High-Frequency GaN-Based Induction Heating Versatile Module for Flexible Cooking Surfaces

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***Abstract*—Induction heating is nowadays the leading heating technology due to its superior efficiency and performance. In recent years, flexible cooking surfaces have arisen as the preferred choice offering best-in-class user performance. However, there are significant technical and manufacturing challenges that must be addressed to obtain flexible and high-performance implementations. This paper proposes the use of modular induction heating cells taking advantage of GaN technology to provide a flexible implementation outperforming current state-of-the-art solutions. The proposed approach has been verified using an experimental prototype, proving the feasibility of the proposed system.**

***Index Terms*—Induction heating, resonant power conversion, home appliances, wide bandgap semiconductor, gallium nitride**

I. INTRODUCTION

INDUCTION heating (IH) is nowadays the leading heating technology [1] for modern industrial processes, medical and domestic applications due to its superior efficiency and performance which leads to safe, cleaner and more repetitive processes. Among the many applications of IH, flexible cooking surfaces (Fig. 1) are gaining great attention due to their versatility and user performance [2]. However, there are still significant challenges to be addressed to obtain a high-performance and high-power density implementation suitable for this architectures.

In the past, several approaches have been proposed including the use of a set of inverter-coil pairs [3], multiple-output inverters [4, 5], or the combination of several inverters with mechanical relay interconnections. These solutions are able to manage multi-coil systems in domestic applications [5, 6]. However, all of them suffer from performance limitations and complex implementation when dealing with a high number of coils due to manufacturing complexity. Moreover, there is an increasing need to face power density limitations motivated by the severe space restrictions imposed in home appliances. Consequently, high efficiency [7, 8] and high power-density implementations are required. In this context wide bandgap devices offer an excellent opportunity for performance improvements on induction heating applications [9, 10].

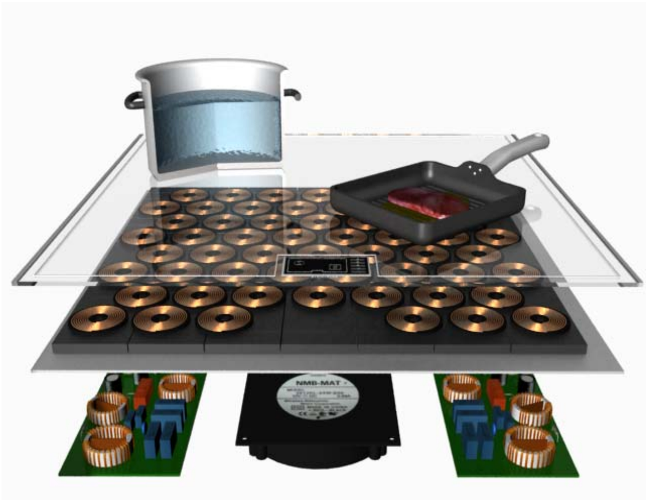


Fig. 1 Flexible cooking surface induction heating appliance.

The aim of this paper is therefore to propose a high-frequency GaN-based versatile modular architecture to achieve a high-performance flexible cooking surface implementation. The proposed approach follows a modular architecture where each power converter is implemented together with the induction coil, leading to an effective implementation. Besides, the proposed converter can operate at high frequency taking advantage of cost-effective GaN devices, being able to achieve all-metal heating.

The remainder of this letter is organized as follows. Section II details the proposed architecture, including the proposed power converter and its control strategy. Section III covers the implementation and experimental results, including details about the thermal and PCB implementation. Finally, Section IV summarizes the conclusions of this paper.

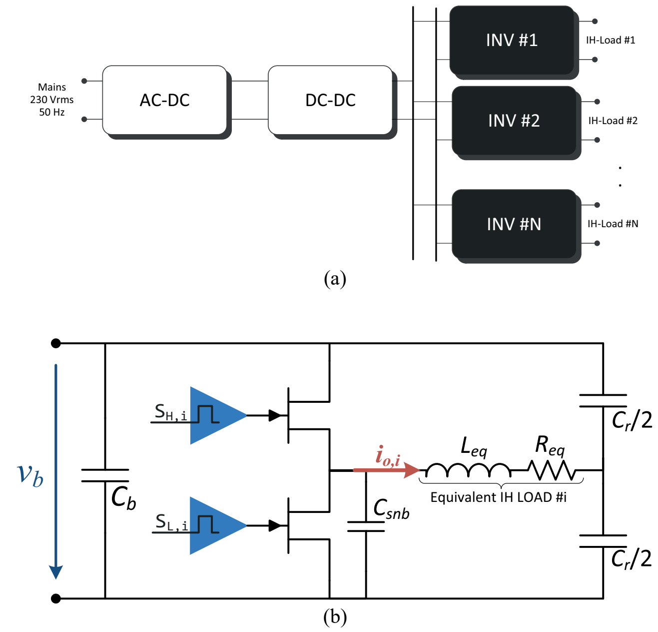


Fig. 2 Proposed power converter architecture (a) and inverter cell topology (b).

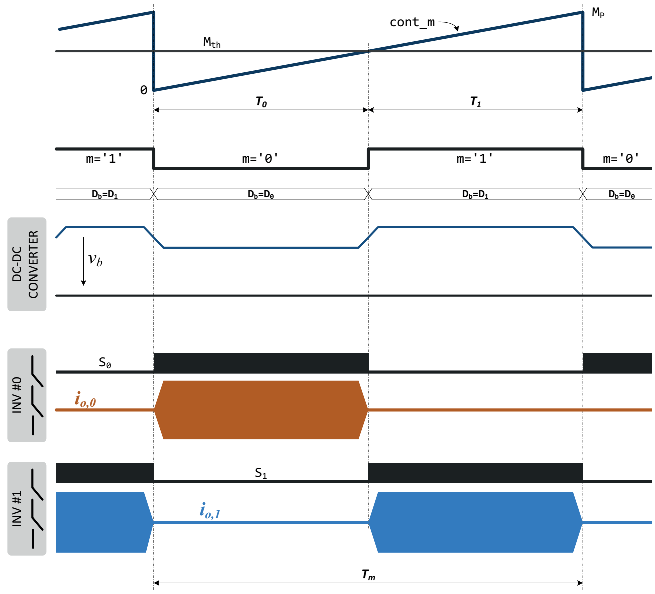


Fig. 3 Proposed modulation strategy for multi-load control.

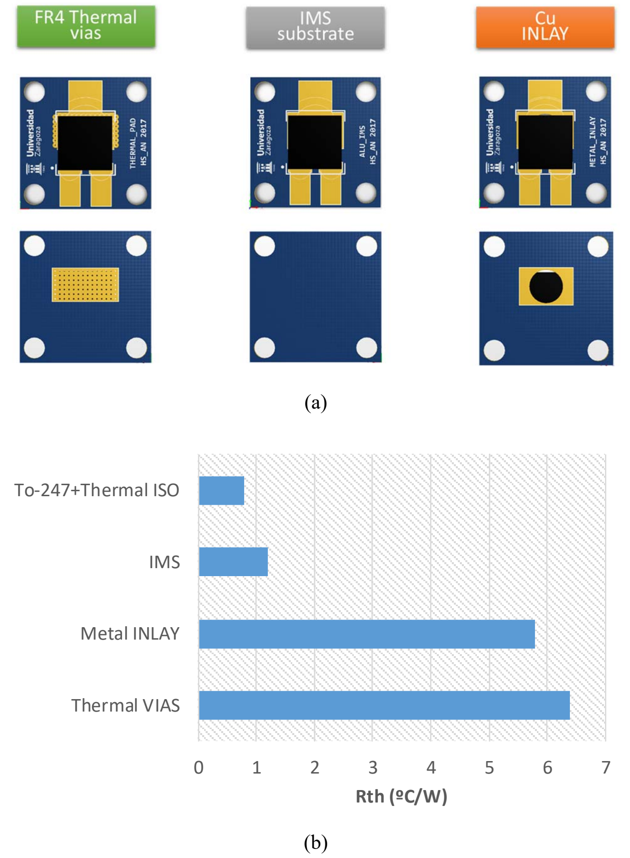


Fig. 4 Thermal management: evaluated alternatives (a) and equivalent thermal resistance (b).

II. PROPOSED ARCHITECTURE

A. Power converter

The proposed power converter architecture is composed of a rectifier plus a dc-dc converter able to control the bus voltage of all the inverter units connected to it Fig. 2(a). Usually, flexible cooking surfaces requires n>20 coils to achieve good performance. Each inverter cell is composed of a half-bridge topology [11] plus the resonant tank, composed of the equivalent circuit of the coil L_{eq}, R_{eq} and the resonant capacitor, C_r (Fig. 2 (b)).

In order to achieve zero voltage switching, the power converter is usually operated above the resonant frequency, which is defined as $f_o = 1/2\pi\sqrt{L_{eq}C_r}$. In this specific design, the power device output capacitance, C_{oss} will act as snubber capacitor C_{snb} reducing dv/dt, especially at low current operation.

One of the key challenges of domestic IH heating is the highly variable operating range due to different materials and geometries. This is especially important when dealing with multi-layered pots and highly conductive materials, where the analysis of the penetration depth δ plays a fundamental role. Penetration depth which can be calculated as $\delta = \sqrt{1/\pi f \sigma}$, where f is the excitation frequency generated by the inverter cell and σ is the material conductivity. Usually, commercially available Si-based inverters operate between 20 kHz to 100 kHz due to IGBT technology limitations. However, in order to reduce the penetration depth to minimize multi-layered pots

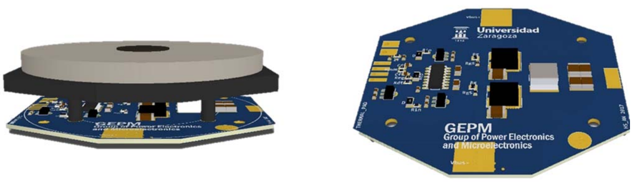


Fig. 5 Inverter cell render.

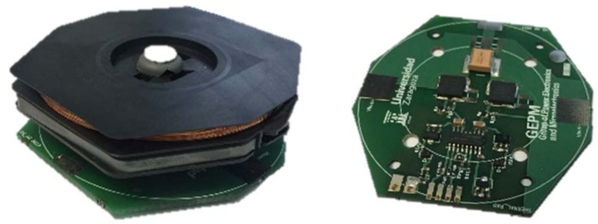


Fig. 6 Experimental prototype: single-coil inverter cell.

issues and enable high resistive materials heating, the proposed converter will take advantage of the use of GaN devices to operate at frequencies significantly higher.

B. Modulation and control strategy

The modulation and control strategy must ensure that the target output power is delivered at each coil while avoiding acoustic noise and complying with EMC standards [12], among other constraints [13]. The proposed control strategy combines square wave control [14], i.e. frequency control, pulse density modulation (PDM) [12, 15, 16], i.e. activation time control, and bus voltage control by using the common dc-dc converter to achieve the desired output power regardless the number of IH loads and operating conditions.

Fig. 3 shows an example of the proposed control strategy for two loads. PDM is applied so only one load is active at a time to enable different switching frequencies, i.e. square wave control, while avoiding acoustic noise. Besides, in order to be able to operate at frequency as close as possible to the resonant frequency to minimize harmonic generation, the bus voltage is adapted to for each load.

III. Implementation and Experimental Results

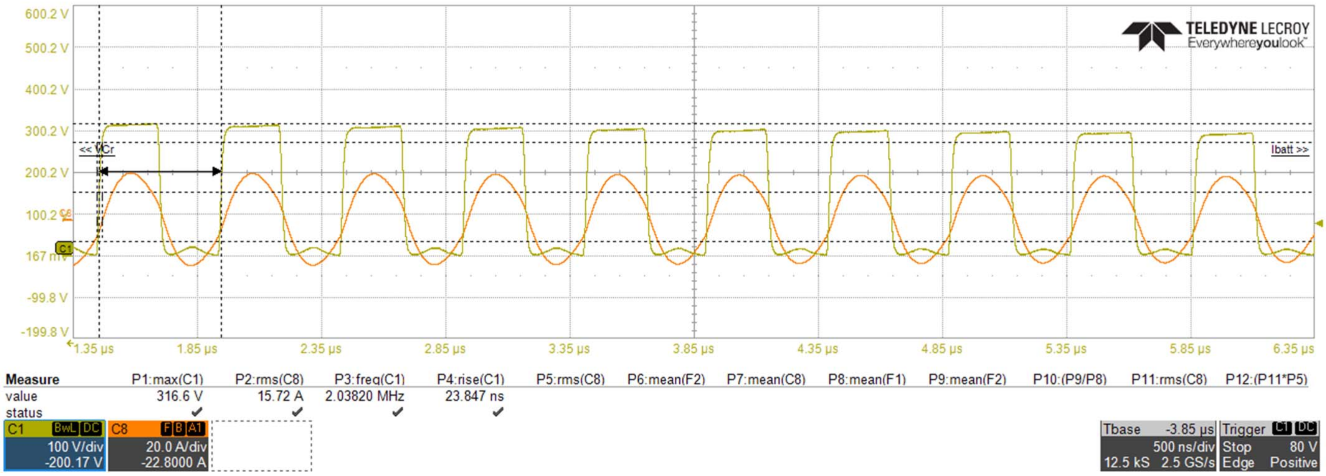
In order to prove the proposed approach, an experimental prototype has been designed and built. The proposed inverter features TPH3208LDG and TPH3208LS GaN devices from Transphorm. These devices follow a cascode configuration and the complementary pin distribution design ensures low stray elements for high frequency operation. In order to achieve high frequency IH, the resonant frequency has been set at 1.95 MHz. The IH coil has been designed to be L_{eq} = 1.5 μH whereas the resonant capacitor is C_r = 4.4 nF. Besides, ferrite flux concentrators have been used to maximize load coupling while avoiding coupling between adjacent inductors [17].

One of the key design challenges of the proposed multi-cell approach is to achieve proper thermal management [18] while achieving a high power-density implementation. To overcome this challenges, several alternatives have been evaluated, including the use of thermal vias in standard FR4 substrate, Insulated Metal Substrate (IMS) and metal (Cu) inlays (Fig. 4(a)). These alternatives have been evaluated using resistors with the same package, and the equivalent thermal resistance is summarized in Fig. 4 (b). IMS achieves the better thermal performance at a higher cost, whereas thermal vias and metal inlays achieve similar performance for this given implementation. Consequently, thermal vias were selected as the thermal management solution to achieve a high-power-density and cost-effective implementation. Fig. 5 shows a render of the final appearance of the inverter cell prototype with the induction coil attached in the top.

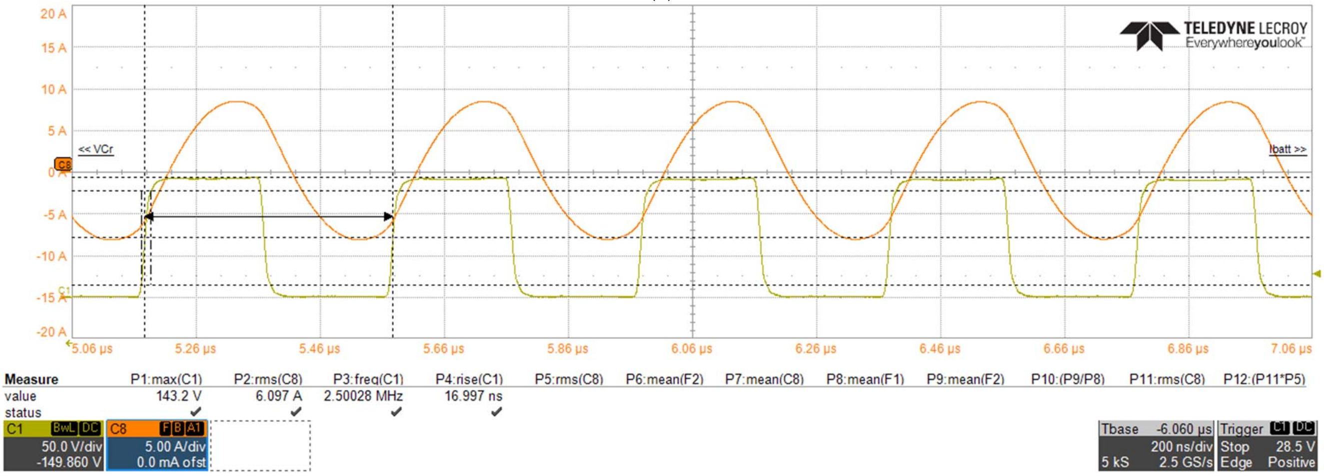
The proposed implementation has been built and tested using an 8-cm inductor using Litz wire for high frequency operation. Fig. 6 shows an individual inverter cell attached to the inductor, providing a full modular implementation. The main experimental waveforms of the proposed converter are shown in Fig. 7. Firstly, maximum power operation at 2 MHz is shown, proving the proper converter operation with 15 A RMS output current (Fig. 7 (a)). Besides, the operation at 2.5 MHz with output current reduced to 6 A RMS is shown in Fig. 7 (b). These results prove the effectiveness and high-power-density implementation achieved, together with its smooth operation at maximum power.

IV. Conclusions

Flexible cooking surfaces are the highest exponent of high performance IH systems providing the user with the highest degree of freedom and performance. In order to implement such system, this paper has proposed the design and implementation of a high-frequency GaN-based modular inverter. The proposed design takes advantage of GaN devices to operate at frequencies higher than 2 MHz, improving pot heating, and its thermal management system has been analyzed and optimized to obtain a high-power-density implementation. The proposed system has been experimentally verified under real operating conditions, proving the proper converter operation. As a conclusion, the proposed approach is considered as a high-performance alternative for future IH flexible cooking surfaces.



(a)



(b)

Fig. 7 Output current and output voltage operating at (a) 15 A RMS at 2 MHz and (b) 6 A RMS at 2.5 MHz.

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REFERENCES

[1] O. Lucía, P. Maussion, E. Dede, and J. M. Burdío, "Induction heating technology and its applications: Past developments, current technology, and future challenges," *IEEE Transactions on Industrial Electronics,* vol. 61, no. 5, pp. 2509-2520, May 2014.

[2] O. Lucía, J. Acero, C. Carretero, and J. M. Burdío, "Induction heating appliances: Towards more flexible cooking surfaces," *IEEE Industrial Electronics Magazine,* vol. 7, no. 3, pp. 35-47, September 2013.

[3] H. Fujita, N. Uchida, and K. Ozaki, "A new zone-control induction heating system using multiple inverter units applicable under mutual magnetic coupling conditions," *IEEE Transactions on Power Electronics,* vol. 26, no. 7, pp. 2009-2017, July 2010.

[4] H. Sarnago, O. Lucía, M. Pérez-Tarragona, and J. M. Burdío, "Dual-Output Boost Resonant Full-Bridge Topology and its Modulation Strategies for High Performance Induction Heating Applications," *IEEE Transactions on Industrial Electronics,* vol. 63, no. 6, pp. 3554-3561, 2016.

[5] O. Lucía, J. M. Burdío, L. A. Barragán, J. Acero, and I. Millán, "Series-resonant multiinverter for multiple induction heaters," *IEEE Transactions on Power Electronics,* vol. 24, no. 11, pp. 2860-2868, November 2010.

[6] I. Millán, J. M. Burdío, J. Acero, O. Lucía, and D. Palacios, "Resonant inverter topologies for three concentric planar windings applied to domestic induction heating," *Electronics Letters,* vol. 46, no. 17, pp. 1225-1226, 2010.

[7] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "High efficiency parallel quasi-resonant current source inverter featuring SiC MOSFETs for induction heating systems with coupled inductors," *IET Power Electronics,* vol. 6, no. 1, pp. 183-191, 2013.

[8] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "Multi-MOSFET-based series resonant inverter for improved efficiency and power density induction heating applications," *IEEE Transactions on Power Electronics,* vol. 29, no. 8, pp. 4301-4312, August 2014.

[9] H. Sarnago, O. Lucía, and J. M. Burdío, "A comparative evaluation of SiC power devices for high performance domestic induction heating," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 8, pp. 4795-4804, August 2015.

[10] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "Improved operation of SiC-BJT-based series resonant inverter with optimized base drive circuit," *IEEE Transactions on Power Electronics,* vol. 29, no. 10, pp. 5097-5101, March 2014.

[11] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "Analytical model of the half-bridge series resonant inverter for improved power conversion efficiency and performance," *IEEE Transactions on Power Electronics,* vol. 30, no. 8, pp. 4128-4143, August 2015.

[12] O. Lucía, J. M. Burdío, I. Millán, J. Acero, and D. Puyal, "Load-adaptive control algorithm of half-bridge series resonant inverter for domestic induction heating," *IEEE Transactions on Industrial Electronics,* vol. 56, no. 8, pp. 3106-3116, August 2009.

[13] S. Lucia, D. Navarro, B. Karg, H. Sarnago, and O. Lucia, "Deep Learning-based Model Predictive Control for Resonant Power Converters," *arXiv:1810.04872,* 2018.

[14] O. Lucía, J. M. Burdío, I. Millán, J. Acero, and L. A. Barragán, "Efficiency oriented design of ZVS half-bridge series resonant inverter with variable frequency duty cycle control," *IEEE Transactions on Power Electronics,* vol. 25, no. 7, pp. 1671-1674, July 2010.

[15] V. Esteve *et al.*, "Improving the efficiency of IGBT series-resonant inverters using pulse density modulation," *IEEE Transactions on Industrial Electronics,* vol. 58, no. 3, pp. 979-987, March 2011.

[16] H. Fujita and H. Akagi, "Pulse-density-modulated power control of a 4 kW, 450 kHz voltage-source inverter for induction melting applications," *IEEE Transactions on Industry Applications,* vol. 32, no. 2, pp. 279-286, March/April 1996.

[17] J. Acero, C. Carretero, R. Alonso, O. Lucía, and J. M. Burdío, "Mutual impedance of small ring-type coils for multi-winding induction heating appliances," *IEEE Transactions on Power Electronics,* vol. 28, no. 2, pp. 1025-1035, February 2013.

[18] E. Laloya, O. Lucía, H. Sarnago, and J. M. Burdío, "Heat management in power converters: from state-of-the-art to future ultra high efficiency systems," *IEEE Transactions on Power Electronics,* vol. 31, no. 11, pp. 7896-7908, 2016.