Induction Heating Appliances: 50 Years of Technological Success Paving the Path for Sustainable Homes

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Abstract — Creating a sustainable future is a transdisciplinary challenge where industrial electronics plays a key role by providing environmentally friendly solutions to daily processes. Domestic device electrification is a powerful tool for sustainable energy consumption and indoor air quality improvement. In this context, this magazine paper covers a relevant example of household appliance electrification with improved energetic performance: domestic induction heating.

Domestic induction heating has now been in the market for 50 years. This magazine paper reviews the main historical milestones in electrical cooking appliances, and it presents the enabling technologies and advances behind the success of current induction heating technology. Besides, recent technological development advancements and future trends are introduced showing the potential of induction heating to help paving the path to create a sustainable future.

Index Terms — Sustainable development goals, Industrial Electronics, Induction Heating, Home Appliances.

I. Foreword

Induction heating (IH) appliances have been in the market for 50 years, offering a cleaner alternative to gas, coal, or electric resistive heating with important benefits in terms of efficiency, safety, heating speed, and accurate control and performance [1]. This electrified heating method is a clear example of how industrial electronics possess a unique capability to impact our daily lives through a transdisciplinary use of technology, providing sustainable solutions. IH appliances combine the latest advances in microelectronics, power electronics, electromagnetics and electromechanical integration, among others, to develop new appliances that make our daily life easier and more sustainable.

After 50 years of commercial success and great technological evolution, this paper highlights the role of industrial electronics in creating a sustainable future, reviews the history of cooking technologies and induction heating, details and discusses the main enabling technologies and their state-of-the-art, and forecasts future advances and design trends.

II. INDUSTRIAL ELECTRONICS AND SUSTAINABILITY

Industrial Electronics (IE) discipline includes a wide variety of technical areas devoted to applying electronics and electrical sciences for the enhancement of industrial and manufacturing processes. As reviewed in [2], it acts as a key enabling technology for a myriad of domestic, biomedical, transportation, and industrial applications, making IE inherently multidisciplinary, and with many interdisciplinary synergies. As such, it is also called to greatly contribute to sustainability in the coming years.

Sustainability is a complex concept that includes all the technical and humanistic disciplines combined to achieve a balance between economic progress and the use of resources. In this context, in 2015 all the United Nations Member States adopted The 2030 Agenda for Sustainable Development. The core of this agenda is a set of Sustainable Development Goals (SDGs) that provides guidance to achieve sustainable development. These are constantly updated and reviewed, to assess its status and adapt to the always evolving social, economic and technical context.

While IE presents related drawbacks in terms of manufacturing and lifecycle of electronic components [3], it is fundamental to achieving several SDGs, and its capacity for innovation across diverse applications enables disruptive advancements that can create significant benefits in many other areas. In this paper, special attention will be paid to SDG 11: Sustainable cities and communities. In particular, and more related to IE actions, target

11.6 pursues "reducing the adverse per capita environmental impact of cities, including by paying special attention to air quality […]", and target 11.B "increasing the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change […]". This paper presents a technical solution to improve domestic sustainability through some of the latest scientific achievements in the field of industrial electronics. These advances are focused on improving a key process in our daily lives, such as cooking. Besides, as a consequence of the research and development efforts in the growth of these electronic products, a positive impact in SDG 9 is also produced, more specifically in target 9.5. Moreover, from the industrial point of view, the production patterns, basis of SDG 12, are also deeply analyzed to improve the product lifecycle, increasing recyclability and resource efficiency, lowering environmental impact, and reducing the carbon footprint.

In this context, this paper presents a relevant example of sustainability achieved through the electrification of domestic cooktops [4, 5]. To do so, many efforts have been made to optimize the product during its useful life [6] by improving its performance, efficiency or even components from an environmental point of view [7, 8]. This research effort, which has upgraded domestic induction heating technology to a new level of sustainability, has brought maturity to the technology, boosting its impact. Moreover, product development is still reliant on the latest research outcomes.

III. DOMESTIC INDUCTION HEATING HISTORY

According to Maslow's hierarchy of needs, human beings require to meet their food needs to advance towards more elevated emotions. To do so, humans have always applied the best cooking techniques available at the time.

At the end of the 19th century, as a result of early large-scale generation and distribution of electricity, a multitude of new electrical devices appeared. As had happened throughout history, this new technology was applied to cooking, producing the first commercial resistive electric stoves in the 1900s. That was a leap forward in our homes, allowing cooking without the need to use a fuel element and achieving improved control, cleanliness and safety. But the applications of electricity to cooking did not stop there. According to some versions, in 1945, Percy LeBaron Spencer, a Raytheon Company engineer researching magnetrons for radar applications, accidentally discovered that a candy bar he was carrying had melted during the workday. Investigating this phenomenon led to the development of the microwave oven, an appliance that is now widely used in many homes. At the end of the 20th century, in a context in which aspects such as speed and convenience of cooking, energy efficiency and safety became increasingly important, a new heating technology broke through supported by its intrinsic benefits: induction heating.

A. Faraday's law: an old acquaintance with new applications

Induction heating stoves base their operation on a well-known, but at the time unused for cooking, physical principle: electromagnetic induction. The experiments performed by the British physicist Michael Faraday resulted in the formulation, in 1831, of the principle of electromagnetic induction which was later complemented by Henry Lenz. This principle is used in a multitude of applications, including generators and transformers, allowing, undoubtedly, the great deployment of electricity in the late nineteenth century. In order to improve its application, several studies, as the one developed by James Prescott Joule, focused on the heat generation in electrical circuits, emphasizing the negative effects of the process and aiming for their mitigation.

However, at the beginning of the 20th century, recognizing the potential of this phenomenon, a new application emerged: induction heating [9]. It consists of the circulation of an alternating current of a certain frequency, usually in the range of tens or hundreds of kilohertz, through a coil to generate a variable magnetic field which is applied to the target material. According to Faraday's law, eddy currents or Foucault currents will be induced in it (Fig. 1). These currents, generate heat as a consequence of the resistive nature of the material due to the Joule effect, being the predominant heat generation mechanism in most industrial and domestic applications of induction heating. Besides the induced currents, magnetic hysteresis appears on materials with ferromagnetic properties, leading to additional power dissipation, making it advisable to use such materials.

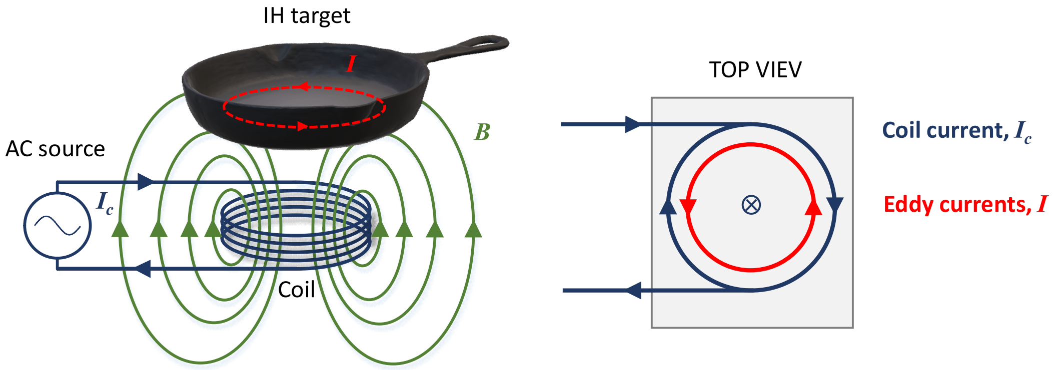

Fig. 1. Eddy currents (I, red) are induced on the surface of a cookware piece when applying an alternating magnetic field (B, green) generated by the flow of an ac current (I_c, blue) through a coil.

The electrothermal mechanisms explained above clearly allow the identification of some of the advantages that justify the growth of the technology to its actual maturity. Firstly, heating takes place directly in the target piece. This results in much faster and more efficient heating, increasing control over the process. It is also a non-contact power transfer, thanks to the electromagnetic field generated, achieving safer heating, and allowing us to keep the interface material, i.e. cooking surface, at a lower temperature, greatly facilitating cleaning.

For these reasons, induction heating, being completely different from those heating technologies used before, started to be used in industrial applications, mainly in metallurgy [10, 11]. But the application to the domestic environment was not immediate. The first references to domestic induction heating systems are the patents of Willis Mitchell and Arthur F. Berry around the 1900s. However, neither of them was commercialized, mainly because of the difficulty at that time of generating high-frequency electromagnetic fields in a simple, efficient and industrializable way. It was not until the second half of the 20th century that several advancements enabled the adoption the technology, with deep industrial roots, in the domestic area.

B. Induction heating: where microelectronics and power electronics meet to create a singular product.

Several technological developments occurred in the second half of the 20th century that made the commercialization of modern induction stoves possible (Fig. 2), primarily due to the development of power electronics.

Modern electronics is usually considered to have started with the invention of the first transistor at Bell Laboratories in 1947. Subsequent technological advances in structure, miniaturization and industrialization enabled an unprecedented technological breakthrough powered by electronic systems. Moreover, the development of power semiconductors enabled the emergence of the first applications of modern power electronics. First, thyristors (SCR, 1954) appeared, which allowed processing high power, but at low frequencies, improving the performance of industrial induction heating. Later, power transistors (BJT, 1960s; MOSFET, 1970s) were developed, with capabilities to process high powers at higher frequencies and total control of their state, being suitable for domestic induction heating.

The first commercial induction range was developed by Westinghouse Electric Corporation in 1972 [12]. Still, it was the invention that possibly changed power electronics forever, the insulated gate bipolar transistor (IGBT), attributed to B. Jayant Baliga in the early 1980s, the one that enabled the domestic breakthrough of the technology.

Paired with the development in power devices, the advances in power topologies, leading to the adoption of resonant converters, further increased the performance of domestic induction cooktops.

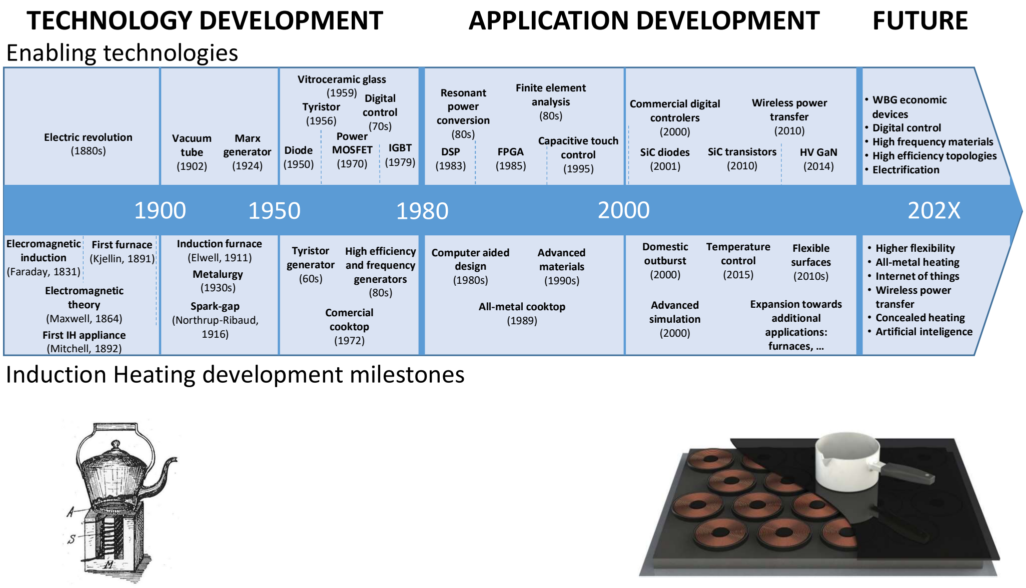

Fig. 2. Enabling technologies and IH development milestones.

Likewise, in parallel to the advances in power electronics, unprecedented advances in microelectronics were made, allowing the design of integrated control circuits, such as microprocessors, digital signal processors, and other programmable devices, which made it possible to perform increasingly complex functions at a reduced cost.

With these two technologies, power electronics, as a fundamental element for energy processing, and microelectronics, which allows precise control of the former, by the end of the 20th century sufficient tools were available for the design of a new generation of more efficient, reliable and cost-effective induction cooktops. 50 years later, IH technology has changed the way we cook and process energy in our homes. The next section details the main architecture of IH home appliances and its main enabling technologies.

IV. DOMESTIC INDUCTION HEATING ENABLING TECHNOLOGIES

The main building blocks of an IH cooktop are presented in Fig. 3. There, a two-stage conversion can be seen: firstly, a rectifier is used to obtain a dc voltage from the mains 230 V ac and then, an inverter is used to generate the required alternating current, with a frequency in the range of 20 kHz to 75 kHz, to avoid acoustic noise and minimize electromagnetic interferences (EMI). When circulating through the coil, this current produces the magnetic field that is applied to the cookware. Additionally, a filter stage is included to fulfill electromagnetic compatibility (EMC) regulations. Finally, the complete converter is controlled by means of a digital control stage.

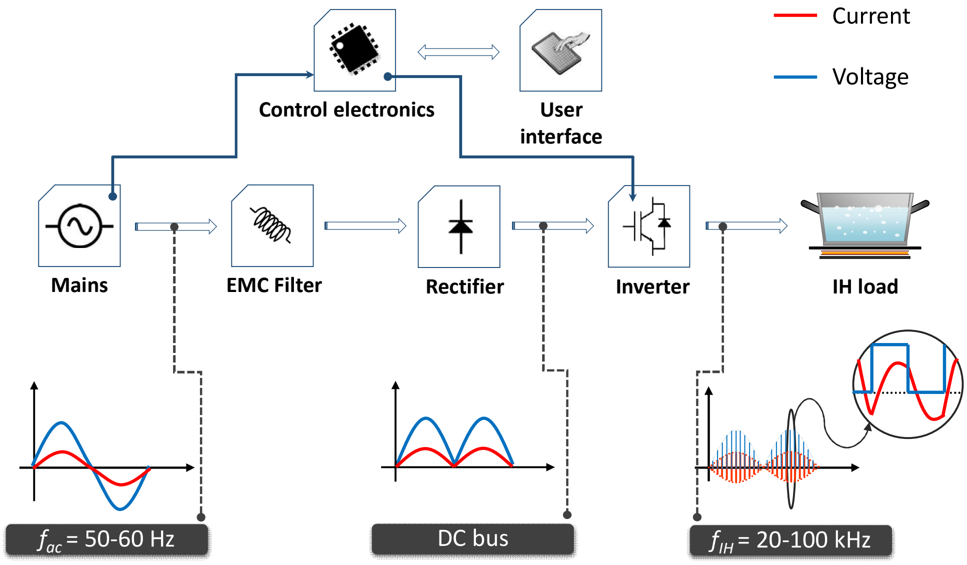

Fig. 3. Main building blocks of a typical IH equipment.

The maturity of the technology brings to the market complete appliances with several stoves, i.e. several inductors, with rated powers between 1 kW and 3.6 kW. Therefore, the electronic power and control systems, which are the core of the induction cooktop, require additional components and structures to configure a fully functional product.

As it is shown in Fig. 4, the technology is integrated in a compact case that provides structural support. The inductor is a planar spiral coil with several ferrites beneath that operate as flux concentrators, improving the electromagnetic coupling with the vessel and consequently the inductive power transfer. Moreover, an aluminum plate between the electronics and the coils provides electromagnetic isolation, and the vitroceramic glass, capable of withstanding high temperatures, serves as a support for the container to be heated while providing electrical isolation. Additionally, other elements, as the user interface, are required to achieve a proper cooking experience. The most relevant technologies from the IE point of view to achieve a fully functioning appliance are presented in the next lines.

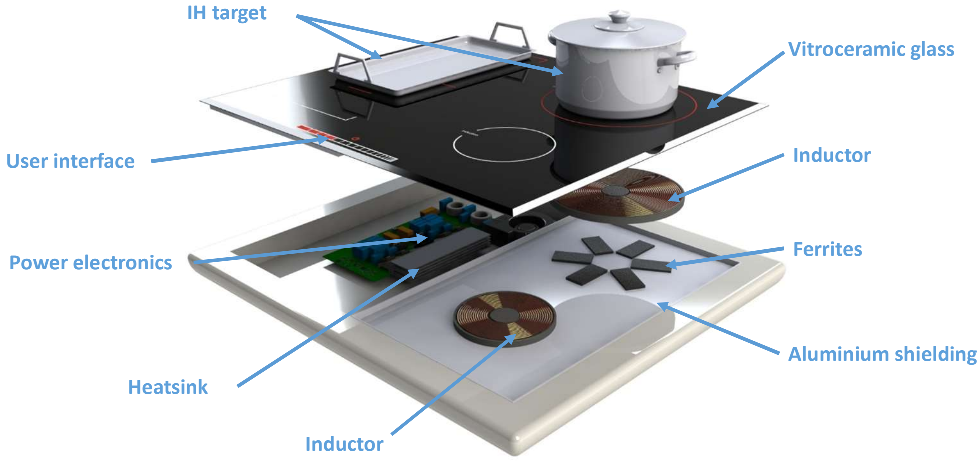

Fig. 4. Complete induction cooktop.

Classically, in order to conceptualize the cooking appliances, development has addressed the problem from different perspectives. From the electronics perspective, research has focused in the optimization of three different areas: the inductor-load system, the power converter, and the control electronics and modulation strategies [13]. In this chapter, the enabling technologies in each one of these groups are presented more in-depth.

A. Inductor-load system

The inductor-load system allows the transformation of the electrical energy into heat in the cookware base. It commonly comprises the coil, the cookware, and several additional components (Fig. 5 (a)).

The coil is generally the most relevant part, and its geometry is determined to produce a homogeneous temperature profile in the cookware base while achieving high efficiency. Thus, it is adapted to the stove size and shape, being usually constructed as a single layer or multilayer planar spiral coil. The main parameters for its design are the number of turns and the characteristics of the cable. In the beginning, a simple round wire was selected for the coil, being shortly after substituted by a rectangular section one to increase the surface-to-volume ratio. Nowadays, inductors are built with multistrand isolated wires, also known as Litz wires [14] as they achieve a tradeoff between efficiency and cost at the interest frequency range, from 20 kHz to 75 kHz.

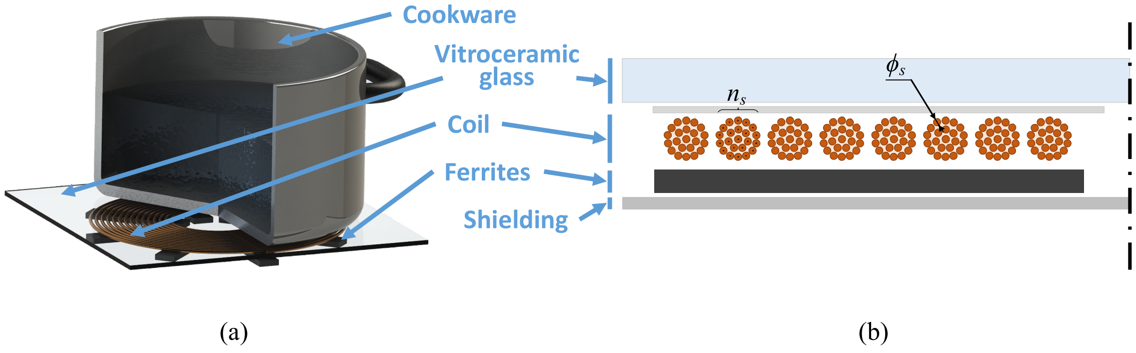

Fig. 5. Main components of the inductor-load system (a) and inductor section with Litz wire parameters (b).

Below the coil, several ferrite pieces, a high-permeability low-dissipative material are usually placed. Ferrites represent a low reluctance path for the magnetic flux and, therefore, they improve the magnetic coupling between the material and the coil. The coupling improvement is echoed as an increase in the efficiency of the electromagnetic energy transfer [15]. Ferrites can also present several drawbacks, such as magnetic losses, saturation due to overheating, and considerable weight.

An additional electromagnetic shielding layer, made of a low-dissipative metallic material, usually aluminum, is placed underneath to minimize interference with the electronics. Aluminum not only shields the electronics from the magnetic field but also contributes to compliance with applicable EMC regulations.

In order to design the inductor, the proper wire has to be selected, and the configuration has to be analyzed. Litz wire is defined (Fig. 5 (b)) by the number of strands, n_s, their diameter, ϕ_s, and the twist type, which can be calculated for a design frequency to achieve maximum efficiency. The strand radius should be less than the skin depth of the fields at the considered frequency, and the number of strands can be defined by the current flow at the nominal power. However, the number of strands of a Litz wire can be optimized by analyzing the nature of the ohmic losses. These losses have a dc component and an extra contribution due to two ac effects: skin and proximity effects. The higher the number of strands is, the lower the dc resistance but the higher the proximity losses. Conversely, the lower the number of strands is, the higher the dc resistance but the lower the proximity losses. Consequently, the optimum number of strands corresponds to the balance between dc plus skin and proximity losses [16].

The inductor presents usually a circular shape, and the number of turns is determined depending on the maximum power, inverter topology, and mains voltage. In order to do so, analytical modeling, and finite elements analysis (FEA) models have been used. The latest allows simulating the complete inductor-load system, considering the coil and material properties, geometries and operation parameters, i.e. coil and material temperature [17], magnetic field frequency [14, 18], magnetic field strength, etc. However, numerical methods require a long computation time, being more appropriate for the design verification. Moreover, the different order of magnitudes in component sizes, e.g. Litz wire strand vs cookware, requires the use of hybrid analysis [19], which simplify the wire model in the FEA tools. Lately, elliptic or squared inductors have been designed to achieve better adaptation between the inductors and cookware.

With these models not only a proper coil design with reduced power losses can be produced, but also the equivalent impedance of the coupled inductor-vessel system can be obtained. The equivalent impedance is required given the key relevance of this element in the design of the power converter. From the electrical point of view, it has been traditionally simplified to the series connection of equivalents resistance, R_{eq}, and inductance, L_{eq}, [20]. These parameters depend on many factors as the frequency, properties of materials, the structure of the induction-load system (ferrites, shielding, shape, distances…), and the excitation level. However, this simple model eases the mathematical treatment of the converter and its simulation and the physical analysis of the power transfer, as the heat generated is represented by the power dissipated on the resistance.

The efficiency of the electromagnetic energy transfer, also called induction efficiency, is defined as the energy transferred to the cookware by the energy supplied to the inductor-load system. The latter term includes winding, ferrite, and shielding losses. The inductive efficiency can be written in terms of resistances each one representing the losses in a part of the inductor-load system [21].

$$\eta_{ind} = \frac{R_{pot}}{R_{pot} + R_{winding} + R_{ferrites} + R_{shielding}} \tag{1}$$

The induction efficiency is a metric of the suitability of a design and usually is adopted as figure of merit for the design of inductor systems.

An additional concern when designing the inductor loads system, that has been more relevant with the development of induction cooktops with flexible cookware placement [22], is the coupling between the coils. In these cooktops, coils are contiguously placed, making it possible that several coils are covered by the same cookware piece. This situation is equivalent to several coils sharing the same core and thus, the design of low-mutual inductance coils has been analyzed in order to minimize the coupling [23].

Apart from electromagnetic considerations, temperature also affects the electromagnetic properties of materials [17], and, consequently, the parameters R_{eq}, and inductance, L_{eq} are also temperature dependent. The aforementioned dependencies (frequency, temperature, excitation level, etc.) make the modeling, characterization, and design of an induction system a multi-evaluated problem.

B. Power converter

The typical implementation of the power conversion scheme follows a two-stage ac-dc-ac converter architecture. Classically, the first ac-dc rectifying stage is common for all stoves while the dc-ac inverter is dedicated to each of them.

The rectifying stage provides a dc-link voltage while ensuring proper mains power consumption. The simplest implementation, and thus, the most common, relies on a full-bridge diode rectifier with a low-value dc-link capacitor. This way, it provides the dc-bus and high-frequency-current decoupling required by the inverter while ensuring an input power factor close to unity [24, 25] without the need for an additional power factor correction stage. Moreover, when the induction heating load non-linear effects make it necessary, the inverter modulation is adapted to ensure sinusoidal consumption. This allows to reduce the EMC filter requirements but results on a high-ripple dc voltage, decreasing the rms voltage.

On the second stage, an inverter generates the medium-frequency current transferred to the inductor [26], typically in the tens of kHz range. Several inverter topologies have been proposed focusing on different aspects such as efficiency, component number, or control complexity. Some early solutions implemented the inverter with a non-resonant topology [27] due to their inherently safe behavior, as there is no power transfer and no overcurrent when the cookware is removed. However, the tendency has been towards resonant or quasi-resonant inverters. These solutions include, besides the coil, an additional resonant capacitor, C_r, forming a resonant tank. This way, oscillating current, as a result of the capacitor and coil energy interchange, is achieved, resulting in higher efficiencies and power management capabilities [28]. In the following lines, the most common single-load topologies for IH are presented, classified according to the number of switching devices:

- Quasi-resonant single-ended (SE), or single-switch, topologies present the lowest possible power device count [29, 30]. However, these devices require high voltage blocking capabilities as they operate up to 3 to 4 times the mains peak voltage. Fig. 6 shows the voltage source zero-voltage-switching (ZVS) inverter and current source zero-current-switching (ZCS) inverter implementations of this single-switch topology. Their main disadvantage is the reduced number of modulation parameters to control the transmitted power, being the on-time the control parameter for the ZVS implementation, and the off-time the control parameter for the ZCS one. This results in a reduced controllability range, highly dependent on the load, leading to decreased efficiency when operating outside the soft-switching region. Moreover, current source inverters (CSI) require additional bulky inductors and are considered not suitable for compact and cost-effective implementations, i.e. domestic IH.

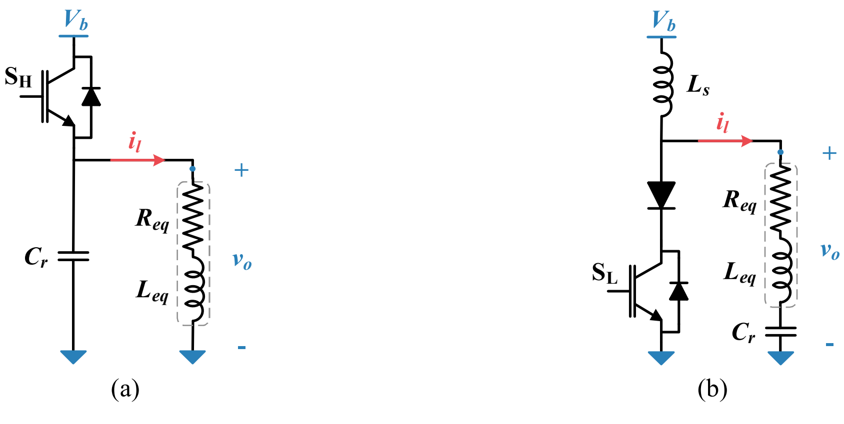

Fig. 6. Single-ended quasi-resonant inverters: voltage source zero-voltage-switching inverter (a), and current source zero-current-switching inverter (b).

• Half-bridge (HB) inverter topologies use two switching devices [31, 32]. The half-bridge series resonant inverter is currently considered the best alternative in terms of performance, cost, and complexity for the power levels considered in induction cooking. Consequently, the implementation using IGBTs and antiparallel diodes (Fig. 7) is used due its low cost and robustness. For this topology, the resonant capacitor is implemented in a split configuration to decrease the bus current harmonics. Additionally, operation is preferred above resonant frequency to achieve a ZVS commutation and by means of snubber capacitors, C_s, in parallel with the switching devices, the turn-off losses can be mitigated.

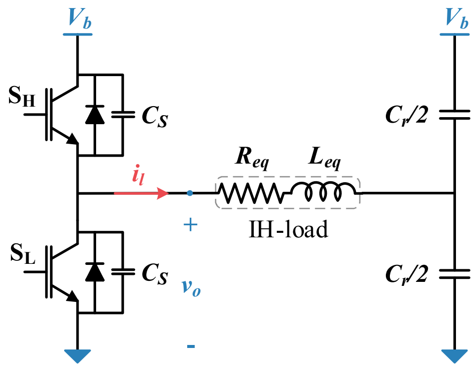

Fig. 7. Half-bridge series resonant inverter using split resonant capacitor and capacitive snubber networks.

• The full-bridge (FB) topology [33, 34] requires four switching devices, as it is shown in Fig. 8. It allows a higher output power as the voltage applied to the load is doubled in comparison with the HB configuration. The high reliability and efficiency of this topology makes it the most suitable one for industrial applications [20]. For this reason, the first end-user commercial applications where proposed based on it.

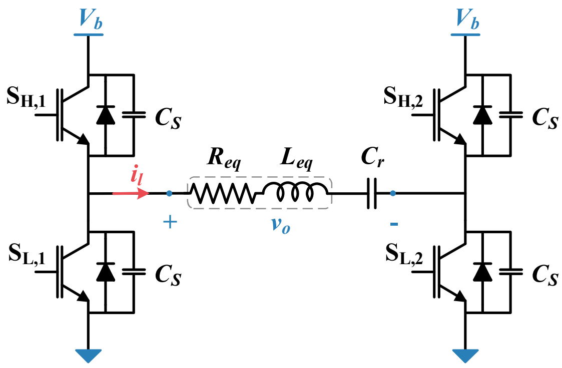

Fig. 8. Full-bridge series resonant inverter.

Higher flexibility in the topologies enables more complex modulation strategies, which provide several advantages on the operation. A wide spectrum of them would be presented in the control subsection.

Moreover, as aforementioned, commercial cooktops present several stoves. Therefore, to minimize the number of power devices and thus idle electronics while ensuring proper power transmission, several multi-output topologies have been proposed in the literature. These solutions, depending on their design procedure, can be classified in three different categories [35]. The first one includes the usage of single output inverters combined in a structure that share the remaining building blocks, i.e. the filter, rectifier and control electronics [36]. The second relies in load multiplexation, i.e. comprises the solutions that use a single output inverter and a IH load selection method [37]. Currently, the most common implementation of this technique use electromechanics relays to select IH load connection. The third and most heterogeneous one includes all the multi-output inverters, derived from classical topologies and with complete solid-state implementations. These solutions allow modulation strategies that operate at frequencies in the same order of magnitude as the excitation frequency applied to the coil [18, 38, 39].

It is also important to note that home appliances must comply with electromagnetic compatibility and safety standards to be commercialized. From the safety standards point of view, IEC 60335 Series are the most important, covering aspects such as electric contact, heating, fire risk or materials resistance, among others. Considering the wireless power transfer nature of this application, in the area of EMC radiated emissions standards are very relevant, as well as conducted emissions, covered in IEC 61000 series, CISPR 14-1 (emissions) and CISPR 14-2 (immunity), mainly. All these standards allow marking the appliance with the mark required for commercialization such as CE in Europe or UL/FCC in the US and the equivalent in other world regions.

C. Control electronics and modulation strategies

The main purpose of the control architecture is to process the necessary information for a safe and efficient cooking. In order to do so, the control electronics and peripherals shall generate the required activation signals for the converter to provide proper power transmission to the load based on the user input, guaranteeing that the currents, voltages and temperatures in the power devices and passive components remain within the expected conditions. In order to do so, constant monitoring of the load characteristics and adaptation of the modulation strategies to physical perturbations, e.g. material heating, cookware movement by the user, etc. have to be provided.

Control electronics are classically divided into three main blocks: the measurement system, the control logics, and the gate signal generation. Moreover, to provide a high-performance user-friendly product, connectivity functions are also included. In order to implement these functional blocks, several microelectronic solutions are used. The simplest solutions rely on one or more microcontrollers (μC). The most complex ones combine the μC with additional specific hardware, which is usually implemented on an Application Specific Integrated Circuit (ASIC) or a Field-Programmable Gate Array (FPGA) [13, 40], taking advantage of its parallelization capabilities, using the μC only for high-level tasks (Fig. 9).

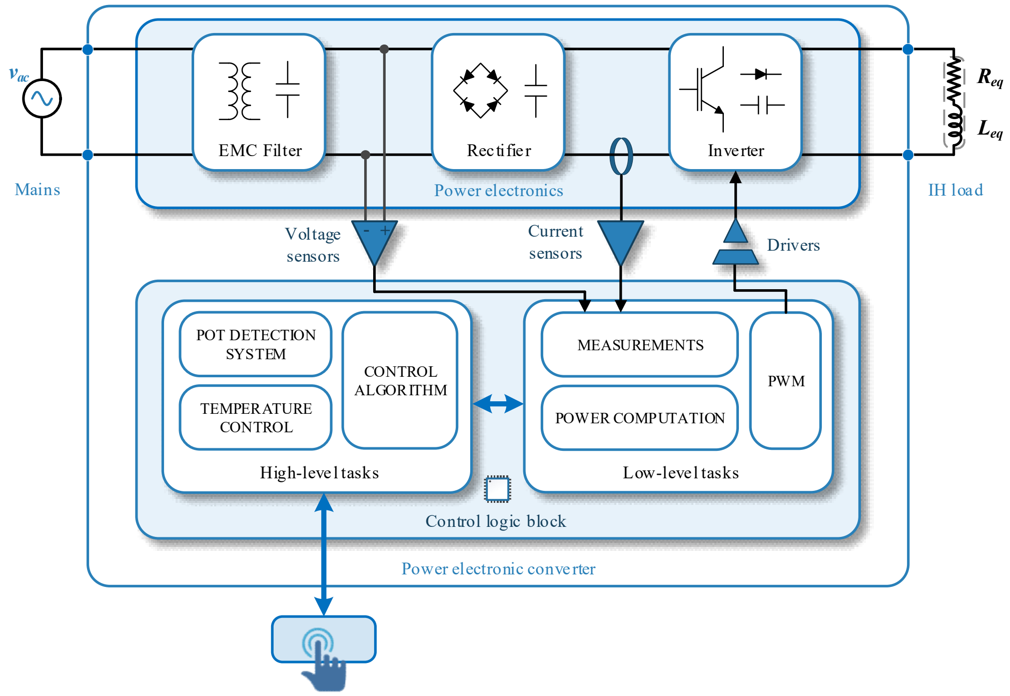

Fig. 9. Block diagram of the control stage of the IH converter.

The measurement system's purpose is the acquisition and processing of the electric signals of the power converter, typically the bus voltage, the inductor current, or the resonant tank applied voltage, and device temperatures. To do so, it requires the sensing circuitry, analog-to-digital converters and implemented digital signal processing algorithms. These algorithms allow monitoring and provide the different magnitudes needed for the control of the power electronics, such as transmitted power [41], load equivalent impedance [42], rms and peak currents and voltages, etc. Additionally, due to the interest of a more precise temperature control, thermal measurements of the cookware, by means of infrared sensors, or surface temperature measurement, which allows the estimation of cookware temperatures through precise modelling of the system [43], have also been proposed.

The control logic processes this information and, based on the selected control algorithm and the power level selected by the user, the modulation parameters that define the gating signals are generated.

With the modulation parameters as inputs the device gate signals are generated in a block with PWM capabilities. The modulation strategies depend on the inverter topology and have a great responsibility in the overall performance of the induction heating equipment. When using the resonant HB and FB topologies, which are the ones that present a higher number of degrees of freedom, the most common modulation strategies are the following:

- Square Waveform (SW) uses the inverter switching frequency, f_{sw}, as the power control parameter [44] (Fig. 10 (a)). The evolution of the transmitted power can be seen in Fig. 10 (b) for a series resonant inverter (SRI) and the converter usually works over the resonant frequency to operate under ZVS condition, leading to an inductive behavior and decreasing the power with the frequency increase. Therefore, the efficiency decreases for lower powers as the switching frequency, and thus the switching power losses, are greater. This solution allow the application of spread spectrum for EMI reduction.

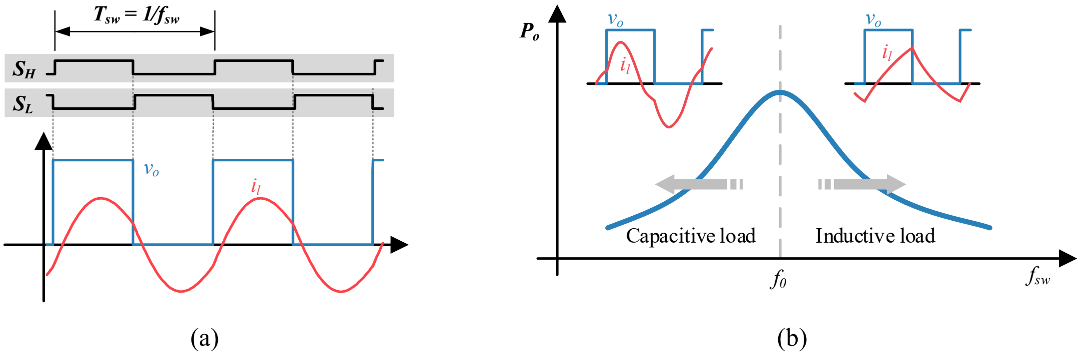

Fig. 10. Square waveform modulation parameters (a) and output power, P_o, and main waveforms of a resonant load as a function of the operation frequency, f_{sw} (b). The detailed waveforms depict the inverter output voltage, v_o, and current through the coil, i_l.

- Asymmetrical Duty Cycle (ADC) presents the duty cycle, D, as an additional control parameter, which results in an uneven voltage application (Fig. 11 (a)). This strategy allows a decrease in the transmitted power without increasing the switching frequency, leading to good efficiency in the medium-low power range [44, 45].

- Phase Shift Control and Asymmetrical Voltage Cancelation (AVC) require a FB inverter to be implemented. In both cases, the displacement between the leading and the lagging leg of the full bridge generates an additional 0V voltage level [33]. This way it is possible to control the transmitted power without changing the switching frequency or even the duty cycle (Fig. 11 (b)).

- Pulse Density Modulation (PDM) relies in the inverter alternative activation and can be used in combination with any of the aforementioned strategies to provide low power (Fig. 11 (c)). This is a very common and simple strategy as the output power is proportional to the active time, $t_{on,PDM}$, over the period, T_{PDM} [46]. However, power pulsation generates voltage fluctuation in the mains, which is limited by EMC standards.

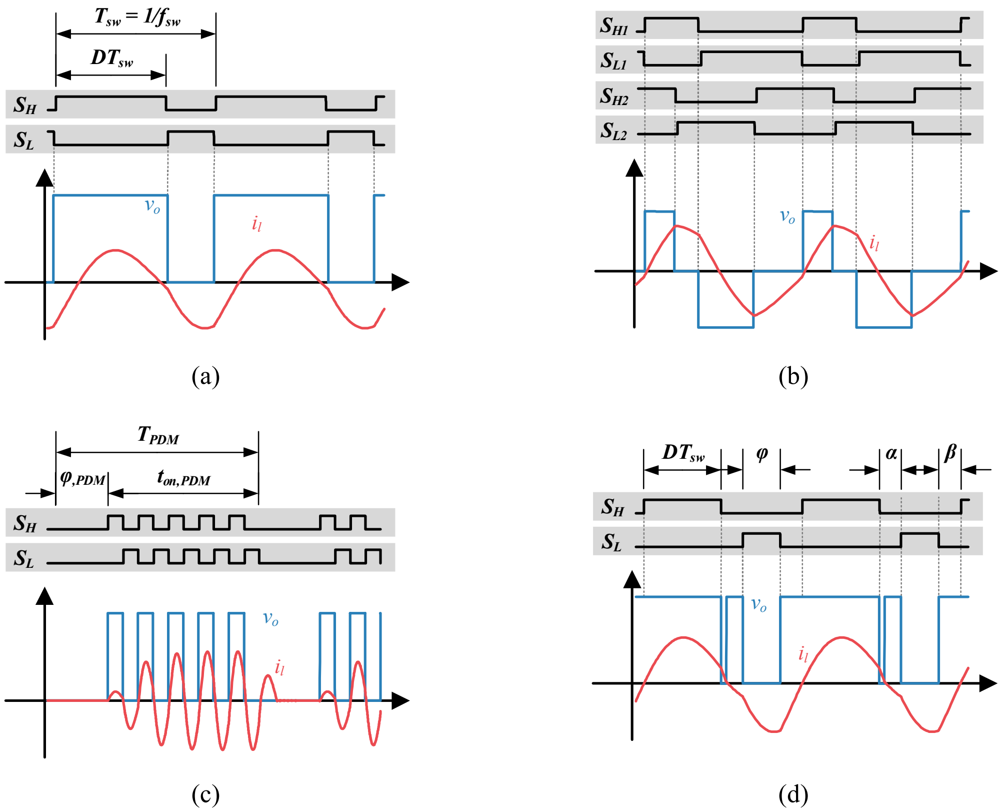

Fig. 11. Main modulation strategies: asymmetrical duty cycle (b), asymmetrical voltage cancelation (b), pulse density modulation (c), and non-complementary modulation (d).

- Discontinuous modulation strategies allow a non-complementary activation of the transistors of the inverter, leading to uncontrolled states where the voltage applied to the load depends on the current path [47] (Fig. 11 (d)).

These strategies present a high dependency with the load quality factor, Q, to achieve current discontinuity and therefore the generalized denomination non-complementary modulation strategies is also used.

V. FUTURE DESIGN TRENDS AND CHALLENGES

It is important to note that, besides the laudable effort to provide high-performance solutions in all aspects of our daily life, the driving force in the domestic IH development is to maximize its market penetration, pushing IH cooktops to lead the home appliance market against other heating technologies. In 2020, 66% of the 233 million hobs installed in Europe were electric, with the induction share being a 41%, slightly surpassed by radiant [4]. However, the 2020 sales presented a 70% market share for electric hobs, with a 50% of migrations from gas hobs towards induction cooktops, making it the current market leading technology. The American market, even though being pioneer in the IH development, presents a low penetration. According to [5], in California, only a 30% of residential cooking hobs are electrical being the induction share a 10%. Thus, the research effort is shaped to create different products with improved capabilities, being nowadays the most relevant prospective fields the ones presented in Fig. 12.

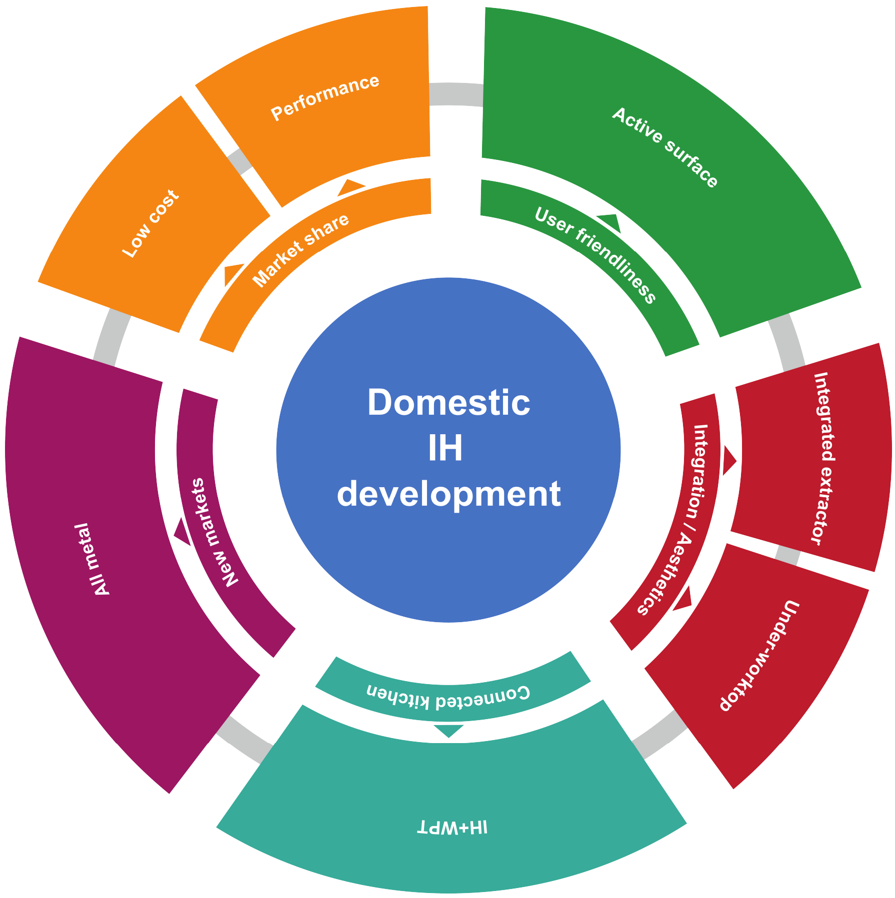

Fig. 12. IH development driving vectors and solutions.

As the spearhead for differentiation, active surface cooktops aim at eliminating cookware positioning restrictions, improving user-friendliness. Appliance integration goes a step forward, considering combining other parts of the kitchen into the cooktop. The integrated extractor simplifies the installation while the under-worktop solution substitutes the vitroceramic glass by the countertop, to provide a cleaner surface. Moreover, the similarities between induction heating (IH) and wireless power transfer (WPT) opens the possibilities of cordless small domestic appliances.

With a different approach, prospecting new markets requires overcoming the limitations of IH by being able to heat all metal utensils. In order to do so, higher frequencies are required. Moreover, the current market of induction cooktops is highly segmented: High-performance solutions aim for a high-quality cooking experience without economic restrictions, allowing the implementation of the latest transdisciplinary developments, and low-cost markets, that provide more accessible products, optimize the widely known solutions to decrease their cost.

Due to the maturity of the technology, the development approach is becoming more and more holistic, providing solutions that aim at improving performance by addressing simultaneously several IH-cooktop building blocks. Therefore, in this chapter, innovative research is classified by its impact on any of the aforementioned research challenges. The analysis aims to highlight their main contributions, while pointing out their impact on the development of new trends. Based on that, further developments may reach performance levels yet to be achieved.

A. Active surface

Fig. 13. Prospective research field, active surfaces. Image courtesy of BSH Home Appliances.

Active surfaces aim at improving the user experience by not constraining the cookware size, shape or placement over the cooktop [22]. In order to do so, these solutions erase the stove distribution (Fig. 13) by tessellating the surface with a medium to high number of small-size coils, presenting a level of flexibility several steps beyond size-adaptative concentric-coils systems.

Since its first proposal and in order to achieve high performance implementations several challenges have been faced. The need of small low-mutual-coupling coils with high efficiency has been addressed in the literature [23], being also relevant the size and shape to provide homogeneous heating with a good performance. Moreover, due to the medium-high number of coils used in the active surface, the design of inverter solutions with a reduced number of power devices has been the main reason for the development of the multi-output inverters presented in section IV [18, 38, 39].

More recently, power solutions answer to the need for higher resolution active surfaces, i.e. active surfaces that are able to control the transmitted power in smaller regions, either for using smaller cookware or improving heat homogeneity.

On the one hand, the approximation of using a higher number of small low-power coils in the active surfaces is undertaken by the design of new multi-output topologies, derived from any of the classical inverters. These solutions take advantage of improved semiconductor technologies, aiming at solid-state converter implementations. Recently developed solution in [48] presents a FB with a switch-diode module in series with each load allowing independent activation. Additionally, a five switch FB for independent power control based on AVC is used in [49]. In [25] a combination between HB and SE topologies with ac-ac implementation ensures independent power control. Moreover, a matrix structure, derived from the HB, is presented in [50] to minimize the number of power devices. Additionally, the usage of new wide band-gap (WBG) power devices with its improved switching characteristics also allows non-resonant solutions [51]. A different approximation uses this WBG technology for a dedicated low-power inverter for each coil [52], being the mutual effects of adjacent coils and the centralized power control analyzed in [53]. In the control field, progress on neural networks also enable more advanced features in these topologies. For example, each coil of a flexible surface, and its electrical parameters, which allow to calculate the coverage, are used in [54] to obtain the cookware size.

On the other hand, solutions that present medium size coils are also being evaluated, presenting bigger challenges in the IH-coil design. The usage of squircle coils is proposed in [55] to improve heat homogeneity. Another solution, in this case aiming for higher efficiency, relies on bigger coils with an overlapping to ensure higher sensibility of the cooktop to small cookware [56]. From this design point of view, not only coil design is being addressed, but other challenges in the power control are evaluated, providing modulation solutions that aim for precise transmitted power to partially covered coils [57], being implementable by means of model predictive control (MPC) [58].

B. *Integrated solutions*

(a) (b)

Fig. 14. Prospective research fields, integrated exhaust (a), under worktop implementation (b). Image courtesy of BSH Home Appliances.

Integrated solutions aim at improving the relationship between the cooktop and the kitchen. Most of the approaches are adopted from the mechanical area. However, electronics are an enabling technology to provide high-performance solutions. The two most relevant products are the integrated exhaust (Fig. 14 (a)) and under-worktop (Fig. 14 (b)) implementation.

The first one, the incorporation of the extractor structure in the center of the cooking zone, is possible thanks to the low temperatures on the vitroceramic glass and inside the cooktop case, which parmit the inclusion of additional electronic components. This solution allows air recirculation within the kitchen, presenting a positive impact on the thermal efficiency of the home by not disposing air at a comfortable temperature.

The second one, the integration of the electronics in the countertop, is a consequence of the transparency of the non-conductive materials to the influence of the magnetic field. The avant-garde approach to this solution takes advantage of improvements in the electronic power devices and inductor systems to increase the distance between the cookware and the induction coil [59]. Moreover, solutions with intermediate coils to increase the distance between the primary coil and the cookware are also prospected, being hybrid solution between large distance IH and inductive wireless power transfer (WPT) [60, 61].

C. Induction heating combined with wireless power transfer (IH + WPT)

Fig. 15. Prospective research field, WPT. Image courtesy of BSH Home Appliances.

The similarities between the induction cooktops and the wireless power transfer converters have opened the possibility to replace wired connections in small domestic appliances (SDA) with receiver coils and operate them directly over the cooktop surface (Fig. 15).

The requirements of both the IH cooktop, which operates as a primary, and the secondary, which comprises a SDA with the receiving coil, are being deeply analyzed in the literature. The topic presents several aspects concerning the different actors in the product lifecycle that have to be addressed. The first one is the user factor, as it requires the IH-WPT apparatus to operate even under misalignment conditions. Another one is the need to reach a compromise between the simplicity of the power electronics and control loops and the interoperability of primary and secondary circuits. To do so, an effort is being made towards a consensual WPT standard for cordless kitchen [62].

From the research point of view, these problems are also analyzed. A dual-functional system that operates with square waveform when the load is a cookware piece and chooses a constant frequency when the secondary is a SDA is proposed in [63]. Another solution that provides power to a resistive secondary is presented in [64].

An additional concern is the need for proper load detection to avoid heating foreign objects [65]. This problem arises as the system requires wireless communication for the WPT function, for which a minimum start-up power has to be transmitted. Thus application of foreign object detection (FOD) algorithms in WPT is proposed for mixed IH WPT systems [66].

Moreover, related to the topic but leaving behind the IH capability, the development of concealed WPT systems in the countertop to power those SDA is also being prospected [67].

D. All metal

The heating capability of IH depends on the currents induced in the material and the inherent resistance of the material to the current flow. This resistance is called sheet resistance and is defined as the inverse of the conductivity times the magnetic field penetration depth. The penetration depth, $\delta = 1/\sqrt{\pi f \mu_r \sigma}$, changes with the frequency, f, material conductivity, σ, and material permeability, μ_r. Therefore, materials with high conductivity present a reduced resistance and cannot be heated by standard cooktops with high efficiency.

Given the penetration depth definition, it is clear that the increase in the magnetic field frequency can provide a solution in which the cookware resistance is bigger than the coil one. However, it has been limited by semiconductor technology and its limitations in high frequency medium power transmission. Furthermore, the higher the frequency, the higher the ac-dependent losses in the windings, which reduces the efficiency of the power transfer [21].

In order to overcome these problems, frequency doubler FB modulation strategies are proposed [68]. Moreover, the improvement of semiconductor devices, the capability to operate above 100s of kHz, and the availability of Litz wires with strand diameters below one hundred microns has enabled the design of HB all metal applications [31, 69].

Additionally, the capability of the FB to operate each leg at a different frequency allows the development of solutions where several excitation frequencies coexist. In [70] a dual frequency FB is proposed in a ac-ac implementation with half rectifier and [71] integrates the rectifier in a second FB.

Alternative solutions propose reconfigurable series to series-parallel resonant circuits depending on the load [72, 73]. Additionally, more complex configuration, with two coils have been proposed [74].

E. Low cost

When compared with other heating technologies, IH presents better performance at the cost of higher complexity. Therefore, in order to achieve high cost-value, efforts to reduce the specific components is significant.

The most straightforward approach to navigate the highly competitive cost-oriented markets is the minimization of the number of power devices. Thus, in the last decade, solutions that aim at eliminating part of the rectifier appear in the literature. For example, [75] connect the mid-point of the HB inverter to a mains terminal, achieving a boost configuration. From a different design procedure, [76] proposes a single switch direct ac-ac topology.

These solutions offered several advantages besides the reduction in power components. However, being the full bridge rectifier an efficient implementation in energetic and monetary terms the solutions have been driven to optimize the inverter by means of reconfigurable topologies, minimizing the idle time of the electronics [77]. In this context, [65] rethinks the class-E single-switch quasi-resonant inverter. It provides a reconfigurable dual-output inverter that, for single output situations, is able to increase the power range. In order to do so, it requires the parallelization of both switch and resonant capacitor.

The dual-output approach is also analyzed in [78]. There, the three-switch half bridge [18, 39], proposed in the 90s, is reviewed in order to ensure ZVS operation with two different loads powered simultaneously with different power levels.

When considering more advanced cooking surfaces, as size-adaptative by means of concentric planar coils, more advanced topologies are proposed as a cost-effective feasible solution to avoid a two-inverter implementation. A configurable self-resonant coil powered by a single-switch topology is provided in [79], ensuring proper heat distribution depending on the cookware size.

Moreover, the redundancy of the load detection ancillary circuitry can be analyzed. Approaches to reduce the number of components aim at using the IH coil as a sensor given that the magnetic field, and thus the current through the coil, depends on the presence or absence of cookware. To minimize excitation circuitry, measurement of the system response during operation has been studied. One step further, to reduce the number of measurements required for load characterization [80] presents a solution that provides the load quality factor, Q, by measuring the resonant capacitor voltage. Additionally, in order to consider the optimal parameter to be measured, [81] compares several solutions for a quasi-resonant topology. Moreover, new trends aim at minimizing the transferred power to the load for initial load detection. In [82] measuring the response to a short number of pulses is evaluated.

Lastly, not only electronics are designed to achieve high-performance low-cost applications. The resonant tank is also analyzed in order to provide solutions in the coil construction. The implementation by means of PCB coils is being considered [83]. Additionally, the usage of aluminum wire for the coil has been proposed as a solution.

F. High performance

Performance solutions aim at improving the cooktop behavior in terms of energy efficiency, which results in improved reliability, longer life expectancy, faster heating, etc. and power transmission, improving cookware heating homogeneity. Moreover, user experience is a cornerstone for this development.

In order to do so, new designs are more focused on performance optimization of small areas, leading to less holistic solutions.

From the power converter point of view, the usage of new semiconductors is one of the most relevant approaches to improve efficiency [32, 84]. Additionally, the inclusion of a PFC stage is being prospected not only to improve mains power consumption but also to achieve higher bus voltages and reduce the current through the power devices [85]. Moreover, this additional stage is proposed to reduce acoustic noise [86]. Solutions that aim at distributing the currents between different IH coils have also been proposed, as the three-phase one in [87]. Others propose solutions in combination with the coil design. For example a five transistor FB to power two coupled concentric planar coils, improving heating homogeneity is analyzed in [88].

The development of new ferrite cores aim at improving efficiency by diverting the magnetic field to the coil. However, the distribution of this magnetic field may produce acoustic noise due to the exerted forces over the cookware [89]. Moreover, more complex designs of induction coils are also being studied for their capabilities to increase homogeneity, as the Halbach array type [90], and also cookware materials are analyzed [91].

In order to provide the desired power and achieve fast response and homogeneity in the heating, load identification is relevant. In general, load equivalent parameter estimation has been deeply analyzed, allowing online variation calculation [92]. Recently, some outcomes use this information to improve the pot detection system (PDS) by estimating cookware-size or material by means of neural networks [93] or clustering [94].

Relying on the load parameters, control algorithms have been developed. In order to include the parameter variation due to temperature increase or misalignment, a curve fitting algorithm is proposed in [95] and an adaptative optimization paradigm in [96]. Moreover, MPC is also proposed for its usage in IH [58, 97].

Last but not least, the estimation of the temperature in the cookware that allow a temperature mode control instead of a power mode control has also been analyzed recently, including non-centered cookware [98].

A classification of the avant-garde solutions presented in this chapter is summarized in TABLE I. There, besides its classification attending to the IH products, each of the solutions is related to the most impacted system in the cooktop.

TABLE I. LATEST CONTRIBUTIONS TO DOMESTIC IH DEVELOPMENT

	Power electronics	Inductor-load system	Control electronics
Active surface	[48] Multi-output FB with load series switch-diode. [49] Three switch leg FB for multi-output operation. [50] Matrix multi-output solutions. [51] Non-resonant multi-output FB. [52, 53] Dedicated HB module. [25] HB and SE multi-output ac-ac converter.	[55] Squircle coils. [56] Overlapped inductors.	[54] Neural network cookware size calculation. [57] Modulation strategy for single-frequency multioutput converter. [58] MPC of multi-output converter.
Integrated	[59] Far range IH.	[60] Coiled cookware for long distance IH. [61] Coiled secondary for shape adaptation.	
IH+WPT	[63] IH+WPT system with resonant capacitor selection.		[66] Foreign Object Detection.
All-metal	[31] All metal design of Boost HB. [70] Dual frequency FB ac-ac converter. [71] Dual frequency double FB ac-ac converter. [72] Reconfigurable series series-parallel resonance. [73] Reconfigurable LC-LLLC resonant tank.	[74] Intermediate coil resonator.	[68] Frequency doubler and “tripler” modulations
Low Cost	[76] Single switch direct ac-ac converter. [65] Parallelization of classical class-E to increase power range. [78] Three switch HB to power two loads simultaneously. [79] SE converter with self-resonant coil to adapt to the cookware size.	[83] PCB coils.	[80] Single measure quality factor calculation. [81] Single measure load identification. [82] Low energy load identification.
Performance	[32, 84] WBG usage. [85] PFC for higher bus voltage. [86] PFC for noise reduction. [88] Five switch FB for homogeneity with concentric planar coils. [87] Triple HB for current distribution.	[88] Coupled concentric planar coils for heat homogeneity. [89] Coil design based on exerted forces.	[92] Online load parameter calculation. [93] Neural network PDS. [94] Clustering PDS. [95] Curve fitting control algorithm. [96] Adaptative optimization paradigm algorithm. [58, 97] MPC. [98] Cookware temperature estimation.

VI. FINAL REMARKS

Domestic IH has been half-century enabling a progressive electrification of households. Hoisting its intrinsic advantages, such as fast and precise heating, high efficiency and safe and clean operation, induction has convinced a large userbase of its benefits, becoming the first-choice domestic heating technology. This leading position has been achieved by means of an important research effort, producing progressively sophisticated solutions, with differential features.

To overcome the barriers that prevent the complete adoption of electric cooking, researchers and manufacturers must focus on both technical and cultural aspects. From the design point of view, appliance and operation cost reduction, product life expectancy increase, independence of the cookware, and user experience are major players. For this reason, as presented in section V, the maturity of the technology has not diminished the research interest toward it. Besides, cultural aspects require all agents to better convey to the general public the benefits of IH in comparison with its counterparts, mainly gas hobs, in terms of performance, efficiency, and air quality.

Moreover, future research challenges, consequence of the integration of groundbreaking technologies and new developments in the field of industrial electronics should benefit from the research environment generated around this niche topic, listening to the different voices, but without getting lost in a myriad of paths to improve the appliance. This way, progress based on methodical and structured research and high-quality discussion forecast a future in which new levels of sustainability and user experience will be achieved.

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