Fig. 1, the trend towards lower f_{sw} at low

power levels results in reduced SCC power density for a given technology (with σ_C held constant). To address this trade-off, a switched-battery converter (SBC) was recently introduced in [4]. SBC maintains a near-constant output impedance, allowing to operate at extremely low switching frequencies. In [5], SBC is shown to be capable of delivering output power in the tens of milliwatts range at a switching frequency of 1 Hz, a notable shift away from the MHz range, typically associated with SCCs in Fig. 1. However, it serves as a proof-of-concept using off-the-shelf batteries at the mm^3 scale, which limits the widespread adoption of SBC in compact systems. Recent advancements in solid-state batteries (SSB), as summarized in Table 1, hold the potential to further reduce the size of SBC and enhance its packaging compatibility with IC companion. The primary objective of this paper is to assess the feasibility of scaling down SBC performance (reducing its footprint while not compromising power capacity) using these emerging batteries (as depicted by the grey lines in Fig. 1).

TABLE I. COMPARISON OF SOLID-STATE μ -BATTERIES REFERENCES

Battery reference	Unit	EFL700 [6]	CERACHARGE [7]	TINY [8]
Volume	mm^3	145	15.8	0.33
Footprint	mm^2	660	14.4	3.7
Nominal voltage	V	3.9	1.4	3.9
Capacity	μAh	700	100	20
Volumetric Capacity	$\mu\text{Ah} \cdot \text{mm}^{-3}$	4.8	6.3	60.6
Internal resistance	Ω	100	200	$2 \cdot 10^4$
Rated current	μA	1.10^4	20	>30

Table 1 provides a performance overview of Solid-State Batteries (SSB) across three decades of volume and compares them to one of the batteries used in [5]. Although SSBs have capacities of less than one mA·h, they possess enough power capability to deliver current in the range of 10 to 100 μA (at typical charge/discharge rates). Some of the smaller SSBs exhibit internal resistances of up to several 10's of k Ω , which significantly affects the output impedance of the Switched-Battery Converter (SBC). However, the target application in this context is ultra-low-power DC-DC converters (milliwatts and below), allowing for the manageable contribution of internal resistance ($R_{int} < R_L$).

This paper explores the integration of miniature solid-state batteries into a 2:1 SBC topology, considering their potential for μW output power and sub- mm^3 scale power conversion. It begins by presenting primary scaling principles related to the reduction in battery size and its impact on SBC performance. This is followed by a comparative analysis with inductor- and capacitor-based DC-DC converters. Subsequently, the paper demonstrates experimental performance of the SBC utilizing miniature solid-state batteries, focusing on efficiency, frequency dependence, and output voltage ripple. Finally, a

comparison with results from [5] is conducted to validate the previously mentioned scaling principles.

II. TREND FOR MINIATURIZING SBC

A. Power Density Scaling Law

Switching DC-DC converters employ passive devices like inductors or capacitors for voltage conversion between input and output voltages. In contrast to active components (switches, drivers, controllers), passives significantly influence converter volume, particularly at low power [1], [9]. Increasing passive energy density contributes to enhanced converter compactness. Nonetheless, passive density is closely linked to passive volume, as exemplified for inductors in [10]. At a fundamental level, the power rating of inductor P_L can be expressed as [10]:

$$P_L = f_{sw} B_{sat} J_w A_c A_w \propto \alpha^4$$

Where f_{sw} is the switching frequency, B_{SAT} is the magnetic flux density at saturation, J_w is the wire current density, A_c inductor core section, A_w is the inductor window area, and α is the length scaling factor [m].

For capacitors, the power rating P_C is derived from:

$$P_C = f_{sw} \epsilon E_{max}^2 d A_e \propto \alpha^3$$

Where ϵ is the dielectric permittivity, E_{max} is the dielectric breakdown electric field, d is the electrode plate spacing, A_e the electrode plate surface.

For battery, the power rating P_B is calculated from:

$$P_B = V_{redox} J_{max} A_e \propto \alpha^2$$

Where V_{redox} is the battery redox open-circuit potential, J_{max} is the maximum electrode current density, A_e is the battery electrode surface.

Power density is calculated by dividing the power rating by the volume (α^3). Table 2 presents the first-order scaling laws for the three passive devices under consideration. As explained in [10], Table 2 indicates that having larger inductor volumes results in higher power density since power density scales with α . In the case of capacitors, geometric scaling has no impact on power density, making capacitors more competitive than their inductor counterparts below a certain volume threshold. In contrast, battery power density scales positively with volume reduction, suggesting that batteries could be a strong competitor to capacitors below a specific volume range. This trade-off serves as motivation to explore solid-state batteries in SBC.

TABLE II. POWER RELATIONSHIPS WITH SCALING FACTOR

Unit	Power	Power density
	VA	VA/m ³
Inductor	α^4	α
Capacitor	α^3	constant
Battery	α^2	$1/\alpha$

B. Limits to the Scaling Down

Scaling down the dimensions of a battery also reduces its stored energy. As previously described in [5], the Switched-Battery Converter (SBC) employs unconventional charge/discharge cycles referred to as " μ -cycles." In contrast to the conventional cycles used by batteries in classical applications, SBC utilizes the battery as a flying element in

the DC-DC converter with a very low depth-of-discharge (DoD), typically less than 10's ppm of the battery's nominal capacity. As previously demonstrated in [11] and confirmed in SBC [5], this low DoD operation significantly enhances cycling capability, enabling long-term battery operation in the SBC. However, to ensure long-term operation, even with reduced stored energy due to battery scaling, the μ -cycle has been retained. The DoD can be expressed as follows:

$$DoD = \frac{E_B f_{sw}}{P_B} \propto \alpha f_{sw}$$

where E_B is the battery storage energy capability, P_B is the battery power rating.

The scaling of stored energy and power rating follows α^3 and α^2 , respectively. Consequently, the depth of discharge (DoD) is not maintained at a constant level during scaling. If the switching frequency (f_{sw}) is not appropriately scaled, the DoD could exceed acceptable levels, making it challenging to ensure the reliability of the μ -cycle. Therefore, downscaling is restricted by the DoD. In [5], for mm³ scale applications, the DoD remains below tens of ppm, allowing for battery volume reduction.

Another secondary effect is the increase in leakage current attributed to the reduction in electrolyte thickness. Consequently, battery scaling is limited until a point where leakage losses and cycling capability become problematic.

C. Packaging Opportunity offered by SSB

Solid-state batteries are produced using microelectronic manufacturing methods [8], which renders them exceptionally suitable for die-to-die and wafer-to-wafer integrated packaging alongside integrated circuits (ICs). This compatibility provides a promising pathway for enhancing power density even further.

In contrast to liquid-electrolyte batteries, solid-state batteries can be subdivided into smaller units without experiencing a significant decrease in power and energy densities. This attribute holds significant potential for enabling the integration of multiple flying batteries within Switched-Battery Converters (SBCs), thus facilitating the implementation of gearbox-like topologies, similar to their Switched-Capacitor Converter (SCC) counterparts, to manage various voltage conversion ratios.

Contrary to thick liquid electrolyte batteries with packaging dimensions in the millimeter scale, solid-state batteries exhibit thicknesses in the range of 100 μ m, potentially even lower with wafer thickness reduction [8]. The use of Solid-State Batteries (SSB) in SBCs can result in a slim form factor, particularly advantageous for low-power portable applications.

III. SWITCHED BATTERY CONVERTERS CONCEPT

SBC topologies draw inspiration from SCC, where flying capacitors are substituted with flying batteries. The simplest example is the 2:1 SBC topology depicted in Fig. 2, where the DC output voltage is half of the DC input voltage (VCR = 1/2) when unloaded. However, in the presence of a finite load, the output voltage diminishes as the SBC exhibits a finite output impedance.

In the first phase ($CLK=1$), the flying battery is μ -charged through the output current, experiencing $V_{in}-V_{out}$ across its electrodes. During the second phase ($CLK=0$), the battery

connects between ground and the output node to undergo μ -discharge, discharging the same amount of charge. Under steady-state and ideal conditions, such as equal phase durations, the flying battery solely functions as an intermediate storage element with no state-of-charge shift. In the ideal 2:1 SBC, the output node does not necessitate any bypass capacitors since the battery consistently connects to the output, serving as a decoupling component.

As described in [5], the average battery voltage is established by the DC-DC topology, rather than being inherent to the battery itself (in this case, $V_{in}/2$). To accommodate electrochemical mechanisms, the battery must operate within a safe voltage range, such as the 3.2-to-4.2V range for the TINY battery. This constraint restricts the input voltage range to 6.4-to-8.4V for the 2:1 SBC topology examined in this study.

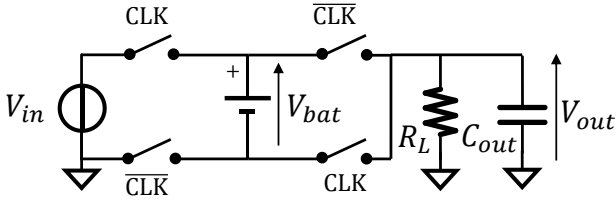


Figure 2 : 2:1 SBC circuit showing $V_{out} = V_{in}/2$ under no-load condition

In contrast to the Switched-Capacitor Converter (SCC), the output impedance of the Switched-Battery Converter (SBC) remains independent of frequency due to the battery's equivalent capacitor, which can be regarded as infinite. However, the battery exhibits significantly higher internal resistance when compared to the Equivalent Series Resistance (ESR) of a capacitor. This is because battery reactions involve ion transfers, which have a lower charge carriers mobility compared to the electrons in capacitors.

Without considering the switching losses, the output impedance is directly linked to the *conduction efficiency* η as follow:

$$\eta = \frac{R_L}{R_o + R_L} = \frac{R_L}{R_p + \frac{1}{(4C_{fly}f_{sw})} + R_L} \quad (1)$$

Where R_L is the load resistance, R_o is the output impedance of the converter, R_p is the equivalent series resistor of the passive ($R_p=R_{int}$ for battery or $R_p=R_{ESR}$ for capacitor), C_{fly} is the equivalent capacitor of the passive. As exemplified in Fig.3, the output impedance can be generally simplified to a simpler expression ($R_o \approx 1/(4C_{fly}f_{sw})$ for capacitor and $R_o \approx R_p$ for battery).

To illustrate the relevant operational region of the SBC, Fig. 3 plots the output impedances of both the SBC and SCC, assuming the TINY battery and a 0.1 μ F flying capacitor featuring roughly the same footprint (but a larger volume, as its thickness is superior to 1mm). Above 115Hz (typical SCC Slow-Switching Limit (SSL) regime operation [12]), the SCC exhibits lower output impedance, indicating its superiority over the SBC. Below 115Hz (typical SBC Fast-Switching Limit (FSL) regime operation [12]), the contribution of the flying capacitor to the output impedance (following a $1/f_{sw}$ trend) surpasses the impact of internal resistance in the SBC. This observation highlights that the SBC consistently performs better than the SCC topology at low switching frequencies.

For low-power applications, this implies that SBC can serve as a solution to achieve both the lowest impedance and the lowest switching losses when compared to passive volumes of equal size.

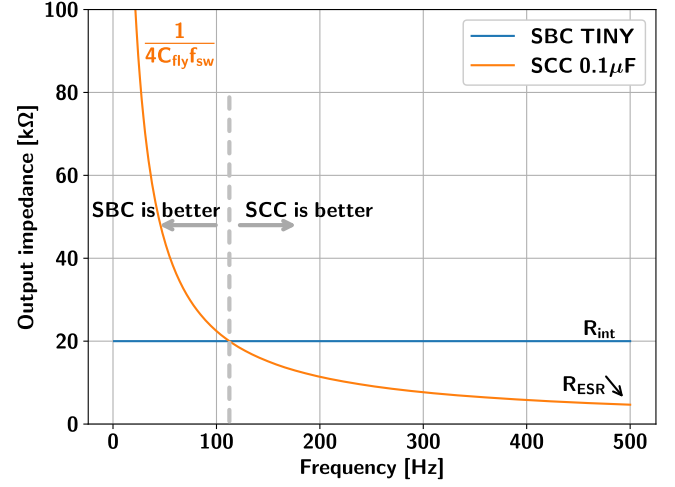


Figure 3 : Output impedance versus switching frequency for both SBC (blue) and SCC (orange) using a flying capacitor value of 1 μ F

IV. SOLID-STATE BATTERY DESCRIPTION

Figure 4 presents a sub millimeter-scale solid-state battery referred to as “TINY” in this paper. TINY boasts an area energy density of 1.5 mAhcm⁻² at a current density of 10 μ Acm⁻² and a power density of 12 mWcm⁻² at a current density of 3 mAcm⁻² [13]. These values represent state-of-the-art performance in comparison to other leading thin-film battery technologies. TINY has dimensions measuring 3.7 mm² and a thickness of 90 μ m. It is constructed with a 20- μ m-thick lithium cobalt oxide (LiCoO₂) cathode, a lithium-free anode, a titanium current collector, and a lithium phosphorus oxynitride (LiPON) electrolyte. TINY is depicted in Fig 4.

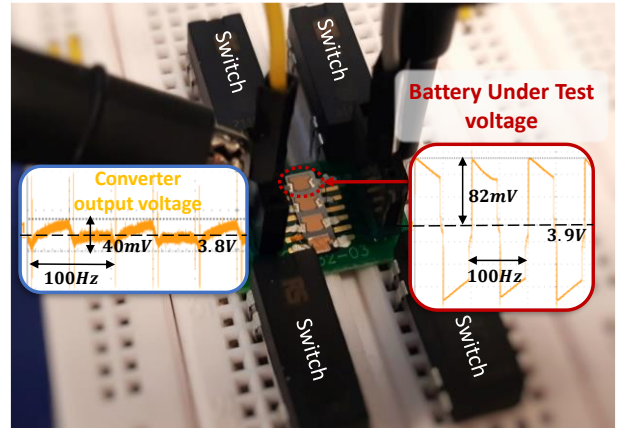


Figure 4 : TINY solid-state battery within the 2:1 SBC circuit

TINY possesses an internal resistance (R_{int}) of several tens of kilo-ohms, which restricts the maximum output power while maintaining high efficiency. With a target of 90% efficiency and considering Equation (1), the load resistance must exceed 100k Ω , resulting in an output power of approximately 0.1mW within the typical battery voltage range (approximately \sim 3.8V).

V. SBC USING SOLID-STATE BATTERY

To accurately characterize the conduction efficiency η at low power levels (0.1mW and below), we employed four

leakage-free micro-mechanical relays [14] to connect the flying TINY to the input, output, and ground nodes following the 2:1 configuration in Fig. 2. The on-state resistance of the switches ($R_{on} \sim 0.2\Omega$) is negligible when compared to R_{int} (tens of $k\Omega$). The time constant of these micro-relays, falling within the 100's μs range, does not limit the targeted switching frequencies in the SBC (in the 10-100Hz range). The battery and output voltages during typical 2:1 SBC operation is illustrated in Fig. 4 using a $360k\Omega$ load resistance ($\sim 30\mu W$).

In principle, no output bypass capacitor is required as explained previously. But, a necessary dead-time between phases introduces an instant where the output is not connected to any battery electrodes, implying a short time at zero voltage without decoupling. To overcome this issue, a small output capacitor (100nF) is introduced, with limited impact on the converter volume. A second solution could be an interleaving of two converter stages outphased by 90 electrical degrees so that the output node is never left unconnected (solution not studied here).

The measurement of output voltage ripple was conducted in a condition where the output capacitor (C_{out}) was intentionally omitted ($C_{out}=0$). Zero-voltage section (ZVS) has been excluded to assess the battery's ability to sustain minimal output voltage ripple regardless of output capacitor size. The 2:1 SBC, even at 100Hz switching frequency, ensures a relative low voltage ripple (below 3.1% at 3.9V output voltage).

Figure 5 illustrates the measured conduction efficiency η in relation to output power at a switching frequency of 100Hz. The observed efficiency aligns reasonably well with the battery's internal resistance, which is measured at $20k\Omega$ following operational characterization. This suggests that the primary contributor to efficiency is the internal resistance, rather than a capacitive component. The SBC is capable of delivering up to $110\mu W$ while maintaining a relatively high efficiency of over 80%. As seen in Fig. 1, the SBC's switching frequency is substantially lower than that of existing SCCs. Once more, the SBC demonstrates its ability to mitigate charge-sharing losses existing in SCC, allowing for low switching frequencies without causing an undue increase in hard charge-sharing losses.

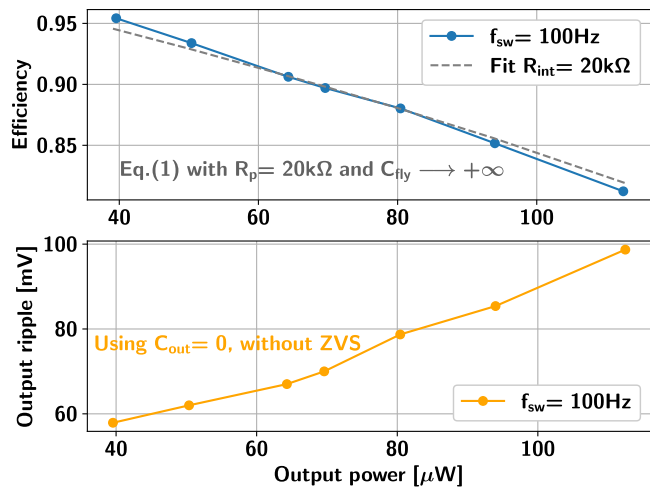


Figure 5: Measured efficiency and output voltage ripple of a TINY-based SBC

To experimentally verify the scaling law provided in Section II, Table 3 presents a comparison of power density in SBC across various flying battery volumes: a NiMH button

cell [5], a commercial solid-state battery [15], and TINY, as used in this paper. While power density doesn't exhibit a linear increase with volume reduction, it remains relatively consistent. The disparity between the first-order approximation previously presented and experimental results could be attributed to two factors: i) the use of different structures and chemistries in these three battery types, and ii) variations in output voltage, efficiency where it is extracted and circuitry. Nevertheless, SBC appears to possess a property similar to capacitor-based converters: no discernible performance penalty when scaling down.

TABLE III. COMPARISON OF SBC POWER-DENSITIES

Parameter	Unit	V6HR	EFL700	TINY
Reference	-	[5]	[15]	This work
Volume	mm^3	74	145	0.33
Normalized volume	-	1	1.96	1/224
Output voltage	V	1.2	3.8	3.9
Max power	μW	$25 \cdot 10^3$	$24 \cdot 10^3$	80
Power density @ efficiency	$\mu W/\text{mm}^3$	340	200	340
	%	84	70	81
DoD	ppm	10	0.5	10

As discussed in Section II, maintaining the necessary μ -cycle operation to ensure the longevity of flying batteries becomes challenging when the battery volume is scaled down while keeping the switching frequency constant. In Table 3, a one-cycle Depth of Discharge (DoD) is estimated based on the driving current and frequency. Remarkably, even though the volume of TINY is over three decades smaller than the others, the DoD remains within the ppm range. This ensures an exceptionally low strain on the battery, guaranteeing long-term robustness over billions of cycles, as observed in [14]. This resilience can be attributed to the remarkable energy density exhibited by the TINY battery, even with a volume below mm^3 .

Results in this section are open-loop, but voltage regulation is possible. Like [16], integrating a linear regulator (LDO) at the SBC output is a viable solution. The SBC's lower frequency eases Power-Supply Rejection Ratio (PSRR) constraints on the LDO, enabling reduced quiescent current and dropout voltage.

VI. CONCLUSION

In summary, this paper presents experimental characterizations of emerging DC-DC converter topologies, specifically the switched-battery converter (SBC), utilizing solid-state μ -batteries. By significantly mitigating charge-sharing losses compared to SCC, SBC enables operation at low switching frequencies (below kHz), effectively minimizing switching losses and maximizing efficiency at low-power levels. The discussion on the scaling properties of SBC highlights the potential of emerging solid-state batteries for seamless integration into IoT nodes. The measured performance demonstrates remarkable results, including a power density of up to $0.34\text{mW}/\text{mm}^3$ and 95% peak efficiency, even at switching frequencies as low as 100Hz, using a sub- mm^3 scale battery. Furthermore, both experimental data from previous studies on SBC and the findings of this work underscore the robust scalability of batteries, maintaining power density even as the battery volume is reduced. These findings indicate promising avenues for the application of SBC and solid-state batteries in ultra-compact, low-power IoT power management IC.

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