Introduction to the Special Section on Induction Heating Systems

INDUCTION heating (IH) systems are a faster, cleaner, and more efficient alternative to conventional heating systems. Its contactless nature provides superior heating performance that has been successfully applied in industrial, domestic, and medical applications. Since the early IH developments in the late 19th century, technology has evolved to provide high-performance and reliable equipment with a wider application spectrum. Nowadays, the number of applications and installed power makes IH of great interest not only from an industrial and economic point of view but also considering its social and environmental impact.

Following this interest, the Annual Conference of the IEEE Industrial Electronics Society (IECON) has organized since 2011 a special session devoted to IH technology. During these years, the main achievements and research lines in the fields of power electronics and semiconductor technology, magnetic component design, and control of power converters for IH have been presented and discussed in these sessions. After these experiences, it is now a pleasure for us to introduce this "Special Section on Induction Heating Systems" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. This Special Section aims at bringing some of the most recent and interesting ideas in this area by the worldwide research community and at presenting some of the latest advancements and developments in the field of IH technology.

The first paper of this Special Section is a review paper written by the Special Section Guest Editors Lucia *et al.* [1], which covers some of the most relevant IH research papers published in recent years, details the current state of the art of IH systems, and identifies some future design trends for such systems. This paper categorizes the main enabling technologies that have made possible the advancement and spread of IH systems and its main applications. Following this classification, the remaining papers of this Special Section can be classified according to the enabling technology focused upon and its main application (see Table I). From this point of view, IH systems can be subdivided into the power electronic system, which generates the required medium frequency currents; the inductor system, which creates the alternating magnetic field to heat up the IH target; and the control system. Papers [2]–[6] are focused on the power electronic systems, papers [7]–[9] are focused on the inductor system, and papers [10]–[12] are focused on the control system. From the application point of view, papers [2] and [5]–[8] are intended for industrial applications, papers [2]–[4] and [10]–[12] detail domestic applications, and finally, in [9], a medical application is discussed.

TABLE I
SPECIAL SECTION PAPERS ACCORDING TO THEIR FOCUS ON APPLICATIONS AND ENABLING TECHNOLOGIES

	Enabling technologies		
Applications	Power Electronics	Modulation and Control Algorithms	Magnetic Components
Industrial	[1], [5], [6]	[1], [5]	[1], [7], [8]
Domestic	[1]–[4]	[1], [10]–[12]	[1]
Medical	[1]	[1]	[1], [9]

The first part of this Special Section is focused on the power electronic system. It is usually composed of a resonant inverter to generate the required alternating magnetic field with high efficiency and power density. Depending on the power range and/or applications, different topologies are applied, as explained in [1]. The first paper of this part is written by Sarnago *et al.* [2], and it proposes a single-switch resonant inverter applied to IH appliances. The proposed converter combines the benefits of direct ac–ac conversion [13] with the cost-effective implementation of single-switch quasi-resonant inverters. Moreover, a multicycle modulation is proposed to improve the output power control. This allows alleviating control limitations of other previous class-E proposals such as [14] and [15]. This converter takes advantage of wide band-gap power devices [16], [17] to improve the converter efficiency and high-temperature performance.

It is important to note that one key design point when dealing with resonant converters for IH systems is to ensure soft-switching conditions and high efficiency in the complete operation range [18]. This can be difficult in some applications, such as domestic ones, due to the highly variable load and output power range. In order to address these issues, Mishima *et al.* [3] propose a current phasor-controlled resonant converter. This converter is based on a dual half-bridge structure, and it uses the phase shift between converters, in a similar way in [19] and [20], to perform the power control. This converter achieves a wider soft-switching operation area and improved output power control, being particularly suitable for variable load IH applications.

Following the same goals of the previous paper, Sarnago *et al.* propose in [4] a full zero current switching (ZCS) quasi-resonant inverter. This converter is based on a half-bridge structure and achieves ZCS during both turn-on and turn-off transitions, regardless of the required switching frequency and output power. As a consequence, a significant reduction on switching losses is obtained, leading to higher efficiency in the complete operation range. In addition, the output power control is simplified, allowing the implementation of efficient and reliable systems.

In [5], Namadmalan and Moghani propose a tunable self-oscillating inverter [21] that features an improved start-up operation. Unlike the previous converters, this approach features a current-source inverter with parallel resonance, which

Digital Object Identifier 10.1109/TIE.2013.2282598

is suitable for industrial IH applications. Compared with classical solutions, the converter proposed in this paper achieves faster dynamics with reduced component stress, improving its reliability.

The last paper of this part is devoted to the power converter reliability [22], which is a general concern among power electronic designers. Esteve *et al.* present in [6] a comprehensive study of a high-power (100 kW) resonant converter. The authors analyze the operation of a full-bridge inverter operating with a modified phase-shift modulation strategy. The efficiency and power cycling capability is deeply studied using a calorimetric method, and as a conclusion, the authors prove that a significant lifetime extension can be obtained.

The second part of this Special Section is devoted to the inductor system, which is the most important magnetic component of an IH system. It is responsible for creating the required alternating magnetic field and, as a consequence, heating up the induction target. Moreover, it is usually a part of the power-converter resonant tank, determining the power-converter operation and performance. Consequently, significant attention has been paid to the design and modeling of the inductor system. In this Special Section, papers [7]–[9] present some models and designs aimed at different IH applications.

Usually, one of the main challenges when designing an IH system is to provide an accurate model of the inductor-load system, particularly when complex and/or variable geometries are present. An example of this is shown in [7], where Kennedy *et al.* present an accurate model for short-coil geometries. This geometry present complex dependence of the coil and IH target geometries, and the prediction of the heating rate becomes difficult. The authors propose an analytical–empirical model that provides good accuracy in a wide frequency operating range. This proposal is thoroughly validated with finite-element method (FEM) simulations and a complete set of experimental measurements.

The design of IH systems intended to heat nonmagnetic elements is particularly challenging. Heating such elements usually entails high current levels, significantly degrading the power converter, the efficiency of the inductor, and the reliability of the nonmagnetic elements, as shown in [23]. In order to address this issue, Mach *et al.* propose in [8] an alternative method for heating such nonmagnetic elements. Instead of generating an alternating magnetic field, the authors propose to use a static magnetic field plus the rotation of the IH target. The proposed system is modeled and numerically solved, and the accuracy of the results is experimentally verified. The most remarkable achievements are the simplicity and robustness of the proposed system, and the efficiency improvement obtained when heating nonmagnetic elements.

Finally, Chen *et al.* detail in [9] a specific inductor design for tumor thermotherapy. This treatment requires the precise and deep generation of a magnetic field to heat up a needle in order to cauterize the targeted tumor tissues [24]. The authors propose in this paper a high-permeability inductor coating to precisely focus the magnetic field, increasing the magnetic flux density. The proposed IH apparatus is modeled and analyzed through FEM simulation and experimentation, showing a significant performance improvement.

The third and last part of this Special Section is focused on the control system. Modern IH systems highly rely on advanced control systems to optimize the power control and heating quality [25], [26], to guarantee the proper converter operation [27], and to ensure the process safety [28], [29]. This part of the Special Section contains three papers [10]–[12] that show some of the current research lines being followed to improve IH systems.

In order to ensure the proper converter operation and measure important parameters, such as the current through the coil and the output power, several currents/voltages need to be measured. Jimenez *et al.* propose in [10] an accurate and cost-effective sigma–delta analog-to-digital (ADC) converter applied to induction appliances. The proposed design is a second-order single-bit sigma–delta ADC that takes advantage of field-programmable gate array (FPGA) technology [30]–[32] for its implementation. A design procedure is fully explained, and in order to assess the accuracy of the ADC, a calibration process with a complete set of experimental measurements is performed. As a conclusion, the proposed ADC is a cost-effective and accurate solution, particularly indicated for consumer goods such as IH appliances.

One of the main difficulties when dealing with IH control systems is the highly variable load [33], [34], which makes the output power control complicated and potentially unstable. In order to address this challenge, Dominguez *et al.* propose in [11] an inverse-based control strategy. The proposed strategy combines different modulation strategies, as in [35], to deal with the load uncertainty and to optimize the response time while ensuring stability. As a consequence, more reliable and higher performance IH systems can be achieved.

Finally, modern control techniques of IH systems includes the control of not only the output power but also of the temperature of the IH target [26], [36]. For instance, advanced control scheme of IH cookers [37] include the control of the pan temperature to provide superior user performance. To implement such feature, Imaz *et al.* propose in [12] an infrared thermometry system based on an InGaAs p-i-n photodiode to detect the pan temperature. To achieve this, a radiation model of the complete system is proposed, including the pan and the vitroceramic glass effects. The accuracy of the proposed sensor has been tested in a domestic IH system, obtaining adequate accuracy for the application with a cost-effective implementation.

Acknowledgment

The Guest Editors would like to thank all the authors that have submitted their valuable contributions and to the numerous and highly qualified anonymous reviewers. They think that the selected contributions, which represent the current state of the art in the field, will be of great interest to the industrial electronics community. They would like to thank Prof. C. Cecati, Editor-in-Chief of the IEEE Transactions on Industrial Electronics (TIE), for giving them the opportunity to organize this Special Section and for all the encouragement, help, and support given throughout the process, and S. McLain and A. Ul-Haq, TIE staff, for their professional support and assistance during the entire preparation of this Special Section.

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