Multi-Output Resonant Power Converters for Domestic Induction Heating

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***Abstract*—Induction heating has become the most relevant domestic heating technology due to its accurate power control, clean operation and high efficiency. Current design tendencies aim to reduce limitations in pot positioning to increase the cooktop versatility and to improve the user experience. These desired flexible surfaces are implemented by means of multi-coil structures which require the design of new multi-output power converters. This paper reviews and classifies the different inverters proposed in the literature to power multi-coil structures, and analyzes them in terms of versatility, performance, and component count.**

Keywords—Induction heating, resonant inverters, multiple output, home appliances

I. INTRODUCTION

Since the first domestic induction heating (IH) cooktops commercialized in the early 70s, IH has become the market leading technology for home appliances due to its fast heating, safe and clean operation, and efficiency [1]. In order to reach this position, research efforts have faced the design problem form different and complementary perspectives.

The main blocks of an induction cooktop are presented in Fig. 1. It includes an electromagnetic compatibility (EMC) filter, a rectifier stage to obtain a DC bus voltage, V_b, the inverter and the IH load which is typically modelled by its series equivalent inductance, L_r, and resistance, R_L [2]. The analysis and optimization of each of this blocks can be pursued separately, however, as they are interrelated, each design choice influence the remaining.

One of the most relevant design challenges of the last 15 years has been the implementation of flexible surface induction cooktops [3]. This functionality aims to boost the product differentiation by creating a new paradigm where pot placement is not constrained anymore, leading to improved user experience. In order to implement such technology, important research has been performed in the fields of electromagnetic compatibility, inductor design, control strategies, and power converter topologies.

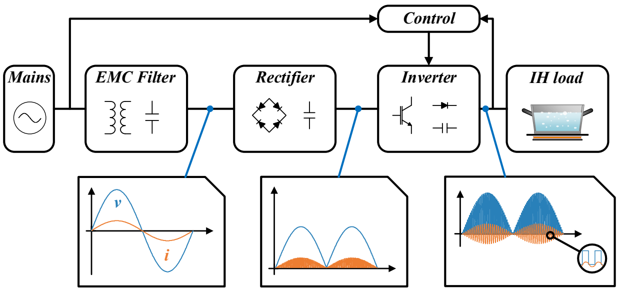

Fig. 1. Domestic induction heating appliance block diagram.

II. INVERTER REQUIREMENTS FOR FLEXIBLE SURFACES

The purpose of flexible surfaces is to allow the placement of any pot with any shape in any position over the cooking appliance. This proposal presents several challenges in order to provide robust, versatile, and cost-effective implementations that improve the user experience.

The surface construction is done by tessellating the area with small or medium size coils (Fig. 2). Thus, the topologies have to present the capability of powering a medium to high number of coil-pot structures, or IH loads, being this quantity higher than the classical four hob structure.

Additionally, the surface configuration eliminates pot positioning and, as a consequence, the pot-coil coupling can vary even between inductors under the same pot. This variation leads to different L_r and R_L parameters for each IH load.

Combining this variation with the different pot power set point the inverters have to allow independent power control in order to ensure safe operation for the topology and optimal power delivery. In order to solve this constraints, the study of multi-output resonant converters has become one of the most prolific research fields in the development of induction-heating flexible-surface appliances [4].

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Considering this background, this paper reviews the state-of-the-art of the resonant power converters proposed for its implementation with flexible surfaces. The remaining of this paper is structured as follows: Section III describes the most relevant design proposals for such topologies in the literature. Section IV analyzes and compares the presented topologies, and Section V draws the main conclusions.

III. MULTIPLE LOAD RESONANT POWER CONVERTERS

With the purpose of presenting a detailed overview of the studied inverters, a classification based on the topology design principle is performed. This group generation splits the multiple output topologies in three categories. The first one includes the clustering of single output inverters that may share, or not, some building blocks, i.e. the rectifier and the filter. The second group, called load multiplexation, comprises the alternatives that use a single output inverter and a configuration method to select which IH load is connected. The third and most heterogeneous group, called multi-output topologies, includes the multi-output inverters that are controlled with different modulation schemes that operate at similar order of magnitude as the switching frequency (Fig. 3).

A. Single-output inverter parallelization

The parallelization of single output inverters, as shown in Fig. 4, is a straight-forward implementation for multi-coil IH systems [5]. A typical induction cooktop, that is comprised of two to four hobs, is then powered by the combination of classical resonant inverters (Fig. 5), such as the full-bridge (FB) [6-8], half-bridge (HB) [9], single-ended – zero current switching (SE-ZCS) [10] or single-ended – zero voltage switching (SE-ZVS) [11, 12].

The use of well-known building blocks allows an easy topology design and implementation. Additionally, due to the single inverter analysis, it is possible to control them with robust and efficient modulation strategies [13, 14].

However, when the coil count increases, the number of power devices grows linearly, being significant for the FB and HB implementations and, consequently, leading to a bulky and expensive implementation. Additionally, independent load power control becomes more complex as switching frequency constraints appear. In order to avoid intermodulation noises [15], single frequency power control strategies increase their relevance and, especially for SE combinations, the calculation of resonant tanks with spaced enough resonant frequencies may be necessary [16]. Therefore, this group is usually used for a low IH load count.

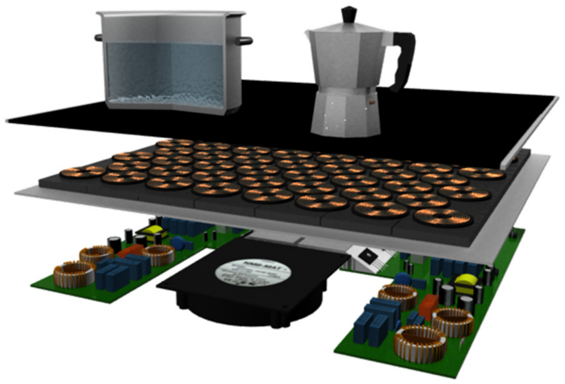


Fig. 2. Induction cooktop with a flexible surface implementation.

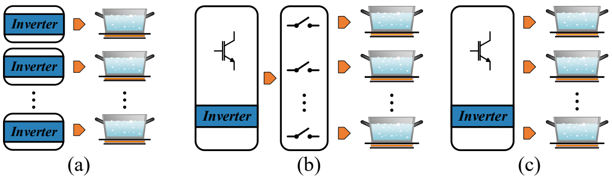


Fig. 3. Classification of the multiple output power converters for application with IH loads: single output inverter parallelization (a), load multiplexation (b), and multi-output inverters (c).

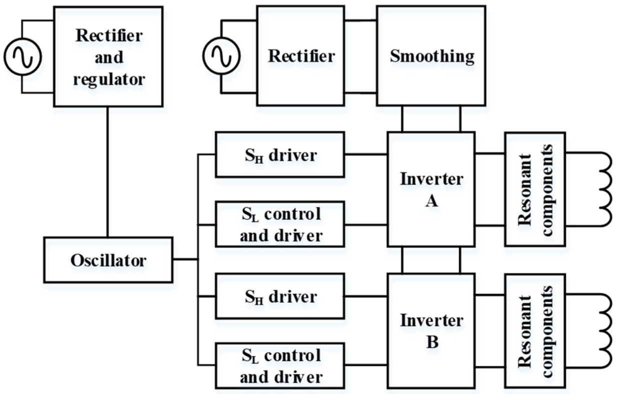
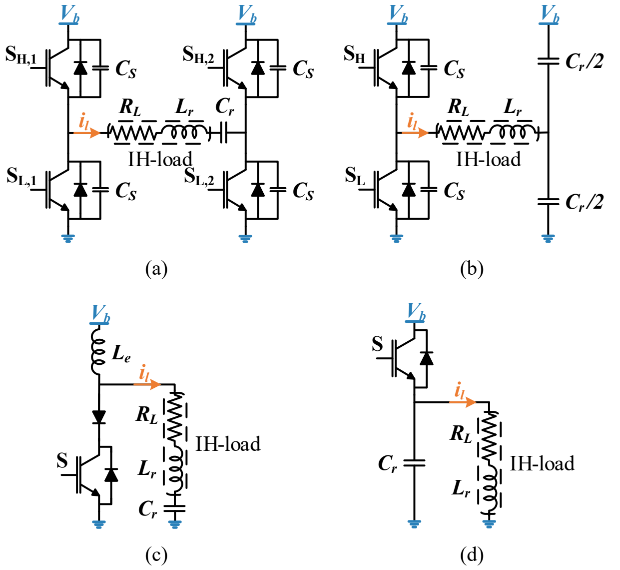


Fig. 4. Inverter parallelization schematic proposed in [5].



(a) (b)

(c) (d)

Fig. 5. Classical topologies used in induction heating: full-bridge (FB) (a), half-bridge (HB) (b), single-ended – zero current switching (SE-ZCS) (c), and single-ended – zero voltage switching (SE-ZVS) (d).

B. *Load multiplexation*

Load multiplexation technique relies on the use of a single inverter to feed two or more IH loads by selecting the current path. As a consequence, the desired output power is reached by the combination of the modulation strategy, i.e. variable switching frequency, and the time averaging of the different IH-load activations.

The most commonly used topology is the series resonant half-bridge inverter with two multiplexed loads (Fig. 6) that may share, or not, the resonant capacitor [17-19]. For both cases, this topology can be extended to the desired number of loads. However, it must be considered that increasing the number of loads may compromise the correct output power control due to the increased constraints in the multiplexed control.

For most of the reviewed architectures, load connection and disconnection is done by electromechanical relays [2]. Consequently, the IH load multiplexation is done at low frequency due to the long turn-on and turn-off relay settling times, that reduce the active times of the loads. This low frequency reduces relay noise repetition [20] but leads to uneven boiling perceived by the user and power consumption restrictions, i.e. the flicker regulations [21]. These are severe limitations of this approach that affects both the user and technical performance of the final implementation.

In order to overcome these problems, [22] proposes a two-inverter topology with a half wave rectifier so that each HB is connected to a mains half-cycle and the remaining is used to reconfigure the relays. This approach solves additional problems as the non-zero current commutation of the relays but reduces significantly the load output power.

In addition to the presented topologies, the load multiplexation by means of an electromechanic relay can be combined with inverter parallelization. This way it is possible to increment the maximum power in the active load by connecting two inverters in parallel when one of them is not being used [15], as shown in Fig. 7. Additionally, this parallelization can improve the inverter efficiency and increase the lifecycle of the power devices [23]. However, the use of relays makes the pot detection system implementation even more challenging [24].

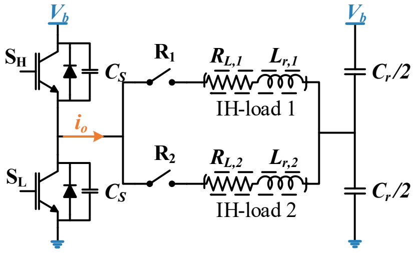


Fig. 6. HB inverter with two multiplexed loads.

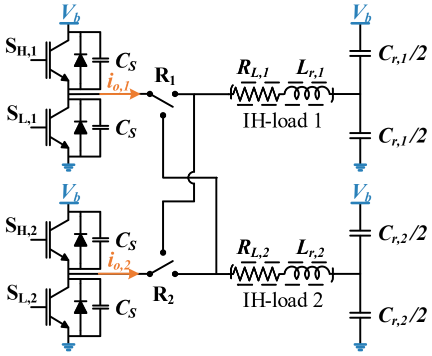


Fig. 7. Half-bridge inverters parallelization scheme to power a single load.

This recombination presents high advantages when the coil layout presents a hierarchy, as occurs with the concentric layouts [25]. In Fig. 8, a concentric planar coil inverter combination is presented. Additionally, this topology shows a resonant capacitor compensation structure due to it being shared by different loads.

C. *Multi-output topologies*

In order to solve the low frequency load multiplexation issues of the relay-based implementations, several multi-output topologies have been analyzed in the literature. Moreover, the proposed alternatives tend to present additional advantages to direct device substitution [26], such as reducing the device count or increasing the inverter versatility. As a consequence, this is the most promising group and, at the same time, the most heterogeneous one.

In [2] a HB topology with parallel IH loads uses frequency selection to choose the active load. This alternative relies on capacitor calculation to generate resonant tanks with spaced-enough resonant frequencies (Fig. 9). This way, power control of the active load can be selected by means of the switching frequency while the remaining resonant loads present high impedance paths. This topology presents several restrictions such as wide switching frequency range, non-ideal infinite impedance paths, and alternative load activation.

In order to power both loads simultaneously, [27] proposes the FB inverter to allow dual frequency operation by using a different switching frequency in each of the legs. This

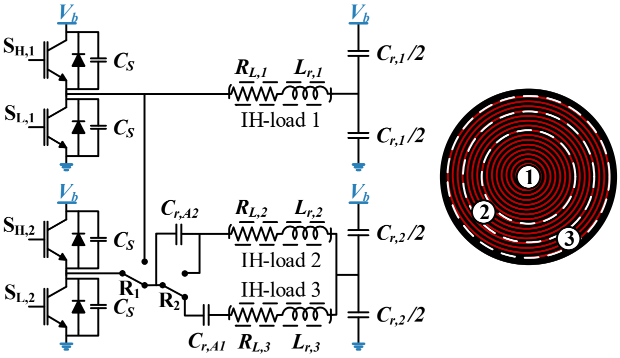


Fig. 8. Half-bridge inverters parallelization for usage with concentric planar coils.

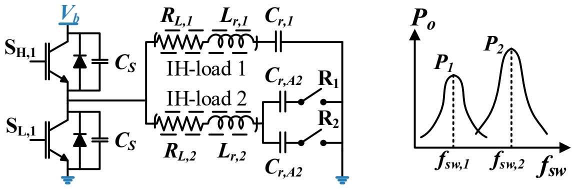


Fig. 9. Frequency-selection-based HB inverter.

technique is also used in industrial IH to improve heating processes in complex geometries [28].

A different synthesis method to obtain a two output FB inverter is utilized in [15]. The two-output three-leg FB inverter shown in Fig. 10 operates with asymmetrical voltage cancelation to obtain independent power control. Additionally, configuration electromechanical relays allow the parallelization of the IH loads in case only one of them is active. In [29] a multiple load generalization is analyzed and the three load with configuration relays is proposed.

In [30] the common leg of the two-output three-leg FB inverter is used to implement a boost power factor correction (PFC) stage (Fig. 11). This modification improves the mains current consumption without increasing the power device count. However, the new topology requires a series inductance an a more complex control.

A similar boost approach to the two-output three-leg FB inverter is followed in [31, 32] obtaining a higher reduction of the device count (Fig. 12 (a)) as only two out of the four diodes of the rectifier are needed. Additionally, the proposed inverter is proposed for any number of IH loads. An alternative form as a combination of paralleled HB inverters is proposed in [33] (Fig. 12 (b)).

In [34], a three switch topology derived from the HB is proposed to power two loads. The inverter, depicted in Fig. 13, operates by creating an alternative path for the current. Thus, depending on the active switch, a HB series resonant structure is defined by the remaining. This inverter is compact and cost-effective and can be generalized to any number of loads. However, the load activation is necessarily alternative and the addition of semiconductor devices in series degrades the current path and increases the conduction power losses.

Based on the same principle, [35] presents a FB structure to power two loads with a shared resonant capacitor and semiconductor devices to short circuit each coil (Fig. 14). As in the previous case this structure leads to an alternative load activation and current path degradation, but in contrast it comprises a higher number of power devices.

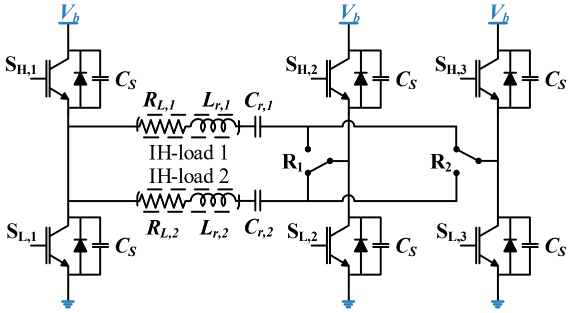


Fig. 10. Two-output three-leg FB inverter.

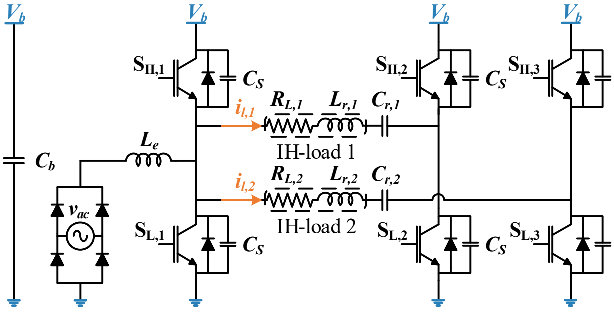


Fig. 11. Two-output three-leg boost-PFC FB inverter.

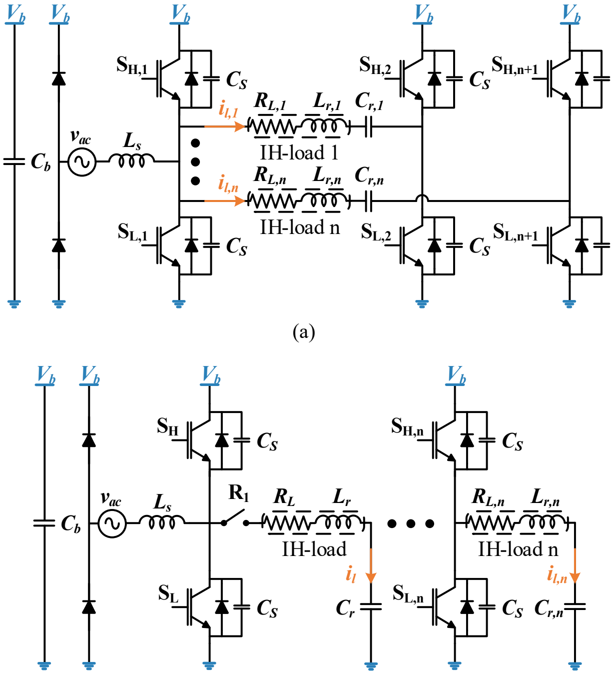


Fig. 12. Multi-output three-leg boost-HB-rectifier FB inverter (a) and HB inverter (b).

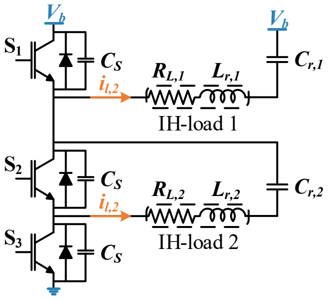


Fig. 13. Two-output three-switch HB-derived inverter.

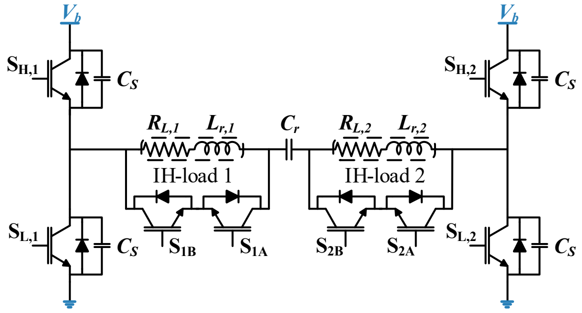


Fig. 14. Two-output series FB with coil short circuit devices.

Several multi-output resonant inverters derived from the HB are proposed in [36]. The first inverter, shown in Fig. 15, uses three switching devices to power two loads both alternatively and simultaneously with almost independent power control. For this topology, single coil activation relies in the coil short circuit. However, for multiple active coil, the power control is done by switching frequency selection and cascaded duty cycle. This master slave hierarchy in combination with ZVS limitations for asymmetrical control reduce the power control flexibility.

The second inverter (Fig. 16) uses two HB inverters to feed four different loads. Two of the IH loads are connected to the midpoint of the HB and their power is controlled by switching frequency selection while the remaining are connected in series between the middle point of the HB, forming a FB, and its power is selected by phase shift. This topology greatly reduces the number of power devices but presents a complex control which can be only applied with similar IH loads.

The last topology (Fig. 17) is described as a three-switch topology generalization. Even though it is a parallelization of single load half bridge topologies, it is included in this subsection because it presents an additional power transistor and an inductance to ensure ZVS commutation independently of the duty cycle. As a consequence, it allows single switching frequency power control.

In [37, 38] a HB common block inverter with an independent load series transistor is proposed. This inverter can operate by multiplexing the loads but also with alternative control modes such as discontinuous control [39]. The topology is presented in Fig. 18 (a) while its deployment to FB is shown in Fig. 18 (b) [40, 41].

In order to obtain similar performance and device count without the need of high current rating in the common block, a time-sharing inverter is proposed in [42]. The converter, derived from the SE topologies, can be seen in Fig. 19 and is

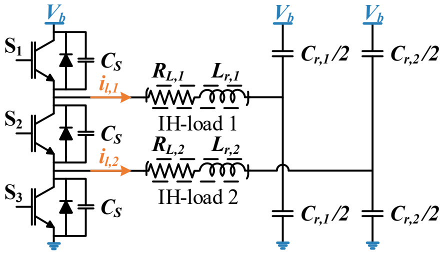


Fig. 15. Two-output three-switch HB-derived inverter with independent power control for two IH loads.

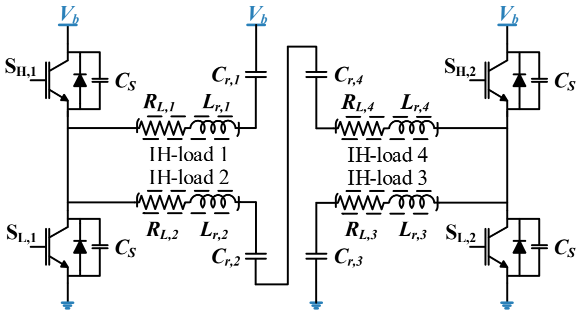


Fig. 16. Four-output two-HB inverter to power four similar IH loads.

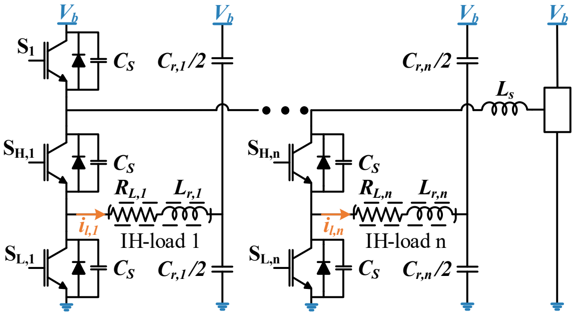
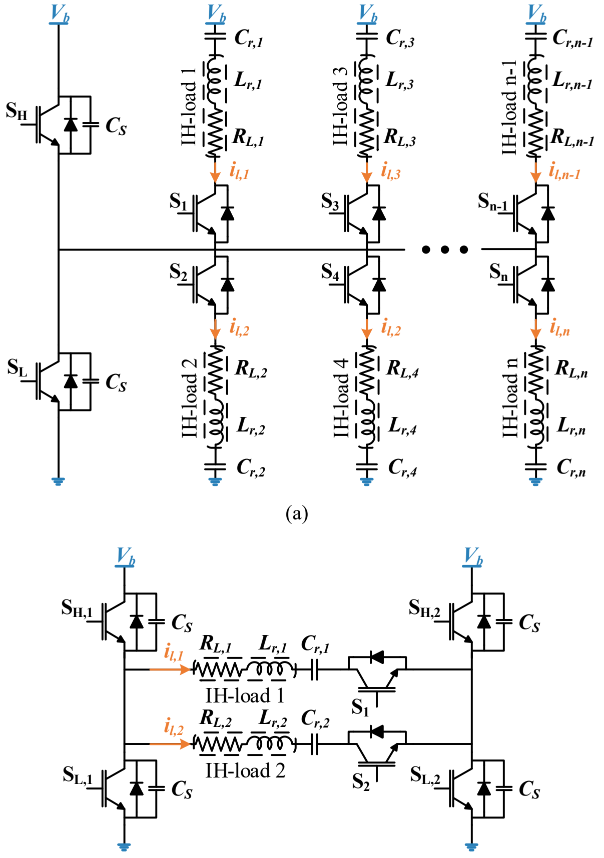


Fig. 17. Multi-output three-switch HB-derived inverter with series coil to ensure ZVS switching.



(a)

(b)

Fig. 18. Multi-output common-HB (a) and common-FB (b) inverters with load-series transistor.

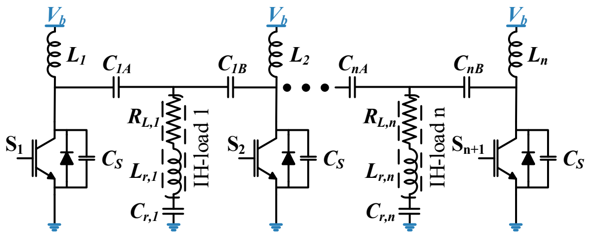


Fig. 19. Multi-output SE-derived time-sharing inverter.

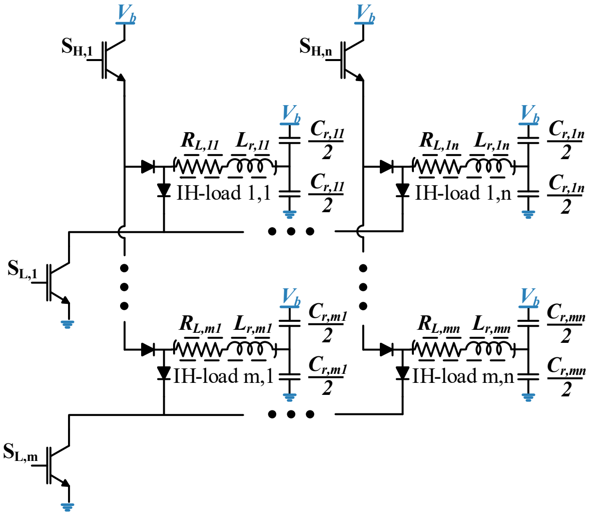
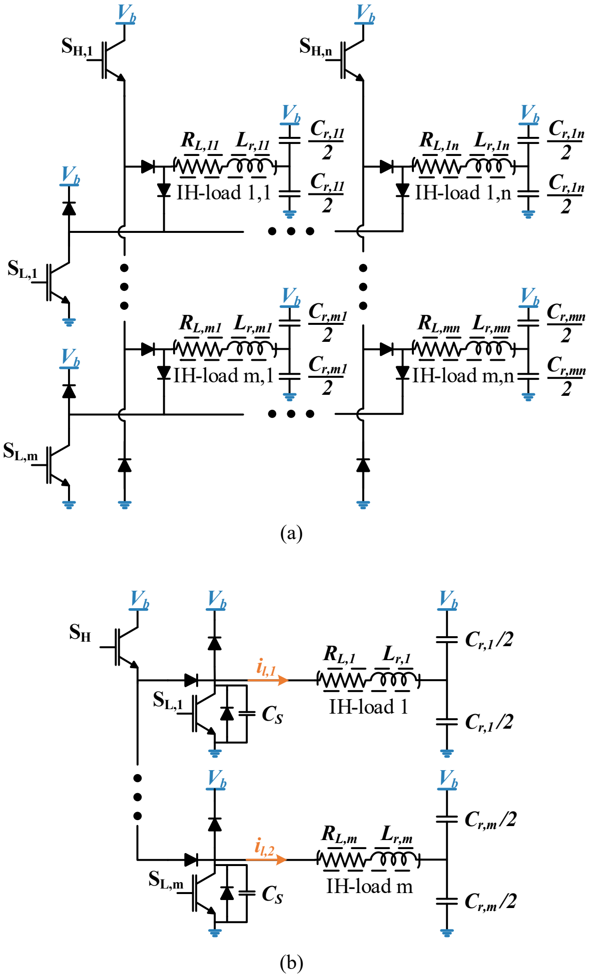


Fig. 20. Multi-output ZCS matrix inverter.



(a)

(b)

Fig. 21. Multi-output ZVS matrix inverter of size *m*x*n* (a) and *m*x1 (b).

operated by phase shift. Even though this topology presents low power device count, it requires the presence of relays to disconnect the inactive loads.

Focused on the maximum device count reduction for high-IH load-number multi-coil flexible surfaces, a ZCS matrix inverter is presented in [43]. The proposed converter can be seen in Fig. 20 and is also derived from SE inverter.

An alternative to the ZCS matrix is the ZVS matrix presented in [44] and derived from the HB. This structure presents a unidimensional version that increases the device count but presents improved power control [45] (Fig. 21).

IV. DISCUSSION

After analyzing the most relevant topologies proposed in recent years, a comparison of the different topology groups based on its main characteristics is performed in TABLE I. In general, multi-output inverters present a higher load maximum deliverable power and better power controllability. This performance is a consequence of the lower relevance of the base topology in the design process, as it can be inferred from the fact that most of the solutions are proposed based on more than one inverter: FB and HB or SE and HB.

A comparative table classifying the detailed topologies according to the required power device number is presented in TABLE II. Additionally, this table presents the normalized mean power column which represents the maximum power, as a percentage of the power at the resonant frequency, i.e. the maximum available power, that is possible to transfer to a load while maintaining power control. This result is averaged between all the active loads.

As it can be seen, the latest developments in multi-output inverters outperform the classical topologies. On the one hand, the parallelization of inverters is improved by converters that present simultaneous load activation and independent power control with reduced device count [15, 29-31]. On the other hand, load multiplexation is upgraded by high-frequency noiseless load activation [37, 40, 41]. Additionally, some promising topologies combine the load selection with a low device count [43, 44].

Based on the state of the art and given the actual commercial approach to induction heating appliances, it is clear the potential of the multi-output structures. Research opportunities have to focus on the development of topologies specifically designed for a high number of loads, >10, and will be linked to:

Elechtromechanic relay elimination: The relay as a cost-effective alternative for reconfiguration of load and inverter connection is the main reason for its usage in commercial

TABLE I. POWER CONVERTER GROUPS COMPARISON

	Inverter parallelization	**Load multiplexation**	**Multi-output topologies**
Power control	▲	▼	▲
Device count	▼	▲	►
Acoustic noise	►	▼	▲
Mains power consumption	▲	▼	►

Red downwards arrow (▼): worse than average, yellow horizontal arrow (►): average, green upwards arrow (▲): better than average.

cooktops. However, they present significant drawbacks such as high settling times or noisy switching. In the literature, multi-output solutions eliminate them at the cost of degrading the current path and increasing the device count. Thus, a future challenge is the prospection of inverter alternatives that minimize the solid state devices in the current path.

Power device usage balance: In order to increase mean time between failures in the power converter, inverter design without critical components, such as shared inverters, is desired. The power balance is not restricted to general topology layout but also to reconfiguration of non-used inverters, as in the case of HB parallelized with relays. The pursuing of this structures with solid state switches will improve the overall performance and reduce the overall inverter failures.

Bus voltage control: The inclusion of low device count PFC or boost structures has proved to increase inverter efficiency and improve mains power consumption. For this reason, the integration of this converters in multi-output inverters improve the performance by reducing the current through the load.

Wide Bandgap devices implementation: The development of WBG devices has increased its application in induction heating applications [46-48]. Due to its characteristics, the implementation of multi-output topologies with SiC or GaN devices leads to an increased overall efficiency of the converter.

TABLE II. TOPOLOGY DEVICE COUNT AND POWER CONTROL COMPARISON

Topology	**Power devices**			**Normalized mean power**
	Transistor	***Relay***	***Diode***	
Parallel FB	4n	0	0	1[a]
Parallel HB	2n	0	4	1[ab]
Parallel SE	n	0	4	1[a]
Multiplexed FB	4	n	4	<(n-1)/n
Multiplexed HB	2	n	4	<(n-1)/n
Multiplexed SE	1	n	4	<(n-1)/n
[2] F. Forrest	2	$n^2/2$	4	1/n[a]
[27] S.K. Papani	4	0	4	2/n[a]
[15] J.M. Burdío [29] S.H. Hosseini	2+2n	0	4	1
[30] S. Zenitani	2+2n	0	4	1
[31] H. Sarnago	2+2n	0	2	1
[33] H. Sarnago	2n	0	2	1[b]
[34] J. Yong-Chae	1+n	0	4	1/n[c]
[35] V. B. Devara	4+2n	0	4	1/n[c]
[36]a F. Forest	1+n	0	4	1[bc]
[36]b F. Forest	N	0	4	1
[36]c F. Forest	1+2n	0	4	1
[37] O. Lucía	2+n	0	4	1
[40] S.K. Papani [41] M. Perez-Tarragoona	4+n	0	4	(n-1) /n
[42] T. Hirokawa	1+n	0	4	1
[43] H. Sarnago	$2n^{1/2}$	0	4+2n	(n-1)/n
[44] H. Sarnago	$2n^{1/2}$	0	$4+2(n+n^{1/2})$	(n-1)/n
[45] P. Guillén	1+n	0	4+2n	1[b]

[a] Limited power control due to switching frequency constraints.

[b] Limited power control due to specific IH reasons (ZVS limits, master-slave configuration, etc.)

[c] Lower efficiency current path due to series-connected power semiconductors.

V. CONCLUSIONS

In this paper, a systematic review of the inverters proposed in the literature for its application in multi-coil induction cooktops has been performed. The presented topologies have been classified in three main groups following the inverter design principle.

Based on the main constraints for the implementation of flexible surface induction heating appliances, the different groups have been compared in according to its common particularities and the topologies have been described in terms of power device count and delivered power.

In conclusion, the recently developed matrix-based multi-inverters combine a high number of desired features, such as low power device count, solid state components implementation and good controllability. Since they present a good trade-off between performance and cost, they are the most promising technology for future domestic IH application.

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