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Liquid-Solid Hybrid Power Converter For High Frequency Energy Conversion

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Abstract

Conventional solid-state power converters are constrained by fixed topologies and high-frequency alternating current losses from skin and proximity effects, limiting adaptability in modern energy conversion systems. Here we introduce a liquid-solid hybrid power converter (LHPC) in which all current-carrying paths and reconfigurable interconnects are formed by electrically actuated gallium-based liquid metal. Using an electric field to manipulate the motion of the liquid metal conductor (LMC), the converter reconfigures between two pairs of topologies: Flyback and Half-bridge, Buck and Boost. We demonstrate open-loop bidirectional reconfiguration between Flyback and Half-bridge modes, and closed-loop bidirectional reconfiguration between Buck and Boost modes. The power electronic circuits are fully constructed from LMC and all converters are implemented on boards fabricated from laser-cut poly (methyl methacrylate) (PMMA), enabling repeatable and reversible topology transitions under different high-frequency conditions with stable performance. Unlike conventional printed circuit board (PCB)-based planar converters, our approach supports rapid circuit deployment, fast recycling, and the creation of multidimensional converter structures, which are made possible by injecting or pumping LMC into PMMA boards.

Keywords: Power converter, liquid-solid hybrid power converter, Reconfigurable, Liquid metal conductor

1 Introduction

Amid swift advancements in electrical and electronic technology, power converters are essential to modern electronic systems. They enable efficient energy transfer, voltage regulation and functional transformation across diverse domains such as renewable energy systems, electric vehicles and consumer electronics. It is reported that over 70% of the world’s electrical energy is processed by power electronics, underscoring the critical role of power converters in the global energy infrastructure[1]. According to MarketsandMarkets, the global power electronics market was estimated at 51.73 billion USD in 2025 and is predicted to increase to approximately 67.42 billion USD by 2030, expanding at a CAGR of 5.4% from 2025 to 2030[2].

As power electronics continue to evolve toward higher switching frequencies and greater functional complexity, the limitations of traditional converter technologies have become increasingly pronounced. For conventional solid conductors in high-frequency power electronics, issues such as skin and proximity effects, increased manufacturing complexity, and challenges in rapid recycling become more pronounced[3].

Skin effect causes alternating current (AC) to predominantly flow near the surface of a solid conductor, reducing the effective cross-sectional area available for current flow[4]. The proximity effect is the redistribution of current in nearby parallel AC conductors due to magnetic coupling[5]. This effect causes the current to concentrate on the side farther from a neighboring conductor when the AC currents flow in the same direction, and closer when they flow in opposite directions. These two effects both cause the current to converge on the surface layer of the conductor, which reduces the cross-sectional area of the conductor through which the current flows, leading to an increase in resistance and thereby raising Joule losses[6].

Moreover, beyond loss and packaging, solid-state interconnects also impose a structural constraint on functionality. Conventional converters are fabricated with fixed copper traces that hard-code a single topology, so multifunctionality and mode switching are typically achieved by duplicating power stages, introducing additional routing networks or redesigning hardware. However, the accessible topology space expands combinatorially with component connectivity and port count[7], suggesting substantial untapped opportunity if converter topology could be reconfigured at the hardware level. The lack of a practical physical platform that can repeatedly and reversibly rewire high-current paths has limited such richness to abstract design spaces rather than deployable systems.

The rigidity constraint arises in widely used power conversion ICs and power modules, where compact packaged converters generate multiple regulated rails for embedded, industrial and consumer systems[8, 9]. Because different loads and functional blocks require distinct voltage levels, systems often rely on multiple dedicated modules, increasing footprint size of the circuit, component count and routing complexity[10]. Yet, once packaged, converter functionality is largely set by hard-wired interconnects and routing, making changes in voltage levels, conversion modes or power-routing schemes dependent on duplicating modules, adding external switching networks or redesigning the hardware. These limitations motivate an interconnect technology that can enable reversible, topology-level reconfiguration of current-carrying paths within a single power conversion IC chip[11, 12].

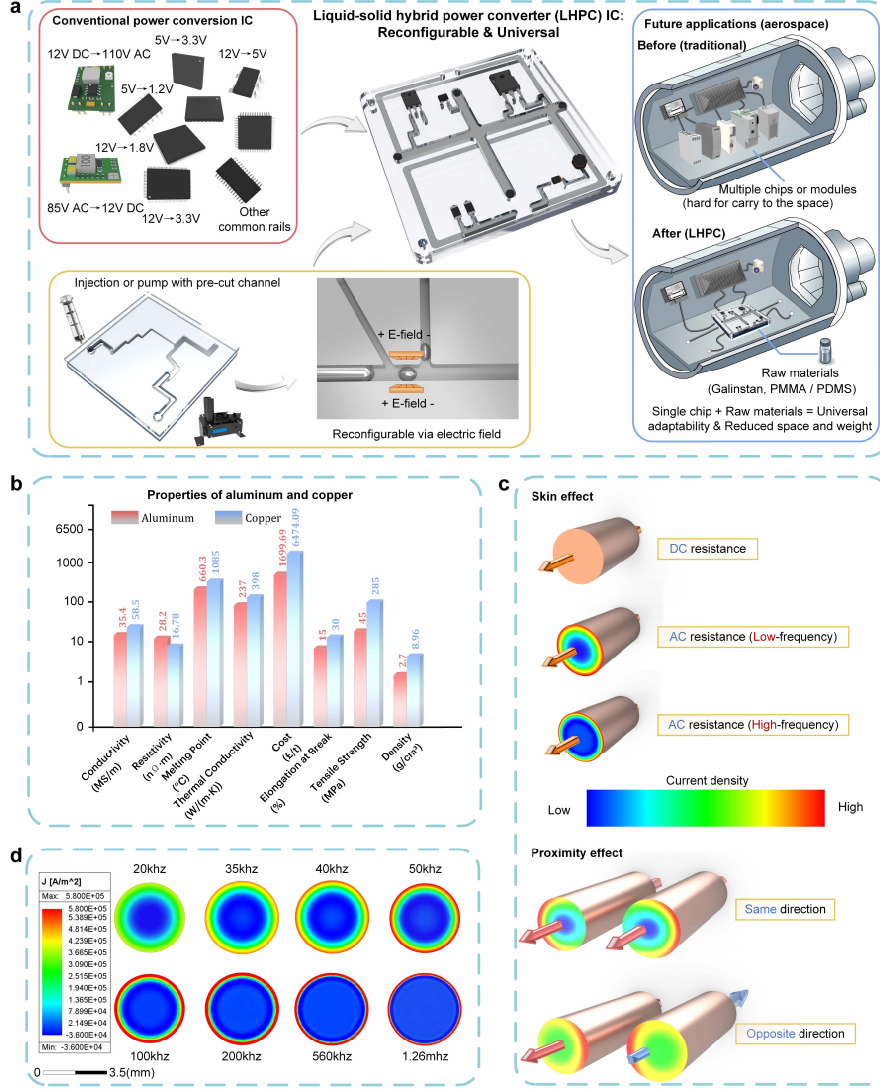


Fig. 1: Power converters across modern life and high-frequency limits of solid conductors: a, Universal reconfigurable LHPC integrated circuit (IC) concept. Multiple dedicated power conversion integrated circuits (ICs) for different voltage rails and functions are consolidated into a single platform by filling Galinstan into predefined PMMA or PDMS channels (via injection or pumping) and inserting solid state devices (for example, MOSFETs). The schematic further highlights a future aerospace scenario, where one reconfigurable module and raw materials could replace many dedicated converter chips, reducing mass, volume and operational complexity. **b**, Material properties of aluminium and copper. **c**, Skin and proximity effects in parallel conductors. **d**, Frequency dependence of skin effect and effective depth.

To overcome the issues mentioned above, we have turned to novel materials such as liquid metal (LM), particularly gallium-based alloys like eutectic gallium indium (EGaIn) and gallium indium tin (Galinstan), which offer a promising balance between electrical conductivity and mechanical flexibility[13, 14].

Here we introduce a liquid-solid hybrid power converter (LHPC) that integrates electrically actuated gallium-based liquid metal conductors (LMCs) with conventional solid-state active devices. By applying electric-field-driven actuation through an electrochemical electric double layer mechanism[15, 16], we controllably translate and redistribute LM segments to form or remove conductive links at designated nodes, thereby enabling topology-level reconfiguration without replacing components. We demonstrate bidirectional reconfiguration between Flyback and Half-bridge converters in an open-loop configuration, and between Buck and Boost converters under closed-loop regulation, on laser-cut multilayer PMMA boards that enable repeatable transitions with stable high-frequency operation(Fig. 1).

LHPC demonstrates an interconnect-programmable route to topology-adaptive power conversion. By embedding reconfigurability into the current-carrying material, LHPC offers a new hardware degree of freedom for converter realization, enabling reversible reconfiguration alongside rapid deployment, recycling, and scalable multidimensional integration.

2 Liquid-solid hybrid power converter

Galinstan, one of the liquid metals, distinguished by its superior electrical and thermal conductivity, excellent biocompatibility, and exceptional fluidity, has become a notable category of functional materials[17–19]. Although the DC conductivity of gallium-based alloys is lower than that of copper, the effective AC resistance difference narrows at high frequency as the current becomes confined to the surface layer in both materials (Supplementary Note 2 and Supplementary Fig. 7)[3]. More importantly, the outstanding electrical conductivity and fluid mobility of liquid metals make them highly suitable as conductors in reconfigurable circuits and allow for dynamic and adaptable designs(Fig. 2).

Given that Galinstan can function as a conductor[20], we propose a new concept for power converters called LHPC. LHPC involves the use of liquid-state conductors in power electronics circuits, replacing traditional solid-state conductors and even passive components while still incorporating traditional solid-state active devices at the same time. LHPC offers greater flexibility in circuit design while maintaining excellent conductivity at high frequency.

2.1 Liquid metal conductor motion control

In power electronic systems, circuit functionality is ultimately dictated by the connectivity of current-carrying paths, rather than by the intrinsic behaviour of individual components. Enabling topology-level adaptation therefore requires a mechanism that can reliably form, remove, and reroute conductive links within the hardware during operation. The fluid and self-healing nature of gallium-based liquid metal conductors

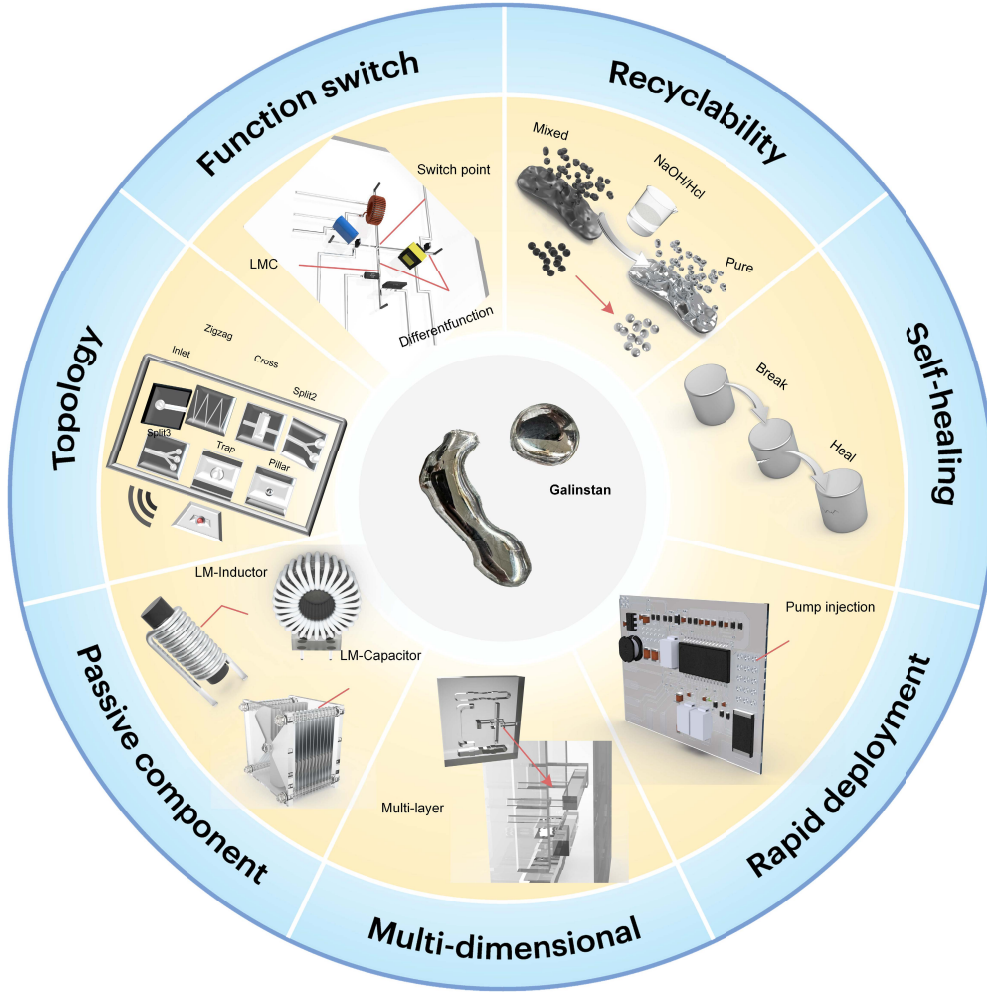


Fig. 2: Advantages of Galinstan for liquid-solid hybrid power converters

provides such a capability, offering a practical route to physically realizable reconfigurable circuits by actively controlling the spatial distribution of the liquid metal within predefined channels.

Accordingly, the defining requirement of LM-based reconfigurable converter is the ability to control the motion of the LMC. Meanwhile, the static LMC parts integrated directly into the circuit path provide stable electrical conduction, ensuring that reconfiguration does not compromise circuit integrity.

To achieve the motion of liquid metal, many mechanisms have been explored, including magnetic field[21], photochemistry[22], electrochemistry[23], acoustics[24], electrical field and so on[15, 25–29]. Among these typical methods, electric fields offer

straightforward electrical control, since their magnitudes, phases, and frequencies can be easily adjusted.

When Galinstan is immersed in the NaOH solution, a chemical reaction between gallium and the NaOH solution leads to the formation of a $[\text{Ga}(\text{OH})_4]^-$ ion, which accumulate on the Galinstan surface and result in a negative charge distribution at the interface[30–32]. This negative surface charge attracts cations from the solution and repels anions via diffuse charge dynamics, leading to the formation of an electrochemical electric double layer (EDL) at the droplet-solution interface. The thickness of the EDL varies on the order of 10 to 100 Å (1-10 nm) depending on the type of electrolyte-metal pair, the electrolyte concentration, the electrical conditions and even the temperature[15]. The Lippmann’s equation describes the relationship between the interface tension and the voltage drop across the EDL[16](Fig. 3).

$$\gamma = \gamma_0 - \frac{c}{2}V^2 \quad (1)$$

where γ is the surface tension, c is the capacitance per unit area of the EDL, V is the electrical potential across the EDL and γ_0 is the maximum value of surface tension at $V = 0$.

To simplify the analysis, the charge within the EDL is assumed to be uniformly distributed. Consequently, the pressure difference across the EDL at each hemisphere can be determined using the Young-Laplace equation, which relates pressure difference to interfacial curvature and surface tension.

$$p = \gamma \frac{2}{r} \quad (2)$$

where p is the pressure difference between the electrolyte and the liquid metal, r is the radius of the liquid metal conductor. Therefore, the pressure difference Δp between left and right hemispheres of the droplet can be expressed as

$$\Delta p = p_L - p_R = (\gamma_L - \gamma_R) \frac{2}{r} = \frac{2\Delta\gamma}{r} \quad (3)$$

where p_L and p_R are the pressure differences between the surrounding liquid and the left and right hemispheres of the LMC, respectively. While γ_L and γ_R are the surface tensions of the left and right hemispheres, respectively.

$$\Delta\gamma = \gamma_L - \gamma_R = \frac{c}{2}(V_R^2 - V_L^2) \quad (4)$$

where V_L and V_R denote the electric potential drops across the EDL on the left and right hemispheres, respectively. The difference in the squared potentials ($V_R^2 - V_L^2$) generates an imbalance in the electric-field-induced surface tension, resulting in a net surface-tension gradient $\Delta\gamma$ that drives the motion of the LMC.

$\Delta\varphi$ is the voltage drop between the two ends of the LMC, which is caused by the current flowing through the LMC and the layer of the electrolyte between the LMC

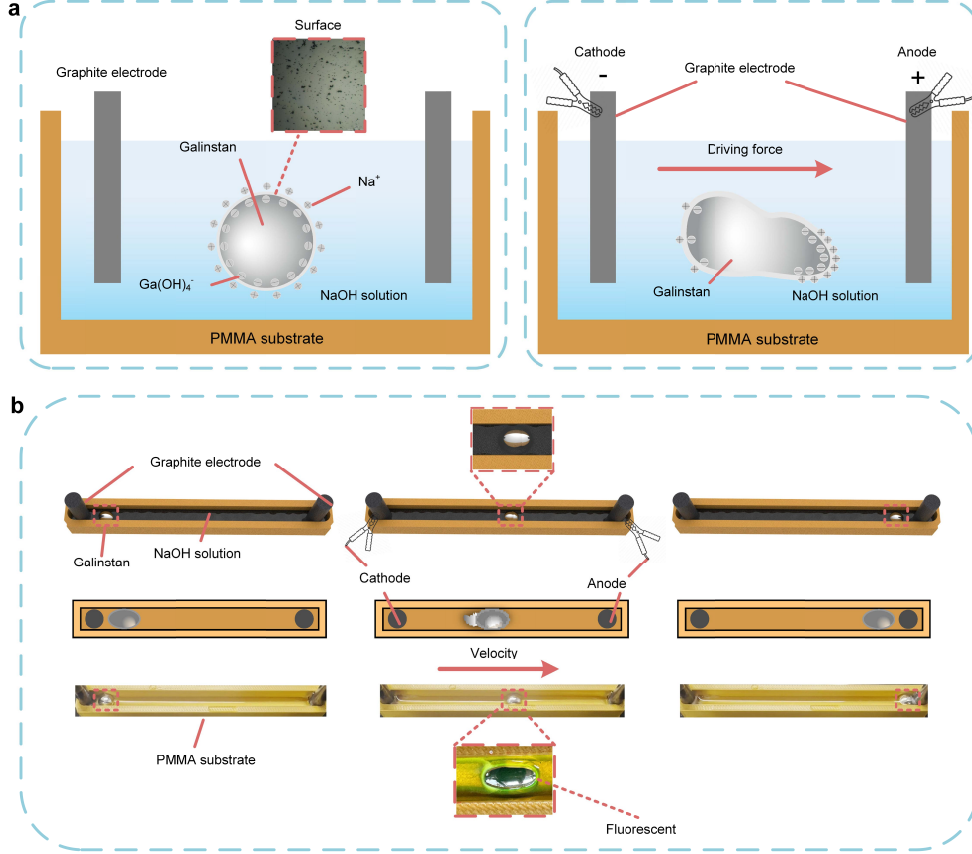


Fig. 3: Definition of EDL on Galinstan and electric-field-driven actuation:
a, EDL around a Galinstan droplet in NaOH with a high-magnification surface micrograph. **b**, From model to experiment: E-field control of droplet translation. (fluorescein traces reveal near-droplet vortex flows that provide the driving force.)

and the channel. This voltage drop can be estimated as

$$\begin{aligned}\Delta\varphi &= IR_d \approx I \frac{2r}{\sigma A_{gap}} \approx \frac{\sigma A_{current} V_{electrode}}{L} \frac{2r}{\sigma A_{gap}} \\ &= \frac{2r \cdot V_{electrode} A_{current}}{L \cdot A_{gap}}\end{aligned}\quad (5)$$

where I is the current in the circuit, R_d is the resistance of the LMC and the thin layer of the electrolyte between the LMC and the channel. σ is the conductivity of the electrolyte, A_{gap} is the equivalent cross sectional area of the electrolyte between the LMC and the channel, $V_{electrode}$ is the electric potential applied across the electrodes, L is the total length of the current path, and $A_{current}$ is the cross-sectional area of

the current path. Equation (5) ignores the resistance of the LMC due to its high conductivity. Therefore, an approximately equal sign is used.

$$A_{gap} \approx \frac{2r \cdot A_{current} - \frac{4}{3}\pi r^3}{2r} = A_{current} - \frac{2}{3}\pi r^2 \quad (6)$$

The EDL is approximated as a capacitor with capacitance per unit area c , such that $q = cV$. Let q_0 denote the initial EDL surface charge density, giving the reference EDL potential

$$V_0 = \frac{q_0}{c}. \quad (7)$$

A finite voltage drop $\Delta\varphi$ along the LMC makes the local EDL potentials asymmetric, which is approximated by

$$V_L = V_0 - \frac{\Delta\varphi}{2}, \quad V_R = V_0 + \frac{\Delta\varphi}{2}. \quad (8)$$

Substituting into $\Delta\gamma = \frac{\varepsilon}{2}(V_R^2 - V_L^2)$, the surface tension difference can be related as

$$\Delta\gamma = q_0\Delta\varphi \quad (9)$$

According to the spherical calculus, the driving force induced by the surface tension gradient of the half sphere LMC can be derived as follows.

$$\begin{aligned} F &= \int_0^\pi \int_0^\pi \Delta p \cdot r^2 \cdot \sin\theta \cdot \sin^2\psi \, d\theta \, d\psi = \pi r^2 \Delta p \\ &= \frac{4\pi q_0 A_{current} \cdot r^2}{(A_{current} - \frac{2}{3}\pi r^2)} \frac{V_{electrode}}{L}. \end{aligned} \quad (10)$$

where θ and ψ are the polar and azimuthal angles in spherical coordinates, respectively.

Assuming that the mass of LMC can be approximated as $m = \rho \frac{4}{3}\pi r^3$, where ρ is the density of the LMC. The acceleration of the LMC, a_F , can be expressed as

$$a_F = \frac{F}{m} = \frac{9q_0 A_{current}}{\rho(3A_{current}r - 2\pi r^3)} \frac{V_{electrode}}{L} \quad (11)$$

According to equation (11), under the ideal conditions, the acceleration of LMC is directly proportional to both the applied voltage between the electrodes ($V_{electrode}$) and the initial surface charge density (q_0), and inversely proportional to the distance between the two electrodes (L). Additionally, the acceleration exhibits a nonlinear dependence on the droplet radius (r). The initial surface charge density itself is influenced by the electrolyte concentration. As the concentration increases, the initial EDL charge density also increases. However, when the concentration is higher than a value, the EDL charge density saturates. Therefore, the electrolyte concentration is also one of the vital factors affecting the control of LMC. The overall mechanical analysis also includes the analysis of the retardation forces (Supplementary Note 1).

3 Reconfigurable topologies in the LHPC

Since the motion of LMC can be controlled by electric fields, we find the potential for topological reconstruction from the motion of LMC. Traditional power converters typically implement a single functional topology on a printed circuit board (PCB) board. Integrating multiple functions onto the same PCB requires complex design processes and additional circuit paths, significantly increasing circuit complexity to accommodate the functional demands of each topology. In contrast to traditional converter, the LHPC eliminates the need for complex circuit designs to accommodate multiple topologies and avoids unnecessary use of additional components and conductive traces. In this study, we designed two experiments to demonstrate the reconfigurability of LHPC. The first experiment demonstrated open-loop reconfiguration between Flyback and Half-bridge topologies. The second experiment extended this concept to a closed-loop high-frequency multidimensional system, enabling dynamic switching between Buck and Boost topologies. It is worth noting that in the following two experiments, most conductors were intentionally designed to enable functional switching without requiring intermediate-mode operation during transitions. This design choice was driven by the need for spatial efficiency and optimal component utilization.

For experimental convenience, the LMC channels on the top poly (methyl methacrylate) (PMMA) layer of the LHPC are left open to facilitate observation and recording[33].

3.1 Bidirectional reconfiguration between Flyback and Half-bridge converter

The first experiment focused on reconfiguring the Flyback converter into a Half-bridge converter. To evaluate electrical consistency and functional integrity, voltage and current were measured at key circuit nodes before and after reconfiguration.

We initially designed the Flyback and Half-bridge circuits in an open-loop configuration to verify that their topologies can achieve the intended functionality. The key components of the Flyback converter include a transformer, two MOSFETs, and two diodes. The Half-bridge converter similarly comprises a transformer, two MOSFETs, and two capacitors. Both topologies were assembled for initial testing, with a signal generator used to provide PWM signals to the high and low side MOSFET gate drivers. The switching frequency was set to 50 kHz, and the result shows the converter operated as intended.

Subsequently, a comprehensive trench layout was designed to accommodate the entire circuit on a PMMA substrate. The overall circuit configuration was analyzed to ensure that the revised trench structure could integrate components from both Flyback and Half-bridge topologies within a single PMMA substrate. Based on experimental results, a channel width of 5 mm was selected as optimal for implementing the circuit layout within the PMMA substrate. A laser cutter was employed to fabricate 5 mm-deep trenches in the PMMA substrate plate according to the designed layout. After placing the components onto the substrate, the remaining channels were filled with liquid metal conductors (LMCs) to establish electrical interconnections (Fig. 4).

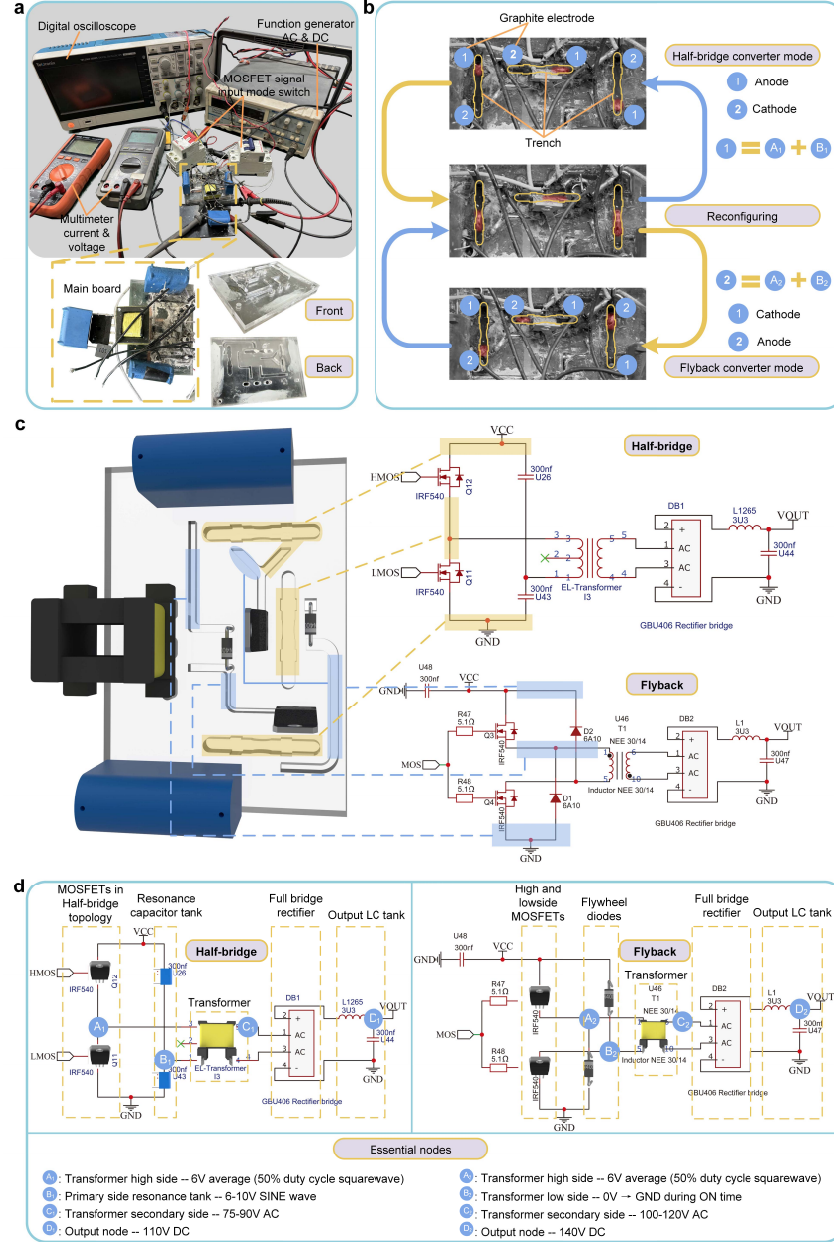


Fig. 4: Flyback to Half-bridge converter reconfiguration process: **a**, Bench setup with instruments; inset, enlarged LHPC module. **b**, Polarity control of graphite electrodes drives Galinstan flow, switching on demand between Half-bridge and Flyback modes. **c**, Spatial-circuit mapping; each Galinstan segment corresponds to a schematic block, covering the full power stage. **d**, Operating schematics for Half-bridge and Flyback with functional blocks highlighted; essential nodes annotated with their operating voltages.

Finally the Flyback converter goes from 12 V to 140 V and the Half-bridge converter goes from 12 V to 110 V.

3.2 Bidirectional reconfiguration between Buck and Boost converter

The second experiment focused on determining the most effective approach for utilizing the LMC to achieve bidirectional reconfiguration between Buck converter and Boost converter. In this experiment, closed-loop control was implemented to validate the practical feasibility of reconfigurable power converter (Fig. 5).

The closed-loop LHPC was based on synchronous Buck and synchronous Boost converters, both employing a Half-bridge structure to facilitate effective mode switching. The inductance value was selected as 100 μH , and the output capacitance was selected as approximately 100 μF by paralleling two 47 μF and two 22 μF capacitors. Current sensing was performed on the low side, while voltage regulation was achieved through direct ADC feedback to the STM32F405 microcontroller. A resistor divider composed of 93.1 $\text{k}\Omega$ and 13 $\text{k}\Omega$ resistors was employed to achieve appropriate voltage scaling for high-frequency operation. To evaluate conductor behavior under typical high-frequency conditions, a PWM signal at 100 kHz with a 50% duty cycle was generated by the STM32.

In this experiment, the power circuit section and the topology-switching circuit section were implemented using LMCs. Under Buck mode operation, the circuit successfully converted 12 V to 5 V at a high switching frequency of 100 kHz. In Boost mode, it achieved an output of 36 V from a 12 V input at 100 kHz switching frequency, delivering approximately 72 W of power to the load. The measured energy conversion efficiency in Boost mode reached 74.4%.

The Flyback/Half-bridge open-loop LHPC provided an initial validation of the feasibility of using LMCs for circuit reconfiguration. In comparison, the Buck/Boost closed-loop LHPC demonstrates the practical viability and reliability of rapid topology switching using LMCs. While the open-loop configuration can achieve structural reconfiguration, it lacks precise output control. The closed-loop system, by incorporating a feedback mechanism, effectively compensates for input and load variations, achieving high accuracy and adaptive response.

However, these advantages come at the cost of increased circuit complexity, as the incorporation of feedback loops, dynamic load management, and PID controller tuning imposes greater hardware demands. Nevertheless, the successful implementation and stable operation of the open-loop and closed-loop converters further validate the feasibility and robustness of LM reconfigurable circuits.

To assess the high-frequency performance of the LHPC, we measured the output voltage and current of a Buck converter operating at different switching frequencies. To evaluate the performance of the LHPC under different practical operating conditions, four sets of experiments were carried out across multiple switching frequencies. The first set consisted of a no-load test. The second set introduced an inductive load, in which the LHPC was connected to three small motors to emulate a light-load operating state. The third set implemented a resistive load by connecting the LHPC to a 2 Ω resistor, representing a medium-load scenario for the overall circuit. The fourth group

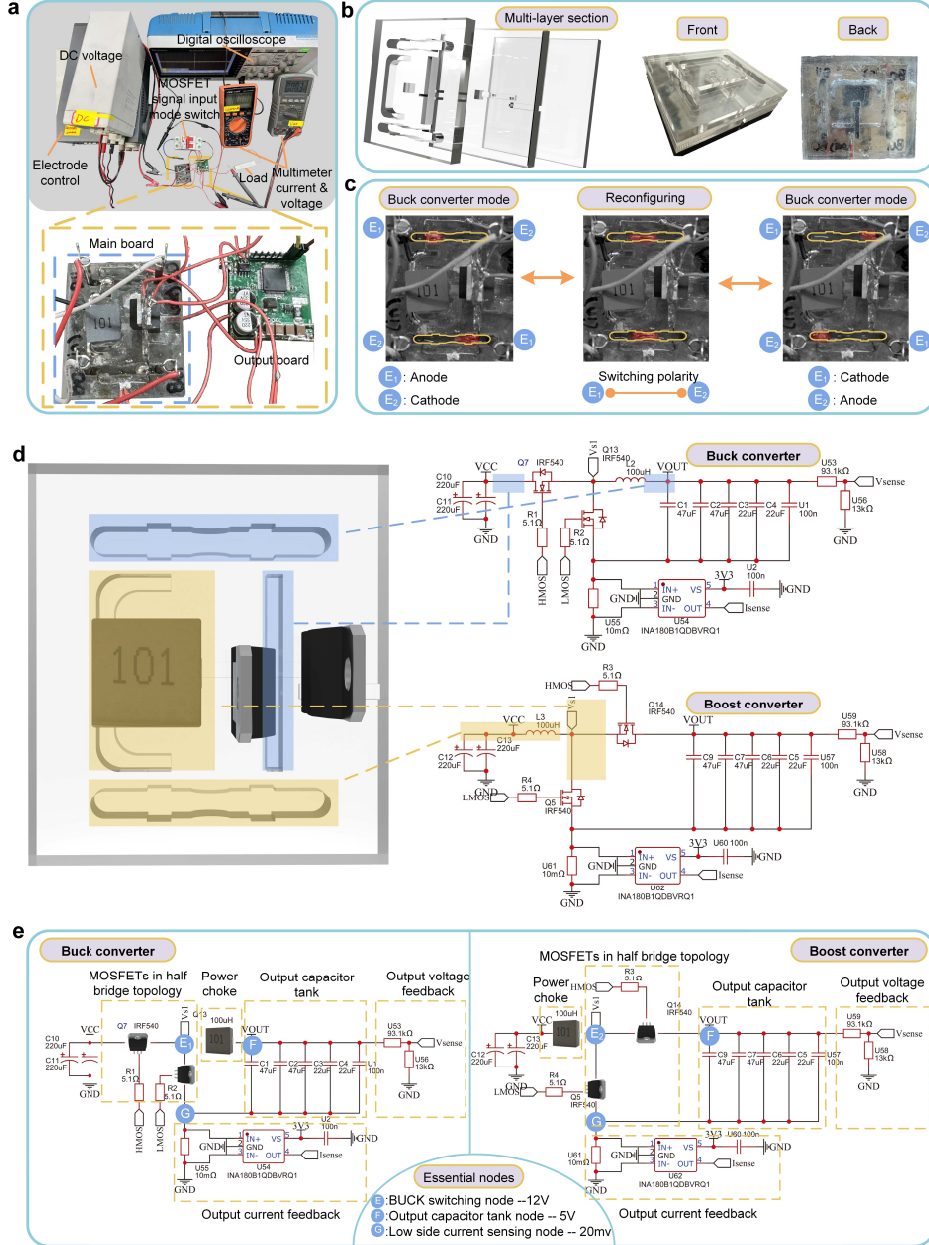


Fig. 5: Buck to Boost converter topologies reconfiguration process: a, Bench setup with instruments and enlarged LHPC module. **b,** Multilayer Buck-Boost LHPC: stacked-channel structure with front and back views of the physical module. **c,** Reversing graphite-electrode polarity drives the continuous Galinstan conductor to switch between Buck and Boost modes. **d,** Spatial-circuit mapping: each liquid-metal segment corresponds to a schematic block, covering the full power stage. **e,** Operating schematics for Buck and Boost with functional blocks highlighted; essential nodes annotated with representative voltages.

used the DC electronic load RK8510B (500 V/15 A/400 W), operating in standard steady-state mode, transient mode, and step-up mode, respectively. Selected data from the heavy-load experiments are presented in the dotted-line graph below (Fig. 6).

The results show that under the LHPC Buck mode, the output voltage remains consistently around 5 V across a wide frequency range from low to 200 kHz, which falls within the typical operating range of Buck converters. The output current also stabilizes at approximately 2 A. At the high switching frequency of 500 kHz, more pronounced fluctuations in the output are observed; however, the average output voltage and current remain stable at approximately 4.9 V and 2 A, respectively. Importantly, voltage and current outputs remain consistent across the typical frequency range (below 200 kHz), indicating that the LHPC delivers stable performance at both low and high frequencies. Based on the recorded data used for power calculations, the efficiency under normal heavy-load conditions is around 70%. The lower efficiency of the Buck configuration in the LHPC, compared to the Boost mode, is primarily attributed to the larger inductance used in the circuit. More data are presented in the supplementary information (Supplementary Fig. 17-21).

4 Multidimensional extensibility

An important feature in both the Buck/Boost and Flyback/Half-bridge demonstrations is the use of a three-dimensional, multilayer circuit structure fabricated on PMMA substrates (Fig. 7). This architecture leverages the intrinsic fluidity of the LM, allowing the LHPC to accommodate complex circuit geometries while reducing susceptibility to failure at sharp turns and folded routing. The self-healing and fluidity nature of the LM further supports robust conduction in spatially constrained layouts [13, 34, 35].

In both experiments, LMCs were embedded in the PMMA layers by injection, enabling rapid circuit deployment and fast recycling [33]. By integrating multidimensional circuit layouts with programmable interconnect strategies, it becomes possible to combine multiple reconfigurable circuit units within a highly compact footprint.

From a functional standpoint, the LHPC architecture enables a predefined and systematically controllable set of topological transformations. For example, in a four-layer PMMA-based architecture where each layer supports four different configurations, the number of reachable states can in principle scale up to 256 through inter-layer connectivity. This modular stacking strategy offers an exponential expansion of accessible circuit topologies within a fixed component set. In parallel, circuit expansion across the x - y , x - z and y - z planes provides an additional route to scalability via increased integration density.

Scalability can also be viewed from a bottom-up perspective, in which the number of components and their interconnections defines the size of the feasible topology space. The exponential growth of feasible power converter topologies with increasing component connectivity has long been recognized in theory, and graph-theoretic frameworks have been developed to enumerate valid topologies for a given set of components and ports. Under shared-inductor constraints, the number of distinct converter topologies increases dramatically, from 36 for three-port configurations to more than 14,393

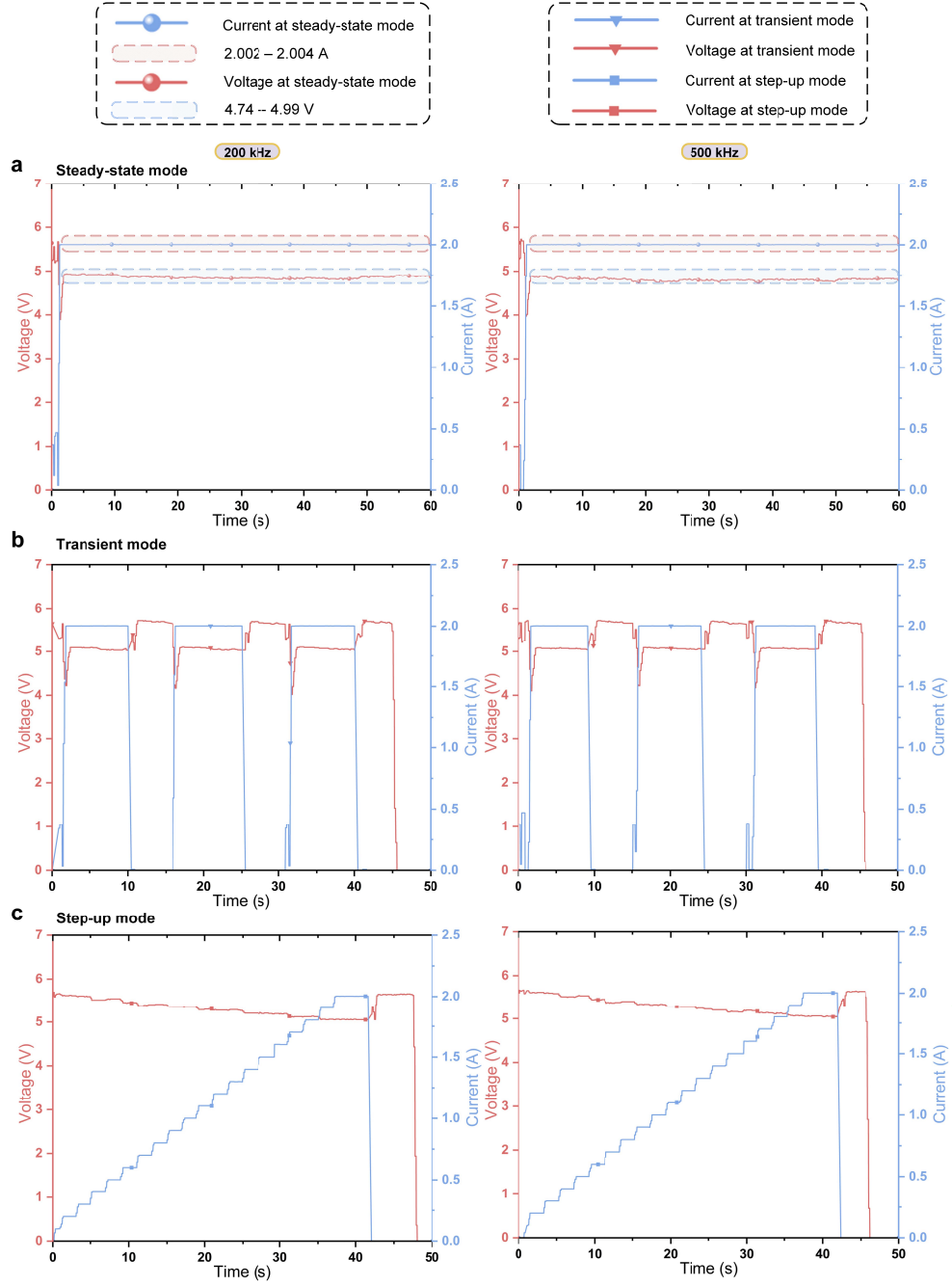


Fig. 6: Output performance of the LHPC at 200 kHz and 500 kHz in heavy-load: Voltage and current output of the LHPC under different loading conditions at switching frequencies of 200 kHz and 500 kHz. Dotted lines represent selected experimental data from reloading tests conducted to evaluate performance stability under varying practical loads.

for five-port systems[7]. However, this richness has remained largely abstract because few physical platforms can rewire electrical connections repeatedly and reversibly to navigate such spaces dynamically.

The LHPC architecture provides a practical route to bridge this gap. Through multilayer stacking and reconfigurable LM interconnects, a fixed set of components can be transformed into a large, programmable set of interconnection schemes, enabling reversible transitions among multiple predefined hardware configurations. Looking forward, the LHPC directly targets a pervasive constraint shared by packaged power conversion ICs and, more broadly, packaged power converters voltage regulator module (VRM) and power management integrated circuit (PMIC) power stages: once a converter is fabricated and packaged, its topology and power routing geometry are largely fixed by rigid solid conductors and hard wired routing[12]. In practice, power delivery networks must supply multiple rails because different loads and functional blocks operate at distinct voltage and power levels; meeting these heterogeneous demands typically relies on deploying multiple dedicated converter modules or regulator chips in parallel[11]. Such multi converter integration increases system footprint, component count and routing complexity, and it also consumes shared resources such as board area, thermal budget and electromagnetic compliance margin. By contrast, the LHPC shifts programmability to the current carrying interconnect itself, enabling a single hardware instance to be repurposed across multiple predefined conversion functions and output requirements by reconfiguring conductive links rather than duplicating power stages. Coupled with multilayer stacking and multidimensional layouts, such consolidation could further reduce volumetric overhead by compressing routing and functional density into a compact three dimensional form factor.

Beyond conventional deployments, interconnect-programmable conversion suggests a frontier direction for extreme environments where mass, volume and operational simplicity dominate design choices. For example, in space exploration or remote-field missions, carrying numerous spare power conversion ICs to cover diverse conversion needs is costly and operationally burdensome. A reconfigurable LHPC-like platform could instead be assembled or repurposed on demand by combining a lightweight substrate with pre-patterned channels and passive structures, a supply of LMC, and a minimal set of solid-state active devices; the conductive paths could then be formed by pumping or injecting the liquid metal, and reconfigured as mission requirements evolve. In this long-term vision, a single reconfigurable power-module platform could, in principle, support a wide range of conversion ratios (for example, 5 V $\rightarrow$ 3.3 V, 12 V $\rightarrow$ 5 V, 3 V $\rightarrow$ 0.7 V, or 12 V $\rightarrow$ 140 V) and be extended toward multiple conversion classes (DC-DC as demonstrated here, and potentially AC-DC, DC-AC and AC-AC with appropriate components and isolation structures), reducing both the number of dedicated chips and the overall system complexity.

In addition to topological variety, this extensibility may enable practical functions such as reconfiguration-based fault mitigation and adaptation to varying operating conditions. More broadly, integrating programmable topology synthesis with physical reconfiguration suggests a shift in converter design, moving from fixed-function circuits toward adaptive systems capable of context-aware operation. This architectural

approach offers a scalable path toward intelligent, multifunctional power processing, with implications for future dense and autonomous energy systems.

5 Conclusions

We have presented a liquid–solid hybrid power converter architecture that integrates electrically actuated liquid metal conductors with conventional solid-state components, enabling rapid and reversible reconfiguration across multiple power converter topologies at high operating frequencies. By dynamically manipulating the current-carrying paths via electric fields, the LHPC transitions between distinct conversion modes within a unified hardware platform.

By using electric field to manipulate LMC, the LHPC achieves reliable bidirectional reconfiguration between Flyback and Half-bridge converters, as well as Buck and Boost converters. Specifically, we demonstrated open-loop Flyback (12 V→140 V) ↔ Half-bridge (12 V→110 V) reconfiguration at 50 kHz, and closed-loop Buck/-Boost reconfiguration (12 V→5 V and 12 V→36 V) delivering 72 W at 100 kHz. The electric field control method significantly simplifies circuit structure, reduces circuit complexity, and enables rapid and convenient topology switching for real-world situations.

The LHPC architecture also offers practical advantages. Owing to the intrinsic fluidity of liquid metal conductors, the material can be directly injected or pumped into pre-etched trenches in PMMA substrates, allowing circuit deployment and recycling within minutes. This fluidity further enables the construction of three-dimensional circuit geometries, as demonstrated in the Buck/Boost experiment. The fluidic continuity and self-healing behaviour of the conductor help maintain electrical connectivity in spatially constrained and sharply routed layouts.

Importantly, the LHPC provides a reconfigurable substrate capable of navigating a large, predefined topological space with a fixed set of components. When combined with multidimensional stacking and programmable interconnects, it offers exponential topological extensibility and high integration density. This represents a fundamentally different design pathway from conventional packaged power ICs and power modules, which are typically fixed in both function and routing once fabricated. By contrast, the LHPC shifts reconfigurability to the interconnect level, allowing a single hardware instance to support multiple conversion modes and output profiles through electrically controlled re-routing.

In this light, the LHPC points toward a scalable approach for future power conversion platforms—enabling multifunctional, adaptive systems with reduced footprint, component count, and routing complexity. This reconfigurable architecture may ultimately support the consolidation of multiple regulated power rails and conversion classes into a compact, programmable module, with potential applications ranging from embedded electronics to modular systems deployed in space, robotics, or other resource-constrained environments.

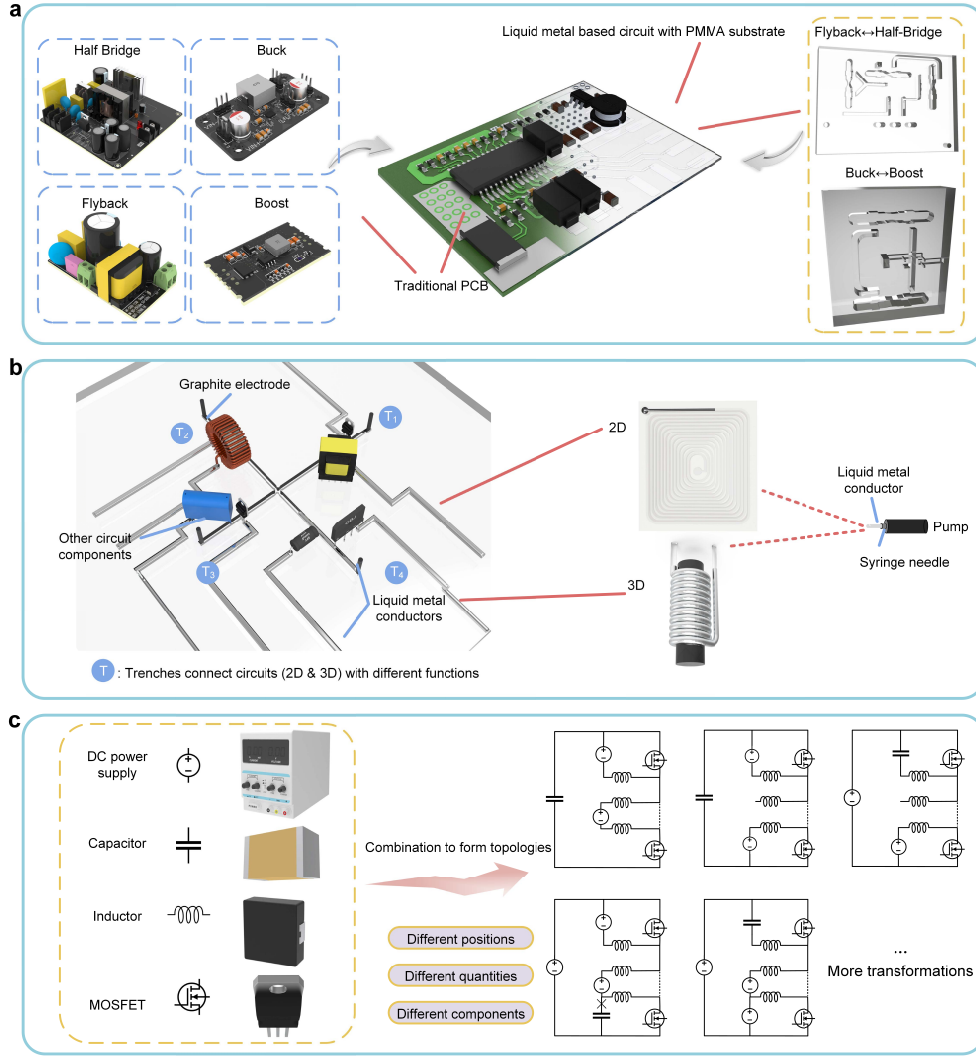


Fig. 7: From traditional converters to liquid-solid hybrid power converters: **a**, Four converters in this study: Buck, Boost, Half-bridge and Flyback are reconfigured in pairs (Buck ↔ Boost; Flyback ↔ Half-bridge) by replacing fixed copper traces with Galinstan-filled channels. **b**, Electric-field-driven reconfiguration of a continuous Galinstan conductor enables switching among circuit topologies without additional structures and with minimal conductor use; the LHPC also supports 2D/3D routing, with the liquid-metal paths formed via pump- or syringe-based injection. **c**, From a bottom-up perspective, diverse power converter topologies can be formed by varying the quantity, type, and spatial arrangement of components. Graph-theoretic methods enable systematic enumeration of valid configurations within this design space[7].

6 Methods

6.1 Testing the loss of copper and Galinstan conductors under high-frequency conditions

A constant-voltage AC power supply was used, with one terminal connected to a $1\ \Omega$ resistor in series, followed by a 3D-printed trench ($58.5\text{ mm} \times 5\text{ mm} \times 5\text{ mm}$, using PLA “silk” filament) filled with Galinstan conductor. An oscilloscope probe was placed across the Galinstan conductor and the $1\ \Omega$ resistor to capture voltage waveforms. The AC source frequency was sequentially adjusted to 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz, and the corresponding oscilloscope waveforms were recorded. Subsequently, the Galinstan conductor was replaced with a copper conductor of same size, and the same frequency sweep and measurement procedures were repeated for comparison.

6.2 Facilities for controlling liquid metal conductors

A conduction test platform was fabricated by fused-filament 3D printing (Panda; manufacturer) using PLA “silk” filament. A rectangular base ($95\text{ mm} \times 9\text{ mm} \times 10\text{ mm}$) was printed with an open trench ($78.5\text{ mm} \times 5\text{ mm} \times 5\text{ mm}$) milled into its upper surface. Two graphite-rod electrodes (radius 1.7 mm; length 5 mm) were inserted into holes flanking the trench, and secured by built-in electrode-holder platforms. A total of 2 mL of 0.5 mol/L NaOH solution was injected into the trench via a stainless-steel syringe, followed by a 0.3 mL droplet of Galinstan. For electrical actuation, a separate graphite electrode (radius 5 mm) was placed directly into its holder and connected to a stabilized DC power supply (15 V). The transit time of the liquid-metal droplet from the positive to negative electrode was recorded as 0.5 s.

6.3 Fabrication of PMMA substrate for liquid-solid hybrid power converters

The multilayer topology conversion devices were fabricated by independently machining each circuit layer from 5 mm-thick PMMA sheets. Following CAD design of the channel geometry, PMMA plates were cut on a CO₂ laser cutter (Eagle X-1309, GM-EAG-X1309).

For the Flyback-Half-bridge configuration (two layers), the perimeter of the laser-cut channels on both PMMA plates was bonded using waterproof epoxy adhesives (Loctite 401 and 502). After adhesive curing, Galinstan conductors were injected into the top-layer channels through pre-drilled inlet ports.

For the Buck/Boost configuration (three layers), the bottom and middle PMMA plates were first aligned and bonded around their channel perimeters. Galinstan was then injected into the bottom-layer channels via ports in the middle layer. After curing, the top and middle plates were similarly bonded, and liquid-metal conductors were injected into the middle-layer channels through ports in the top plate.

6.4 The electronic design of liquid-solid hybrid power converters

The Half-bridge converter consists of two power MOSFETs (Q11, Q12, IRF540) driven in complementary fashion. One side of the transformer primary winding is connected to the midpoint of the MOSFET half bridge, while the other side is connected to a resonant capacitor network. The alternating switching of the high-side and low-side MOSFETs applies a square-wave excitation across the transformer, with each device alternately pulling the primary to VCC or GND. This square wave is pulse-width modulated (SPWM) to synthesize a sinusoidal envelope, resulting in a resonant sinusoidal voltage across the primary tank. The transformer scales this waveform to a higher AC voltage at the secondary winding. A diode bridge rectifier (DB1) converts the AC to DC, which is then smoothed by the LC output filter (L1, U44) to yield a stable high-voltage DC output.

The Flyback converter employs a transformer (T1, NEE 30/14 core) and two MOSFETs connected in a two-switch (class-2) Flyback configuration. Unlike a Half-bridge, the MOSFETs are driven simultaneously using the same gate signal, so that during the ON interval both switches conduct and energy is stored in the transformer's magnetic field. When the MOSFETs turn OFF, the stored energy is released through the secondary winding. On the secondary side, the diode bridge (DB2) rectifies the transformer's output, while clamp diodes in the primary limit voltage stress on each MOSFET to approximately the input voltage. This eliminates the need for snubber circuits, improves efficiency, and allows the use of lower-voltage MOSFETs. The rectified output is then smoothed by the LC filter (L1, C2), yielding a stable high-voltage DC output of about 140 V. This two-switch Flyback differs from the Half-bridge converter in its energy transfer method: rather than applying a continuous sinusoidal excitation, it alternates between energy storage in the transformer (when both MOSFETs conduct) and energy release to the load (when the switches turn off). The result is an efficient step-up DC conversion with reduced switching stress.

The Buck converter is built using a Half-bridge arrangement of MOSFETs (Q7 IRF540, high-side and low-side pair). The MOSFETs are driven with complementary PWM signals from the STM32F405RGT6, producing a controlled duty-cycle square wave at node E1. A power choke inductor (100 μ H) stores energy during the high-side ON state and releases it when the MOSFET turns OFF, thereby reducing the voltage and producing a regulated step-down DC output. The output is filtered by a capacitor bank (C1-C4) to smooth the switching ripple and deliver a stable DC voltage at node F. Voltage feedback is taken from a resistor divider (U53/U56) and supplied to the MCU for closed-loop regulation. For current feedback, a low-side shunt resistor (U55, 10 m Ω) is monitored by an INA180B1 current-sense amplifier (U54), which provides a conditioned signal to the MCU. This allows closed-loop current PID control to be implemented in firmware.

The Boost converter uses a similar Half-bridge MOSFET arrangement (Q14, IRF540 high-side and Q5 low-side). At node E2, the inductor (100 μ H) is charged when the low-side MOSFET conducts, storing energy. When the MOSFET turns OFF, the energy is transferred through the body diode of the high-side device and the inductor current adds to the supply, producing a higher voltage at the output node F.

As in the Buck converter, the output is smoothed by a capacitor bank (C5-C9) to provide a steady high-voltage DC. Voltage feedback is implemented through a resistor divider (U59/U58) to the MCU. Low-side current sensing is again achieved via a 10 m Ω shunt resistor (U61) and an INA180B1 amplifier (U62), with the conditioned signal fed to the STM32F405RGT6. This enables closed-loop current PID regulation, ensuring accurate Boost operation.

Both Buck and Boost topologies are driven by the STM32F405RGT6 microcontroller, which generates PWM signals for the MOSFETs and processes voltage/current feedback. The INA180 current-sense amplifiers provide precise low-side current measurements, enabling digital PID control for output regulation. This structure supports stable DC-DC conversion with real-time monitoring of both voltage and current.

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