# INTEGRATED MAGNETIC COMPONENT FOR INNOVATIVE POWER CONVERTERS

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## ABSTRACT

In industrial, aerospace, and space applications, increasing power demands alongside strict volume and weight constraints mandate the use of resonant or soft-switching DC-DC converters operating at high frequencies. The advent of wide-bandgap semiconductors, such as GaN and SiC, accelerates this transition. These topologies typically require two distinct magnetic components: a transformer for galvanic isolation and a series inductor necessary for soft-switching or resonance. Although integrating this series inductance function via the transformer's leakage inductance is a known concept, it faces two major technical challenges: strict control over leakage inductance tolerance (typically tight, below 10%) and the surge in winding eddy current losses with operating frequency and integrated inductance value. This paper presents the development of magnetic components integrating the series inductor function into the transformer, regardless of its value, with tight tolerances and minimized losses. The developed components achieve power densities ranging from 15 W/cm³ to over 60 W/cm³ across power levels spanning from a few hundred watts to several hundred kilowatts. Operating from tens to several hundred kilohertz, these structures store magnetic energy ranging from a few millijoules to more than ten joules within the integrated series inductor, while guaranteeing an efficiency of at least 99% and thermal performance compatible with demanding industrial and space requirements.

## INTRODUCTION

To meet demanding industrial standards, soft-switching converters have established themselves as a major alternative to conventional hard-switching topologies. Physical constraints inherent to magnetic materials necessitate higher switching frequencies to minimize the volume of magnetic components, which often dominate the overall converter footprint. However, increasing switching frequencies induces severe switching losses in semiconductor devices alongside critical electromagnetic interference (EMI). Soft-switching mitigates these drawbacks by synchronizing transistor switching with zero-voltage (ZVS) or zero-current (ZCS) transitions, thereby eliminating virtually all switching losses while significantly reducing EMI. Implementing this technique typically requires a series inductor, referred to as a resonant or ZVS inductor, at the primary side of the transformer. This requirement introduces a critical design constraint: precise control over the transformer's leakage inductance. Given the tight tolerances imposed on the overall series inductance, uncontrolled leakage inductance can severely degrade converter operation. To overcome this technological bottleneck, at Exxelia Magnetics, we have developed integrated magnetic components designated as Smart Integrated Magnetics (SIM). These components combine the functions of an electrical transformer and a resonant inductor into a single, compact passive device with optimized thermal management. The core principle of SIM relies on the intentional enhancement of leakage inductance combined with the mitigation of both copper and core losses within a reduced footprint. Without specific design precautions at high frequencies, the increased leakage flux induces substantial eddy current losses. Consequently, integrating leakage inductances up to several hundred microhenries requires a re-engineering of the magnetic circuit geometry to properly direct the leakage flux and minimize losses. The design of these components relies on finite element analysis (FEA) simulation methodologies previously introduced at the SPCD 2024 conference, utilizing the Altair suite for multi-physics electromagnetic and thermal modeling.

## CORE LOSSES IN INTEGRATED MAGNETIC COMPONENTS

Unlike conventional transformers, integrated magnetic components exhibit a non-negligible leakage flux that shares the same magnetic core as the magnetizing flux. Consequently, evaluating the operating magnetic flux density solely through Boucherot's formula or Faraday's law of induction is inadequate. To determine the flux density in each branch of the magnetic core, the superposition theorem is applied to an equivalent reluctance network. Assuming a 90° phase shift between the leakage flux and the magnetizing flux, a quadratic sum of these two flux components yields the magnetic flux density per branch, enabling the calculation of the associated core losses. Three-dimensional Finite Element Analysis (3D FEA) is conducted to map the flux density across the core and verify the absence of local saturation. Using Altair Flux, the circuit model shown in Fig. 1 is employed to achieve an accurate flux density mapping. Current source $I_1$ represents the secondary current referred to the primary, while current source $I_2$ corresponds to the secondary current operating in phase opposition to $I_1$. Current source $I_m$ models the magnetizing current, shifted by 90° relative to $I_1$. Primary and secondary windings are coupled between the circuit model and the finite element model, whereas the magnetic core is modeled exclusively within the finite element domain.

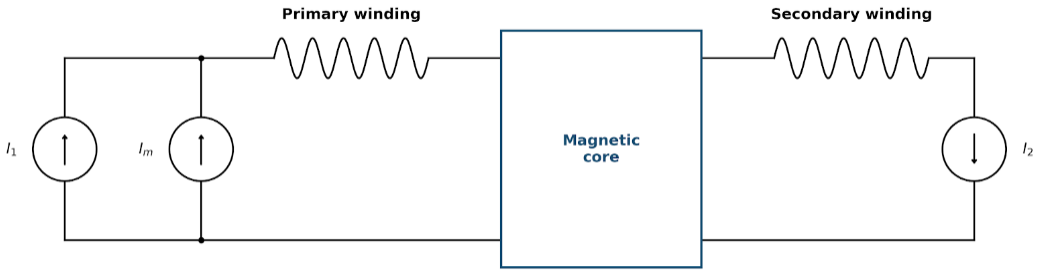



Fig. 1. Schematic of the model used for electromagnetic simulations

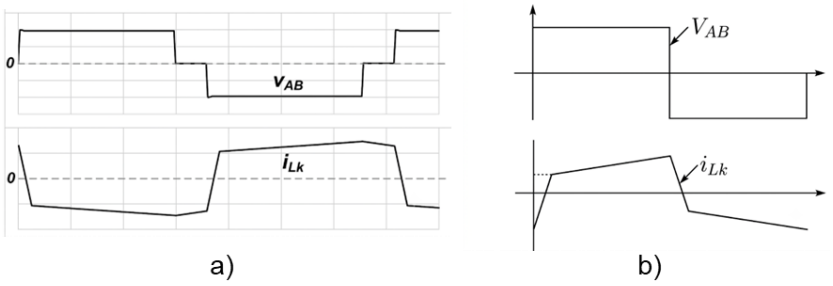



Fig. 2. Signal waveforms of: a) DAB (Phase Shift Modulation) and b) PSFB

Figs. 2(a) and 2(b) illustrate the voltage and current waveforms of soft-switching DC-DC converters. The high harmonic content of these signals (characterized by quasi-rectangular current waveforms) necessitates a Fast Fourier Transform (FFT) spectral analysis to guide the selection of the magnetic material and accurately evaluate core losses. To optimize the overall footprint of the integrated component, custom magnetic core geometries are preferred.

## COPPER LOSSES IN INTEGRATED MAGNETIC COMPONENTS

Because magnetic components operate at frequencies of several hundred kilohertz under waveforms characterized by high harmonic content, minimizing copper losses represents a major design challenge. Indeed, amplifying the leakage inductance leads to a significant increase in leakage flux. Without specific precautions, this stray flux induces additional eddy current losses within the conductors, compounding traditional skin and proximity effects. To address these multi-physics constraints, dedicated design methodologies have been developed at Exxelia to select the optimal winding

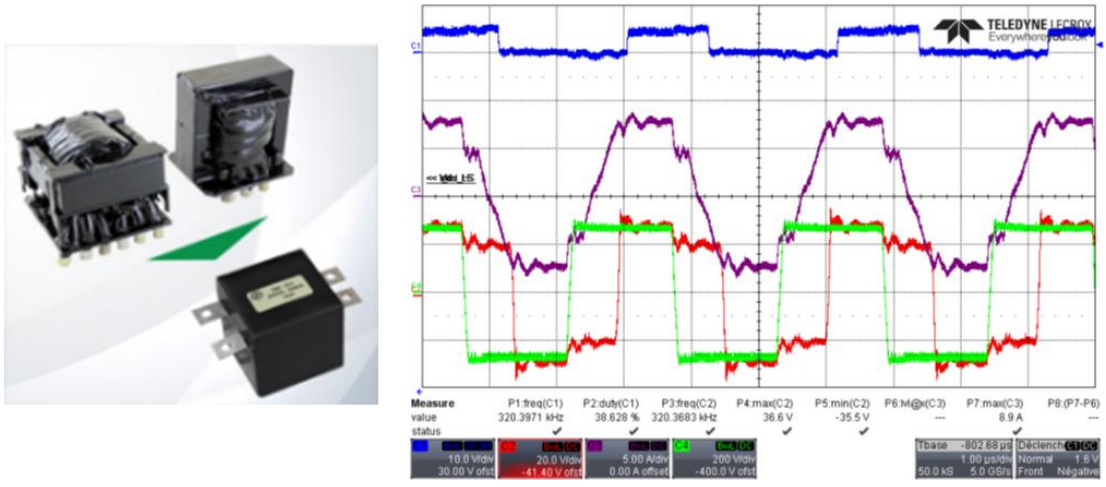
technology based on the geometric and physical requirements of the specifications. This optimization approach relies on the following key criteria:

- Choice between planar or conventional (wound) technology,
- Termination and connection type (through-hole, busbar, lead wire, etc.),
- Thermal dissipation mode (natural convection, forced air, or cold plate),
- Harmonic content of the electrical signals,
- Component mission profile and duty cycle,
- Insulation and dielectric withstand requirements.

## EVOLUTION OF INTEGRATED MAGNETIC COMPONENT DESIGN AT EXXELIA

A concrete benchmark specification was applied between 2020 and 2024 to track the evolution of integrated magnetic components alongside successive updates to design methodologies tailored to customer requirements. The evaluated component is designed for a 2 kW Dual Active Bridge (DAB) converter operating at a switching frequency of 320 kHz with an input voltage of 270V and an output voltage of 28V corresponding to a turn ratio of 10. Fig. 3(a) presents the discrete component solution alongside its equivalent integrated magnetic component. The weight of the integrated component is 250g, compared to 840g for the equivalent discrete implementation. Fig. 3(b) shows the measured voltage and current waveforms across the integrated component to validate its experimental operation. In this trace, the green curve corresponds to the primary voltage, the red curve to the secondary voltage, and the purple curve to the primary current. These experimental waveforms show excellent agreement with the theoretical profiles of a DAB converter controlled via Phase-Shift Modulation (PSM). Following the validation of the initial integrated magnetic component (V1), the various versions designed and manufactured throughout development were compared in terms of efficiency and power density under strictly identical specifications and test conditions. Fig. 4 presents the comparative performance evolution across the six fabricated SIM prototypes. From version V1 to V6, component efficiency increased from 98% to 99.2% (representing a power loss reduction of over 50%), while the gravimetric power density expanded from 1.5 W/g to 6 W/g, illustrating the continuous advancements in the design methodology. In addition to this high-power density, these components are capable of storing up to 50 mJ of magnetic energy within their leakage inductance.

A thermal evaluation was also conducted by embedding a K-type thermocouple inside the core of the fifth version of the component (SIM-V5). As mentioned previously, the device is sized to operate under natural convection; therefore, the temperature rise must remain within acceptable limits without active cooling. Fig. 5 illustrates the temperature evolution of SIM-V5 over a 40-minute test, which was sufficient to reach near-thermal steady state. The maximum temperature recorded by the sensor reached 84°C, corresponding to a temperature rise $\Delta T$ of 57°C above ambient.




*a)* *b)*

Fig. 3: (a) Discrete magnetic components (top) and the equivalent SIM (bottom); (b) Associated waveforms

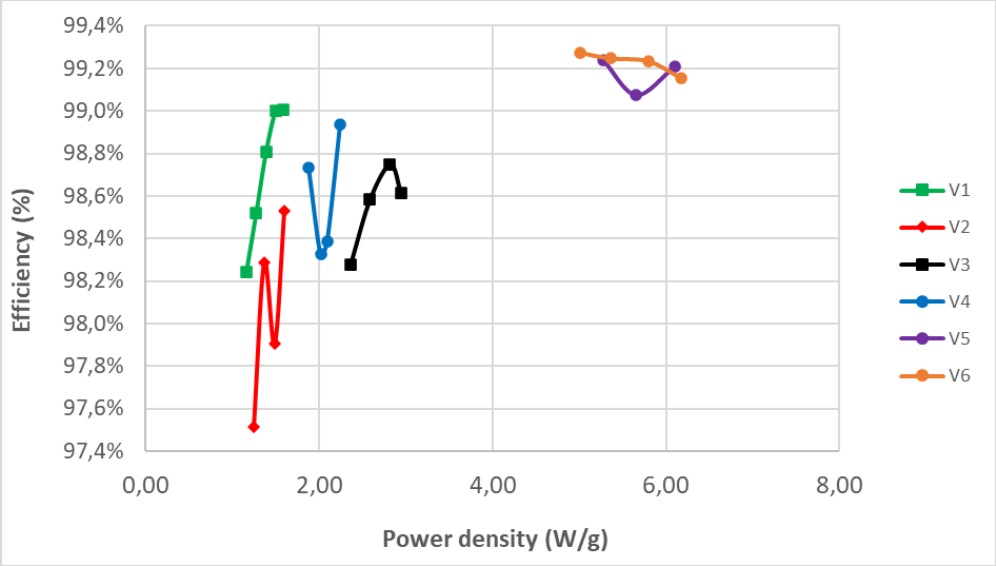



Fig. 4: Comparison of power density and efficiency across different SIM versions

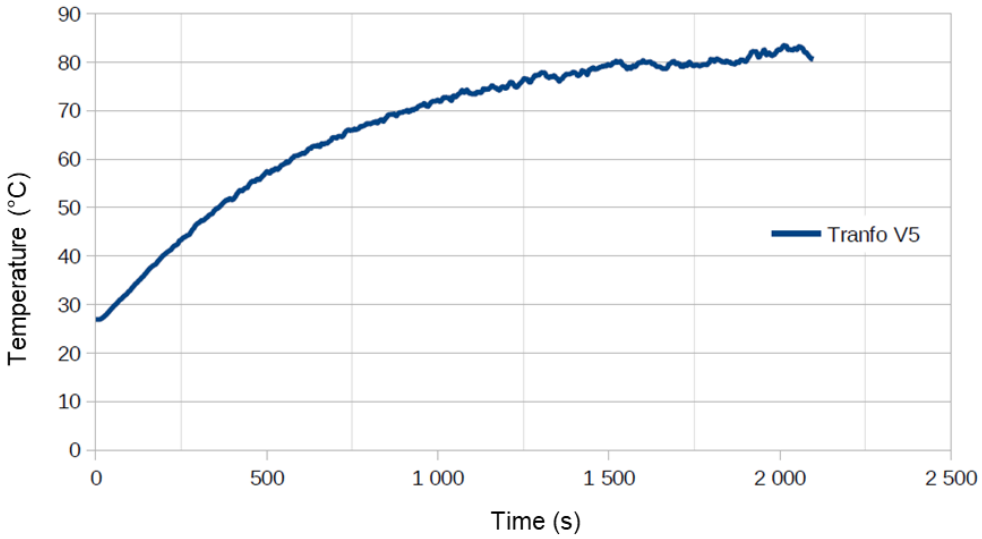
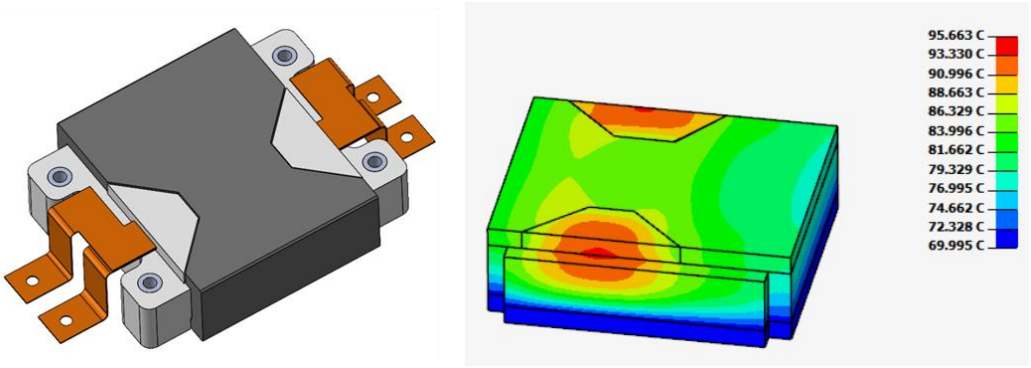



Fig. 5: Magnetic core temperature as a function of operating duration for SIM-V5.

## PRESENTATION OF SOME CUSTOMER-TESTED PROTOTYPES

### Example 1: Space Application (Cold-Plate Cooling without Natural Convection)

A custom integrated magnetic component was developed for a space application operating exclusively through conductive cooling on a cold plate and radiation. The component operates at a switching frequency of 150 kHz under a nominal power of 1 kW (peak power 1.3 kW). It incorporates an inductance of 7.5 $\mu H \pm 8\%$ rated for a peak current of 20 A. Featuring dimensions of 52mm * 64 mm * 20 mm and a mass of 270g, the power losses measured by the customer at nominal power were approximately 7W, yielding an efficiency of 99.3%. The thermal simulation conducted using Altair SimLab predicted a temperature rise of 25°C, demonstrating excellent agreement with the 21°C temperature rise measured experimentally by the customer.




a) b)

Fig. 6. (a) Geometry and (b) temperature distribution of a prototype developed for a space application.

### Example 2: Data Center Application

A high-power integrated magnetic component was designed to operate at a switching frequency of 20 kHz under a nominal power of 350 kW (peak power of 500 kW). The structure incorporates an inductance of $5\mu H \pm 10\%$ rated to withstand a peak current of 2000 A. Featuring dimensions 500 mm * 280 mm * 240mm and a total weight of 95 kg, the estimated power losses at nominal power amount to approximately 954 W, corresponding to an efficiency of 99.7%. The thermal simulation conducted in Altair SimLab predicted a temperature rise of 55°C on a cold plate regulated at 60°C. The component was successfully tested by the customer under these operating conditions.



Fig. 7. Prototype developed for a data center application

The construction details and technical solutions implemented to achieve these performance levels are omitted here to preserve confidentiality.

## CONCLUSION

This paper presented the development of Smart Integrated Magnetics (SIM) combining transformer and series inductor functions into a single passive component. The proposed methodology was rigorously validated through agreement between analytical calculations, multi-physics finite element simulations, and experimental characterizations on prototypes. The approach demonstrates full scalability across an extremely wide power spectrum, spanning from a few hundred watts to several hundred kilowatts, while guaranteeing efficiencies exceeding 99% and high power densities ranging from 15W/cm$^3$ to over 60 W/cm$^3$. Finally, this integration method proves adaptable and applicable to a broad variety of resonant and soft-switching DC-DC converter topologies, offering a proven solution for future generations of power electronics.