

Introduction to the Special Section on Induction Heating Systems

Óscar Lucía, Pascal Maussion, Enrique J. Dede, José M. Burdío

► To cite this version:

Óscar Lucía, Pascal Maussion, Enrique J. Dede, José M. Burdío. Introduction to the Special Section on Induction Heating Systems. IEEE Transactions on Industrial Electronics, 2014, 61 (5), pp.2504-2508. 10.1109/TIE.2013.2282598 . hal-02465820

HAL Id: hal-02465820 https://hal.science/hal-02465820

Submitted on 4 Feb 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Open Archive Toulouse Archive Ouverte

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible

This is author's version published in: <u>http://oatao.univ-toulouse.fr/25249</u>

Official URL: https://doi.org/10.1109/TIE.2013.2282598

To cite this version:

Lucía, Óscar and Maussion, Pascal and Dede, Enrique J. and Burdío, José M. Special section on induction heating systems. (2014) IEEE Transactions on Industrial Electronics, 61 (5). 2504-2508. ISSN 0278-0046

Introduction to the Special Section on Induction Heating Systems

I NDUCTION 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.

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

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]

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 hightemperature performance.

It is important to note that one key design point when dealing with resonant converters for IH systems is to ensure softswitching 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 selfoscillating inverter [21] that features an improved start-up operation. Unlike the previous converters, this approach features a current-source inverter with parallel resonance, which 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 inductorload 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 costeffective 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.

> ÓSCAR LUCÍA, *Guest Editor* Group of Power Electronics and Microelectronics (GEPM) University of Zaragoza 50018 Zaragoza, Spain

PASCAL MAUSSION, *Guest Editor* LAboratory for PLAsma and

Conversion of Energy (LAPLACE) University of Toulouse 31062 Toulouse cedex 9, France

ENRIQUE J. DEDE, *Guest Editor* GH Electrotermia S.A. 46184 Valencia, Spain

JOSÉ M. BURDÍO, *Guest Editor* Group of Power Electronics and Microelectronics (GEPM) University of Zaragoza 50018 Zaragoza, Spain

REFERENCES

- O. Lucía, P. Maussion, E. Dede, and J. M. Burdío, "Induction heating technology and its applications: Past developments, current technology, and future challenges," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [2] H. Sarnago, O. Lucia, A. Mediano, and J. Burdio, "A class-e direct ac-ac converter with multi-cycle modulation for induction heating systems," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [3] T. Mishima, C. Takami, and M. Nakaoka, "A new current phasorcontrolled ZVS twin half-bridge high-frequency resonant inverter for induction heating," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [4] H. Sarnago, O. Lucia, A. Mediano, and J. M. Burdio, "A class-E direct ac-ac converter with multicycle modulation for induction heating systems," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [5] A. Namadmalan and J. S. Moghani, "Tunable self-oscillating switching technique for current source induction heating systems," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [6] V. Esteve, J. Jordán, E. Sanchis-Kilders, E. J. Dede, E. Maset, J. B. Ejea, and A. Ferreres, "Improving the reliability of series resonant inverters for induction heating applications," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [7] M. W. Kennedy, S. Akhtar, J. A. Bakken, and R. E. Aune, "Empirical verification of a short-coil correction factor," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [8] F. Mach, V. Štarman, P. Karban, I. Doležel, and P. Kůs, "Finite-element 2-D model of induction heating of rotating billets in system of permanent magnets and its experimental verification," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [9] C.-C. Chen, C.-C. Tai, S.-J. Huang, Y.-H. Chen, and C.-H. Lin, "Thermotherapy induction heating apparatus with new magnetic-wrapped coil design," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [10] O. Jimenez, O. Lucia, I. Urriza, L. A. Barragan, and D. Navarro, "Design and evaluation of a low-cost high-performance Σ-Δ ADC for embedded control systems in induction heating appliances," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [11] A. Dominguez, L. A. Barragan, A. Otin, D. Navarro, and D. Puyal, "Inverse-based power control in domestic induction-heating applications," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [12] E. Imaz, R. Alonso, C. Heras, I. Salinas, E. Carretero, and C. Carretero, "Infrared thermometry system for temperature measurement in induction heating appliances," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, May 2014.
- [13] B. Saha, K. Soon Kurl, N. A. Ahmed, H. Omori, and M. Nakaoka, "Commercial frequency AC to high frequency AC converter with boostactive clamp bridge single stage ZVS-PWM inverter," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 412–419, Jan. 2008.
- [14] J. M. Leisten, A. K. Lefedjiev, and L. Hobson, "Single ended resonant power supply for induction heating," *Electron. Lett.*, vol. 26, no. 12, pp. 814–816, Jun. 1990.
- [15] H. Omori and M. Nakaoka, "New single-ended resonant inverter circuit and system for induction-heating apparatus," *Int. J. Electron.*, vol. 67, no. 2, pp. 277–296, 1989.
- [16] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "Design and implementation of a high-efficiency multiple-output resonant converter for induction heating applications featuring wide bandgap devices," *IEEE Trans. Power Electron.*, to be published.

- [17] J. Millan, P. Godignon, X. Perpinya, A. Perez-Tomas, and J. Rebollo, "A survey of wide band gap power semiconductor devices," *IEEE Trans. Power Electron.*, to be published.
- [18] O. Lucía, J. M. Burdío, I. Millán, J. Acero, and D. Puyal, "Load-adaptive control algorithm of half-bridge series resonant inverter for domestic induction heating," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3106– 3116, Aug. 2009.
- [19] H. Pham, H. Fujita, K. Ozaki, and N. Uchida, "Phase angle control of high-frequency resonant currents in a multiple inverter system for zonecontrol induction heating," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3357–3366, Nov. 2011.
- [20] J. M. Burdío, L. A. Barragán, F. Monterde, D. Navarro, and J. Acero, "Asymmetrical voltage-cancelation control for full-bridge series resonant inverters," *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 461–469, Mar. 2004.
- [21] H. Sarnago, A. Mediano, and O. Lucía, "Design and implementation of a class-E self-oscillating inverter for cost-effective induction heating systems," *EPE J.*, vol. 22, pp. 11–16, Dec. 2012.
- [22] W. Huai, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics: Challenges, design tools, and opportunities," *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 17–26, Jun. 2013.
- [23] I. Millán, J. M. Burdío, J. Acero, O. Lucía, and S. Llorente, "Series resonant inverter with selective harmonic operation applied to all-metal domestic induction heating," *IET Power Electron.*, vol. 4, no. 5, pp. 587– 592, May 2011.
- [24] P. R. Stauffer, T. C. Cetas, and R. C. Jones, "Magnetic induction heating of ferromagnetic implants for inducing localized hyperthermia in deep-seated tumors," *IEEE Trans. Biomed. Eng.*, vol. BME-31, no. 2, pp. 235–251, Feb. 1984.
- [25] M. Souley, S. Caux, J. Egalon, O. Pateau, Y. Lefevre, and P. Maussion, "Optimization of the settings of multiphase induction heating system," *IEEE Trans. Ind. Appl.*, to be published.
- [26] H. N. Pham, H. Fujita, K. Ozaki, and N. Uchida, "Estimating method of heat distribution using 3-D resistance matrix for zone-control induction heating systems," *IEEE Trans. Power Electron.*, vol. 27, no. 7, pp. 3374– 3382, Jul. 2012.
- [27] H. Sarnago, O. Lucía, A. Mediano, and J. M. Burdío, "Modulation scheme for improved operation of a RB-IGBT based resonant inverter applied to domestic induction heating," *IEEE Trans. Ind. Electron.*, vol. 60, no. 5, pp. 2066–2073, May 2013.
- [28] V. Esteve, E. Sanchis-Kilders, J. Jordan, E. J. Dede, C. Cases, E. Maset, J. B. Ejea, and A. Ferreres, "Improving the efficiency of IGBT seriesresonant inverters using pulse density modulation," *IEEE Trans. Ind. Electron.*, vol. 58, no. 3, pp. 979–987, Mar. 2011.
- [29] O. Jiménez, O. Lucia, I. Urriza, L. A. Barragán, P. Mattavelli, and D. Boroyevich, "FPGA-based gain-scheduled controller for resonant converters applied to induction cooktops," *IEEE Trans. Power Electron.*, to be published.
- [30] O. Lucía, L. A. Barragán, J. M. Burdío, O. Jiménez, D. Navarro, and I. Urriza, "A versatile power electronics test-bench architecture applied to domestic induction heating," *IEEE Trans. Ind. Electron.*, vol. 58, no. 3, pp. 998–1007, Mar. 2011.
- [31] E. Monmasson, L. Idkhajine, and M. W. Naouar, "FPGA-based controllers," *IEEE Ind. Electron. Mag.*, vol. 5, no. 11, pp. 14–26, Mar. 2011.
- [32] C. Buccella, C. Cecati, and H. Latafat, "Digital control of power converters: A survey," *IEEE Trans. Ind. Informat.*, vol. 8, no. 3, pp. 437–447, Aug. 2012.
- [33] H. N. Pham, H. Fujita, K. Ozaki, and N. Uchida, "Dynamic analysis and control for resonant currents in a zone-control induction heating system," *IEEE Trans. Power Electron.*, vol. 28, no. 3, pp. 1297–1307, Mar. 2013.
- [34] O. Jiménez, O. Lucía, L. A. Barragán, D. Navarro, J. I. Artigas, and I. Urriza, "FPGA-based test-bench for resonant inverter load characterization," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1645–1654, Aug. 2013.
- [35] N. A. Ahmed, "High-frequency soft-switching ac conversion circuit with dual-mode PWM/PDM control strategy for high-power IH applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1440–1448, Apr. 2011.
- [36] J. Egalon, S. Caux, P. Maussion, M. Souley, and O. Pateau, "Multiphase system for metal disc induction heating: Modeling and RMS current control," *IEEE Trans. Ind. Appl.*, vol. 48, no. 5, pp. 1692–1699, Sep./Oct. 2012.
- [37] O. Lucía, J. Acero, C. Carretero, and J. M. Burdío, "Induction heating appliances: Towards more flexible cooking surfaces," *IEEE Ind. Electron. Mag.*, vol. 7, no. 3, pp. 35–47, Sep. 2013.

Óscar Lucía (S'04–M'11) received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Zaragoza, Zaragoza, Spain, in 2006 and 2010, respectively.

Since 2010, he has been a member of the Power Electronics and Microelectronics Group and an Assistant Professor with the Department of Electronic Engineering and Communications, University of Zaragoza. In 2009 and in 2012, he was a Visiting Scholar with the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. He is the author of more than 80 technical papers published in international journals and conference proceedings and the holder of 12 international patents and patent applications. His main research interests include resonant power converters and digital control for induction heating applications.

Dr. Lucía is an active member of the IEEE Industrial Electronics, IEEE Industry Applications, and IEEE Power Electronics Societies, participating in several conferences and committees. He is

also a member of the Aragon Institute for Engineering Research. Since 2011, he has coorganized the IEEE Annual Conference of the IEEE Industrial Electronics Society Special Session on Induction Heating.

Pascal Maussion (M'07) received the M.Sc. and Ph.D. degrees in electrical engineering from the National Polytechnic Institute of Toulouse, Toulouse, France, in 1985 and 1990, respectively.

He is currently a Full Professor with the University of Toulouse, Toulouse, and the Head of the Control and Diagnosis Group, Laboratory for Plasma and Conversion Of Energy (LAPLACE), Toulouse. His research interests include control and diagnosis of electrical systems (power converters, drives, and lighting) and the design of experiments for optimization in control and diagnosis.

Enrique J. Dede (M'95) received the Ph.D. degree in electronics from the University of Valencia, Valencia, Spain.

Since 1991, he has been a Full Professor of power electronics with the University of Valencia and a Research and Development Director with GH Electrotermia S.A., Valencia. He is a holder of several international patents on high-frequency inverters for induction heating and the author of more than 200 papers in the field of power electronics. He has more than 30 years experience in the field of power electronics, particularly in the design of high-frequency inverters for induction heating, telecom power, and recently, in the conception and design of fast chargers for electric vehicles.

Dr. Dede is a former member of the European Working Group of the IEEE Industry Applications Society and was the President of the joint Spanish IEEE Chapter of the Power Electronics and Industrial Electronics Societies. He is a member of the International Advisory Board of the Power Conversion Intelligent Motion Europe and Asia, and is the Vice-President of

the European Power Electronics Association (EPE). He was the General Chair of the EPE European Power Electronics Conference in 2009, which was held in Barcelona, Spain.

José M. Burdío (M'97–SM'12) received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Zaragoza, Zaragoza, Spain, in 1991 and 1995, respectively.

He has been with the Department of Electronic Engineering and Communications, University of Zaragoza, where he is currently a Professor, and the Head of the Group of Power Electronics and Microelectronics. He is the author of more than 60 international journal papers and over 100 papers in international conference proceedings and the holder of more than 50 international patents. His main research interests include modeling of switching converters and resonant power conversion for induction heating applications.

Dr. Burdío is a member of the IEEE Industrial Electronics and IEEE Power Electronics Societies. He is also a member of the Aragon Institute for Engineering Research.