Open Access Journal

Journal of Power Technologies 97 (3) (2017) 201–213

journal homepage:papers.itc.pw.edu.pl

A Survey on High-Frequency Inverter and Their Power Control Techniques for Induction Heating Applications

Anand Kumar[a,*], Moumita Sadhu [b], Niladri Das[b], Pradip Kumar Sadhu[a], Debabrata Roy[c], Ankur Ganguly[c]

[a]*Department of Electrical Engineering, Indian Institute of Technology(ISM), Dhanbad, India,*
[b]*Department of Management Studies, Indian Institute of Technology(ISM), Dhanbad, India,*
[c]*Department of Electrical Engineering, Techno India, Batanagar, West Bengal, India,*

Abstract

Intensive use of induction heating (IH) technology can be seen in many areas such as industrial, domestic and medical applications. The evolution of high-frequency switches has facilitated the design of high-frequency inverters, the key element of induction heating technology. Controling output power in a high-frequency inverter for induction heating application is complex. However, the importance of IH technology is not widespread. Induction heating technology requires accurate output power and current control with appropriate dynamics. Several power control techniques have been discussed inrelation to designing high-frequency inverters for IH applications. This paper makes a comprehensive review of the various power control techniques regarding high-frequency inverters for modern IH applications (domestic & industrial).

Keywords: induction heating (IH), high frequency inverter, resonant inverter, PWM, AVC, APWM Introduction

The use of induction heating (IH) technology is growing steadily, with industrial [1], medical [2] and domestic applications [3]. Induction heating technology enjoys many advantages over flame heating, resistance heating, or traditional ovens or furnaces. Some of the advantages are: fast heating, more efficient controlled heating, cleanliness, and safety. These unique advantages of induction heating are driving further research. Induction heating is a process in which metal is heated by means of Foucault current generated by the electromagnetic induction principle [4, 5]. Lying at the heart of the modern IH system is the high-frequency inverter. Modern induction heating technology works on the basis of the time-varying magnetic field which is generated using the HF inverter. This rapid alternating magnetic field penetrates the object (depending on the frequency of magnetic field) and generates electric current inside the object (which is to be heated) called eddy current (also called Foucault current). After that, due to the resistance of the object, the object heats up according to Joule's law of heating effect. If the object is ferromagnetic (like iron), then both eddy current loss and magnetic hysteresis loss will take part in the generation of heat. If the object is non-magnetic, then only eddy current loss will generate the heat. Thus we can say that mainly two physical phenomena are responsible for induction heating: eddy current and magnetic hysteresis.

The beginnings of induction heating technology date back to the 19th century [6] when Michal Faraday proposed the idea of electromagnetism. James C. Maxwell and James P. Joule went on to describe the heating effect of electric current in the conductor, which became the fundamental principle of induction heating. Initially, the principles of Michael Faraday were applied to generators, motors and transformers which were adversely affected by undesirable heating effects due to eddy current. These heating effects were reduced by using laminated core. In the 20th—century researchers thought about how to harness this heating effect for the purpose of steel melting applications. The first patent was filed by Sebastian Z. de Ferranti regarding IH for melting metals in 1887. The first medium frequency induction heating was installed in Sheffield, England by EFFCO around 1927. Around the same time, HF-IH technology was being developed by M. G. Ribaud using spark-gap generators [7]. In the early 20th century studies focused on coreless induction furnaces. This is when high-frequency exciting current started being used in induction heating. Edwin F. Northrup designed the first HF crucible furnace in 1916 which worked at a frequency of 20 kHz powered by a spark gap generator [6]. These were the beginnings of modern high-frequency IH systems. A second round of major revolutions started with the development of power semiconductor switches, such as the bipolar junction transistor (BJT) and the power metal-oxide-field-effect-transistor (MOSFET). Due

*Corresponding author
Email address: anandsingh1025@gmail.com (Anand Kumar)

to this development, the generation of high-frequency current became straightforward. With recent advances in highly reliable power semiconductor switches, the application of IH technology is growing steadily. The developments have also facilitated advances in high-frequency inverters and the design of high quality IH technology for domestic application.

Resonant inverters are used in modern induction heating technology, mainly for the generation of high-frequency current. Further, they are classified as voltage fed resonant inverters and current fed resonant inverters. Various works have been proposed regarding these types of inverter. Also, various topologies have been proposed such as full bridge [8], half bridge [9–11] and single switch resonant inverters [12]. Generally, if the power requirement is more than the 5 kW, i.e. for industrial purposes, full bridge topology is used. But for domestic systems generally less than 5 or 2 kW, half bridge and single switch topology is used. In these topologies, it has been found that due to different stages of power conversion, efficiency deteriorates [13, 14]. Dual output boost resonant full bridge topology was introduced to enhance the efficiency of induction heating systems [15]. Also in order to achieve a fast heating time, increased efficiency, minimum components used and a design cost effective converter solution, a direct AC-AC resonant boost converter for domestic induction heating was designed by Hector Sarnago et.al [16].

To obtain the desired performance, accurate power control techniques have to be designed to control the power of high-frequency converter for IH applications. Regarding power control techniques, various methods have been successfully proposed for a single phase system such as: frequency control [17], pulse width modulation [18], phase shift control [19] and duty cycle control [20]. All of these are conventional methods for controlling the power of the inverter. Recently, new technology has been proposed, such as pulse density modulation [21], asymmetrical control, and asymmetrical voltage cancellation technique [13]. Discontinuous mode control is showing great promise in the field of IH. Also, the researcher found good applications of PLL in power control techniques in high-frequency IH. The various digital controllers have also been proposed by using FPGA and DSP.

However, the amount of work that has been done in the field of HF inverter and their power control techniques is not widely known. This paper has sought to review the recent wide-ranging research in the field of induction heating.

This paper is summarized as follows: Section 2 describes the basic operation of modern induction heating technology and presents a model of IH load. Section 3 introduces a brief review on developed technology in high-frequency converters for IH. Section 4 summarizes the review of recent work on power control techniques in IH converters. Section 5 draws some conclusions and looks to future research.

1. Basic operation of induction heating technology

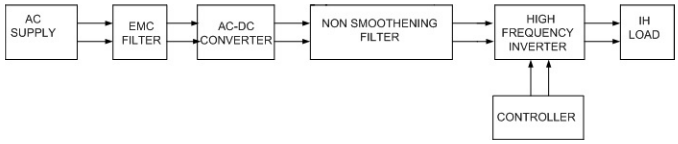

Figure 1: Block diagram of the induction heating system

The basic operation of modern induction heating technology is set out in the block diagram above (Fig. 1). First, the AC power is given to the EMC filter which is used to prevent the voltage and current transient shown in Fig. 1. In modern induction heating technology, a high-frequency inverter is used which works at a very high switching frequency. Due to this, the high-frequency component of current and voltage starts flowing from load to source. So the EMC filter protects the supply from these effects. It consists of passive elements, i.e. inductor and capacitor. After that an uncontrolled rectifier is used which converts AC to DC which is of high ripple content. Then a non-smoothening filter is used. Generally, the value taken for the non-smoothening filter is of the low value of the capacitor. It is used for maintaining unity power factor [21]. This DC voltage is given to the high-frequency converter, which is used to generate high-frequency current and voltage to satisfy the requirement of the IH coil. The control circuit is used to control the output power requirement of induction heating load.

It was seen that when the operating frequency of the high-frequency inverter increases, the skin effect on the conductor also increases. Due to this, heat generated by eddy current is only concentrated on the outer layer [14] of the IH coil.

$$\partial = \sqrt{\frac{\rho}{\pi \mu f}} \tag{1}$$

Where:∂—is the penetration depth, ρ—is the magnetic permeability, f—is the applied frequency.

This effect is reduced by using litz wire, which is well explained in [22]. From the equation 1, with the increase in frequency, the penetration depth in the workpiece or IH coil becomes less. So, depending on the application of IH in different areas, such as induction cooking (35 kHz to 50 kHz), surface hardening of metals (100 kHz to 400 MHz) [14], annealing of metals, brazing, soldering etc, a different frequency is generated by using a high-frequency converter.

Actually, IH load is the induction coil along with the metal which is to be heated. Induction coil has different geometrical shapes which may be spiral, solenoid etc. High-frequency currents flow in this coil. So for the analysis of the electrical phenomenon, this induction coil can be modeled as series (Fig. 2(b)), parallel (Fig. 2(c)) and series-parallel (Fig. 2(d)) (Hybrid model) connection of R_{eq} and L_{eq}. To complete the resonant tank circuit, additional capacitors and inductors are added.

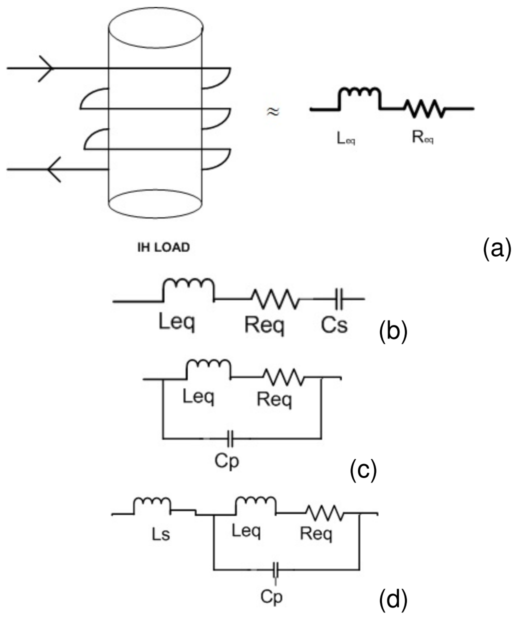

Figure 2: Modeling of IH load (a) basic resonant configuration, (b) series model, (c) parallel model, (d) hybrid series-parallel model

2. High-frequency inverter for induction heating applications

Fig. 1 show the basic power conversion scheme in most induction heating systems. From the above discussion on the basic principle of the IH system, it can be said that the heart of the IH system is the high-frequency inverter. This high-frequency inverter works at very high switching frequency, i.e. about 20 kHz to 100 kHz. Generally, semiconductor switches which are used in DC-DC or DC-AC converters are operated in hard switching mode. During turn-on and turn-off, there is always some amount of voltage and current present across the switches. Due to this, a large amount of switching losses occur. Also, due to the high switching frequency, EMI problem and di/dt or dv/dt type problems occur. Power loss due to switching at a higher frequency can be calculated as [23] and it can be concluded from equation (2) that at higher switching frequency, more power loss across the switches occurs. This deteriorates the efficiency of the converter.

$$P_{sw} = \frac{1}{2} V_{sw} I_{sw} f_s (t_{on} + t_{off}) \quad (2)$$

Where: P_{sw}—switching loss in watt, W; V_{sw}—switching voltage in volts, V; f_s—switching frequency in kHz; I_{sw}—switching current in ampere, A; t_{on}—switch turn-on time in sec, s; t_{off}—switch turn-off time in sec, s;

These switching losses can be reduced by using a snubber circuit, which is connected parallel to the switches. But the total amount of switching losses remains the same because of the passive element used in the snubber circuit, i.e., R, L and C. So this method is rarely used.

Soft switching is another method to reduce the switching losses. In this method, the magnitude of voltage or current becomes zero at the moment of switching. Two types of soft switching are used in a high-frequency converter depending on resonant frequency: Zero voltage switching (ZVS) and Zero current switching (ZCS). ZVS means creating the magnitude of voltage zero across the switches right before the turn-ON. On the other hand, ZCS means creating the magnitude of current zero across the switches right before the turn-OFF. So ZVS reduces turn-ON losses and ZCS reduces turn-OFF losses.

The magnitude of voltage or current is forced to zero by using passive elements, i.e., L or C to create resonance condition. This topology is called the resonant converter. Thus it can be said that the resonant converter is the better choice for the IH system, because it minimizes the switching losses. In the resonant converter, two types of resonant circuit are used: a series and parallel. When power is given to the resonant tank, transfer of energy starts between L and C. Due to this, resonance condition occurs at a specific frequency. This frequency is called resonant frequency ($f_r = \frac{1}{2\pi\sqrt{LC}}$). At this frequency, the magnitude of current reaches its maximum point as does heat generation. This is one of the reasons for using the resonant converter in the induction heating system. In the resonant converter, the frequency of the source for the resonant tank is determined by the switching frequency. Generally, the switching frequency in the resonant converter should be greater than the resonant frequency. This is called inductive switching.

Regarding the resonant inverter and on the basis of a number of switches, various topologies have been proposed, such as Full bridge SRI [8, 24], half bridge SRI and single switch resonant converter [25, 26]. Oscar Fernandez et.al presented a paper [24] which describes the design process of a full bridge series resonant inverter (Fig. 4). This series resonant inverter works at very high frequency. In this paper IGBTs (as a switch) and high-frequency coupling transformer were used for a prototype implementation of FBSRI which is able to deliver a current of magnitude 120 A. The advantages of this converter are that its starting melting time is very much less and it requires less physical space than other conventional furnaces. This converter is designed for industrial purposes. For domestic induction heating applications, generally, the half-bridge series resonant inverter (Fig. 5) is used. Regarding HBSRI, H. W. Koertzen et al. designed an HBSRI for induction cooking applications [9]. In this paper, the idea for calculating the value for the reactive component, the magnitude of voltage and current is discussed discussed. Also, the advantages of half bridge over single switches are discussed. Half bridge SRI can also be used for industrial induction heating purposes. In [10], a prototype was designed which works at a frequency of 50-150 kHz rated at 6 kW for industrial applications. The idea of a PLL control circuit was given, which tracks load frequency irrespective of load variation. In [12] three topologies regarding the single switch resonant converter for induction heating applications were thoroughly discussed. These three topologies were compared using a transmission effective study with simulation and experimental results and it is concluded that topol-

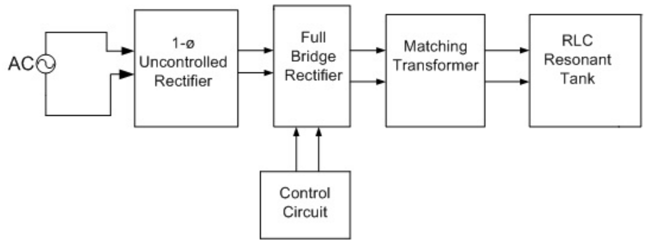

Figure 3: Block diagram of induction heating

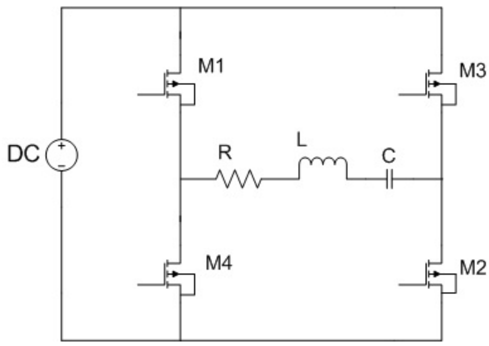

Figure 4: Power circuit of Full Bridge Series Resonant Converter

ogy 2 is the best choice. Also, some advantages and disadvantages are mentioned for each topology. Fig. 6 shows these three topologies. In previous work regarding the single switch resonant converter, it was seen that a DC supply is given to the single switch circuit. But recent work proposed direct usage of AC supply. Shenkman et.al. presented a very basic paper [25] for a single switch AC-AC converter for induction heating applications. In this converter, an attempt was made to achieve a power factor close to unity and output power is controlled by varying switching frequency. The same author (i.e. Shenkman et.al) presents a modified form of his own previous work in [26]. The advantage of this modified form is that it removes the presence of DC component in the load current. Fig. 7 & Fig. 8 show the circuit diagram of the single switch resonant converter and its modified form.

The topological classifications of HF inverters for Induction Heating (or domestic induction heating) are given below,

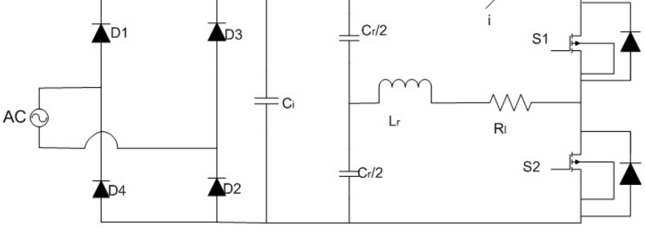

Figure 5: Circuit diagram of Half-Bridge Series Resonant Inverter

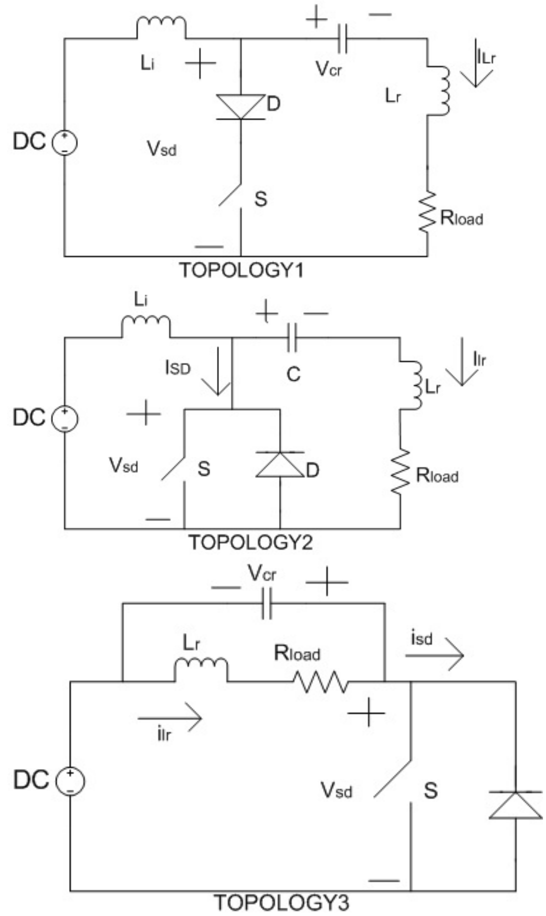

Figure 6: Single switch Resonant Converter for topology1, topology2, and topology3

based on the following aspects:

- On the basis of supply fed to the HF inverter
- On the basis of power control by using fixed or variable DC voltage
- On the basis of resonant circuit used, i.e., series, parallel and series-parallel

When designing the HF inverter for an induction heating system, the ZVS [27] or ZCS [28] condition is always ensured. Generally, it has been seen that the ZVS resonant converter is used for domestic induction heating. There as two types of ZVS converter: a half-bridge series resonant converter and a quasi-resonant converter, which is well explained in [23].

On the basis of the resonant tank, various configurations have been developed such as a parallel resonant circuit, second and third order LLC series parallel resonant circuit [28–33]. Regarding all these configurations, Robert L. Steigerwald [34] proposed a paper in which these configurations were thoroughly discussed and compared, and it is concluded that series-parallel configuration can be used for high power application and is able to maintain excellent efficiency. In [35] and [36], Series resonant RLC circuit is well explained. In [35], Vicenta Esteve et.al designed a voltage fed

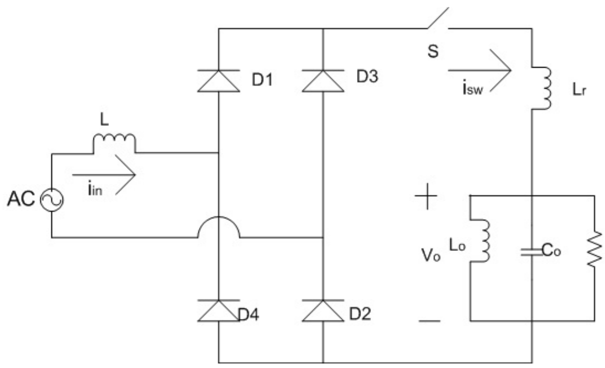

Figure 7: Single Switch AC-AC Resonant Converter

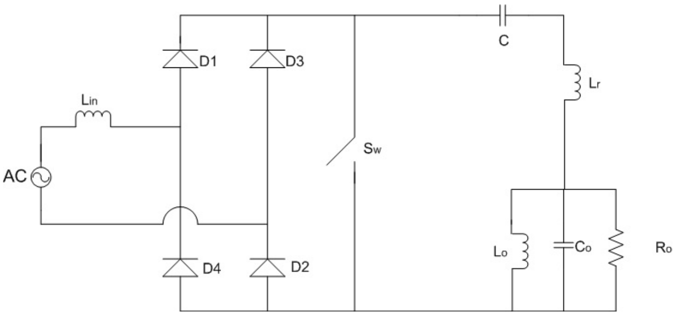

Figure 8: Modified form of Single Switch AC-AC Resonant Converter

series resonant converter for industrial heating applications (50 kW, 150 kHz). In this converter, power control is obtained by using the PDM technique to ensure the optimal ZVS and ZCS condition. Because of this, the inverter works nearer to the resonant frequency irrespective of the output power level. Fig. 9 shows a proposed system configuration for the series resonant load by Vicenta Esteve et.al.

Research shows that the LLC configuration [37–40] can give better performance than SRI. LLC configuration increases the performance of SRI because of its current gain and short circuit handling capability [41]. José M. Espí Huerta et.al [41] presented a design algorithm for an LLC resonant converter. In this paper, three possible oscillator configurations are discussed, i.e., LLC with a single active transformer, the two LLC transformers and the LLC with a single reactive transformer. Fig. 10 shows an LLC oscillator equivalent circuit.

From the above discussion, it can be seen that the classical power converter is designed on the basis of a DC link resonant inverter which is only for single load. Researchers are now working on a multiple coil system, to improve heat distribution and cost effectiveness [42, 43]. Various multi-coil or multi-inverter systems have been designed for both domestic and industrial application. In [44], Oscar Lucia et.al. proposed a novel series-resonant multi-inverter for multiple loads (for domestic induction heating applications). In this work, for prototype and experimental work, four loads were used. José M. Burdio et al. presented a paper [45] in which a series resonant converter was designed for two inductive loads which can supply power independently of their rated value at the same time. For power control, the asymmetrical voltage cancellation technique has been used. Another paper regarding a series resonant multi-inverter system is proposed by Mario Perez-Taragona et. al [46]. It is an extension of previous work done by José M. Burdio. Fig. 11 and Fig. 12 show the proposed configuration of a series resonant multilevel inverter and two output series resonant inverter. In this paper, the converter is designed in such a way that it is able to supply nine loads simultaneously and experimental verification was performed as well. Also, it is seen that when the multi-inverter system is used for multi-inductor load and when operated at the same time acoustic noise is generated due to the difference in the operating frequency of the different inverter. To eliminate this problem, each inverter is controlled by a duty cycle which is operated at a fixed frequency. Also due to the multi-inverter system, the systems become costly, heavy and complex. To eliminate these problems, Yong-Chae-Jung proposed a dual half-bridge series resonant inverter [47] for two loads, by using time sharing control of the different load. Fig. 13 shows a circuit diagram of a single converter/multiple load system, which is presented by Francois Forest et. al. [48], based on a series resonant ZVS inverter and Fig. 14 shows a circuit diagram of DHB-SRI.

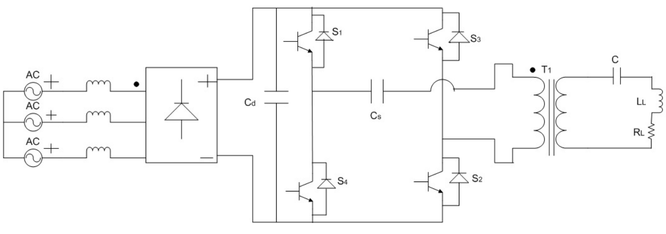

Figure 9: Proposed configuration of series resonant load

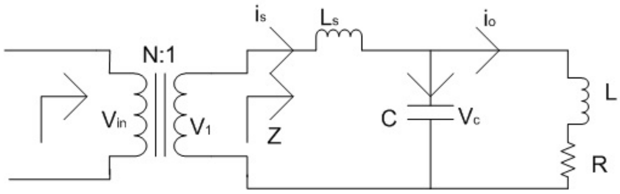

Figure 10: LLC oscillator with an isolation transformer and an L-R series equivalent network of the heating coil.

In the previous proposed scheme, first AC is converted to DC and then again DC is converted to AC, but it is of high frequency (HF).This type of converter is called a two-stage converter. Also, it uses a DC link capacitor.Due to the two stages and usage of the DC link capacitor, it becomes heavy, bulky and costly. Recently, a new conversion scheme has been proposed (i.e. Direct AC-AC conversion) in the field of IH systems. Direct conversion reduces the number of components and the EMI (electromagnetic interference) effect. The only option to achieve direct conversion is to use a Cycloconverter and a Matrix converter.

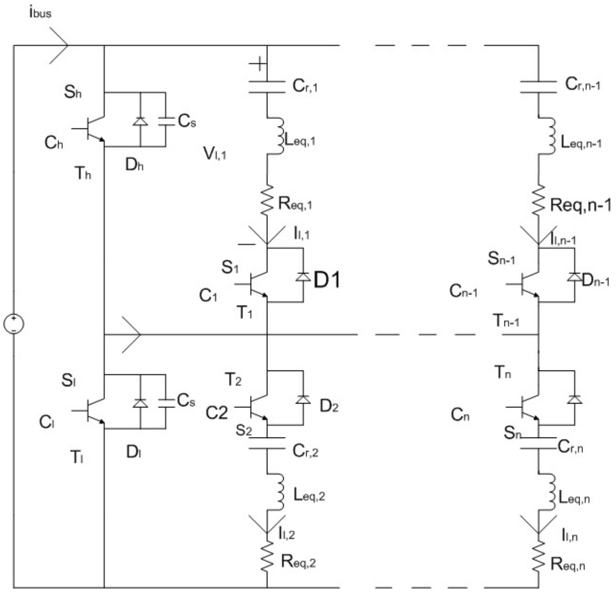

Figure 11: Series resonant multi-inverter configuration

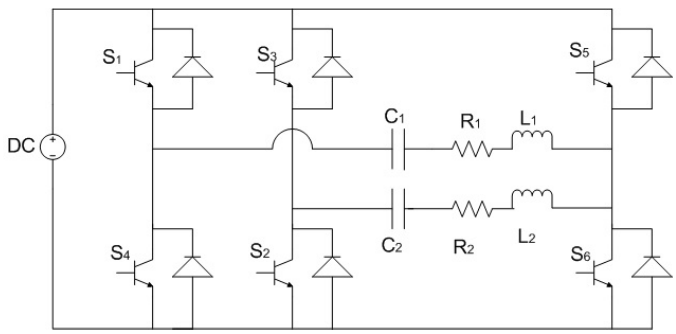

Figure 12: Two output series resonant inverter configuration

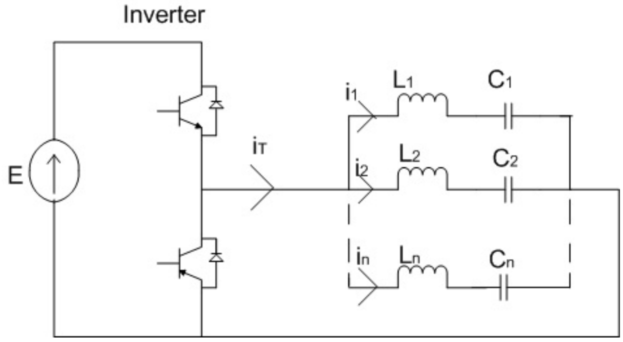

Figure 13: Single inverter/Multiload load configuration

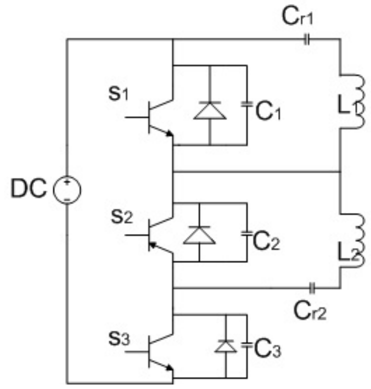

Figure 14: Dual Half bridge Series Resonant Inverter

In [49], the application of a single phase matrix converter (Direct AC to AC converter) for induction heating can be seen, which is also called a full bridge direct AC-AC converter (Fig. 15). Generally, a matrix converter is a combination of bidirectional switches and each bidirectional switch consists of two diodes and two controlled switches. However, the disadvantage of this type of converter is that the number of switches increases. This disadvantage increases the cost and complexity of the power converter. The same configuration (with bidirectional switches) was used in [50] but to implement the half bridge direct AC to AC converter (Fig. 16) the recently developed RB-IGBT (reverse blocking insulated gate bipolar transistor) was used. This has the same disadvantages as the previous implementation. To eliminate all these drawbacks Hector Sarnago et. al [51] proposed a new AC to AC resonant converter, which has been designed and analyzed. This direct AC to AC resonant converter is based on a half-bridge series resonant inverter in which only two diodes are used for rectification. Fig. 17 shows the proposed AC to AC converter for induction heating. In this topology output voltage becomes doubled and load current is reduced for the same output power. This topology is analyzed by using state space method. For experimental verification, a 3.6 kW prototype was designed in which output power can vary from 3000 W to 1000 W. To control output power, square wave and ADC techniques were been used.

Apart from all these converters, researchers are also working on the application of the multilevel inverter for domestic and industrial induction heating due to its various advantages, such as high power level, reduced harmonic effect and reduced voltage stress on power switching devices. This inverter is able to generate voltage level N but it should be greater than 2. Various types of multilevel inverter [52, 53] have been invented such as: (a) Capacitor clamped, (b) Diode-clamped and (c) Cascade multilevel inverter. But unfortunately, the first, two classifications cannot be used in induction heating because of a capacitor voltage imbalance problem [54]. This problem provides an area of ongoing research. Cascaded MLI (Fig. 18) can be used for this application, but it requires separate multiple DC sources [55]. To overcome this problem John I. Rodriguez et. al proposes a single phase, four level Marx-inverter [56] which is based on a Marx generator [Erwin Marx, 1924]. Fig. 19 shows a single phase 4 level Marx-inverter.

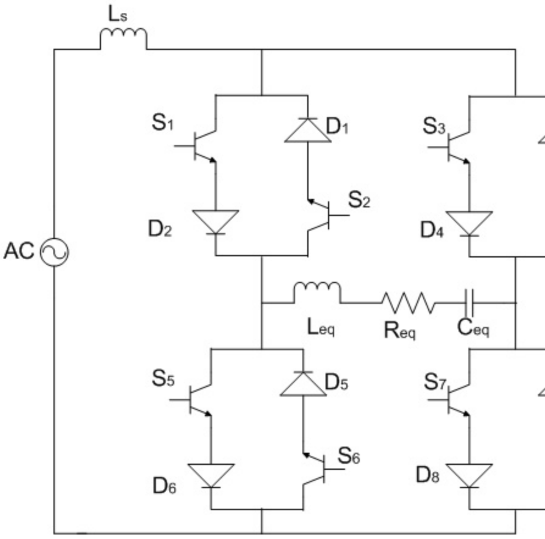

Figure 15: 1-ø matrix converter full bridge topology

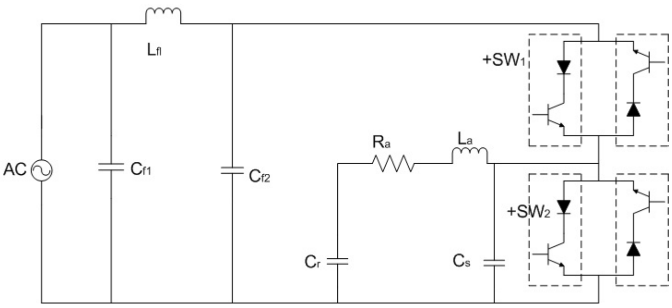

Figure 16: Half bridge topology

From the above discussion, it can be seen that various different topologies have been proposed and some configurations are still to be improved (basically AC-AC converter). This paper mainly concerns itself with reviewing the power converter and related modulation (power control) techniques developed to date for domestic and industrial induction heating applications. In the next section, different power control techniques for induction heating will be discussed.

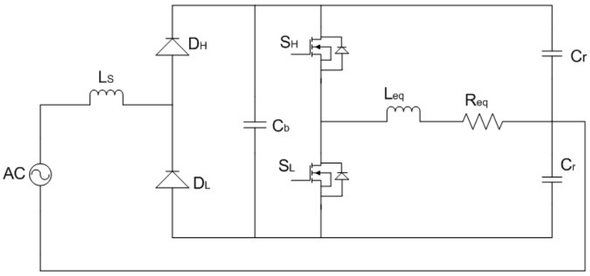

Figure 17: Proposed half bridge direct AC-AC converter

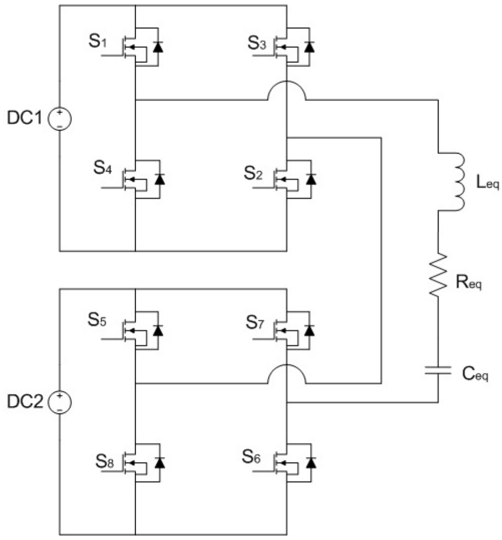

Figure 18: Cascaded MLI configuration for Induction heating

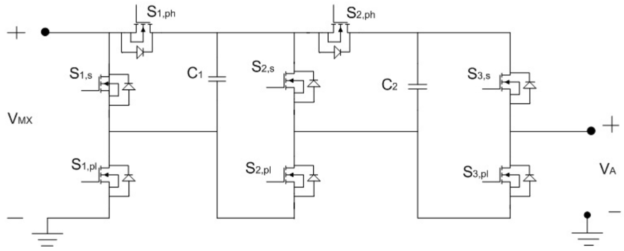

Figure 19: Marx MLI configuration for Induction heating

3. Power control techniques for the high-frequency inverter in induction heating applications

In the previous section, it was seen that high-frequency resonant inverters are widely used in induction heating. Accordingly, to improve heating quality, a good power control technique for the resonant inverter is required. In a conventional inverter or resonant inverter, there are two possible ways of controlling output power. First, the output power can be controlled by varying DC input voltage and, second, by controlling the ON and OFF period of the inverter. In the first method, a controlled rectifier is used with a DC link capacitor which generates variable DC. This variable DC is given to the inverter to achieve an adjustable power level. Cost and size become an issue in this method due to the different stages and arrangement. Also, this method generates poor current supply with higher harmonic distortion. To resolve these problems, a wide range of good modulation and control algorithms for high-frequency inverters have been developed, to obtain the desired output. The following modulation and control algorithms have been developed to date:

1. Frequency Control Technique
2. Phase Shift Control (PS)
3. Asymmetrical duty cycle Control (ADC)
4. Pulse Density Modulation Control
5. Square Wave

6. Discontinuous Mode Control

There are two classifications of frequency control technique: (a) variable frequency and (b) fixed frequency. In the variable frequency control (modulation) technique, output power is controlled by varying switching frequency [36]. But in this method, when switching frequency becomes high, efficiency and output power of the converter decrease [57]. To obtain a wide range of power control, high frequency is required. Also, if switching frequency is less than the resonant frequency, then bulky filter components are required, because they are designed for the low-frequency range. And if the switching frequency is more than the resonant frequency, then switching losses increase. But generally switching frequency higher than resonant frequency is utilized in the resonant converter for induction heating applications to ensure the ZVS condition [23, 58]. However, due to the above-mentioned problem, this method is not applicable for high-frequency inverters. To avoid these problems, fixed frequencies with a variable duty cycle were proposed by [59, 60]. In this method, output power is controlled by a varying duty cycle with frequency kept constant. Two fixed frequency control techniques were developed, the first is phase shift (PS) [61, 62] and the second asymmetrical duty cycle or asymmetrical PWM control [62]. In [19, 63] the use of the PS control technique for a high-frequency full bridge inverter to control output power was proposed. In this technique [64], the phase shift is maintained between the pulses, i.e., G1, G2 and G3, G4 (which is given to the switches S1, S2, and S3, S4). By the variation of phase angle ø [65, 66] between G1 and G2, output power can be controlled (Fig. 21). In Fig. 20 switches for the same leg cannot be turned on at the same time, i.e., S1 and S3 should be turned on and turned off at an interval of 180° out of phase and also each gate pulse should have a 50% duty cycle. This technique is used to obtain symmetrical quasi-square wave output voltage. But for a light load condition in induction heating, ZVS icannot be achieved using this technique. Similarly, it is not suitable for the half bridge resonant inverter.

Another technique for power control, called asymmetrical duty cycle [67], was proposed by Paul Imbertson and Ned Mohan. In this technique, switches S1-S2 and S3-S4 (Fig. 20) operated on a different duty cycle. If the duty cycle of S1-S2 is D then 1-D will be the duty cycle of S3-S4. Here, duty cycle D is the variable enabling output power to be controlled. This different duty cycle operation of switches allows lossless switching. This technique is helpful in reducing input current pulsation [68] and also low conduction losses are maintained. Asymmetrical output voltage waveform is obtained with this technique.

Asymmetrical voltage cancellation is used for power control in most domestic induction cooking appliances [69–71]. This method falls in the category of fixed frequency control. It is more advantageous than PS and ADC, because it reduces both turn off as well as conduction losses without losing the ZVS condition. In [13, 71] the AVC technique as a generalized control is well explained for full bridge series resonant inverters. In this paper, four control variables are taken to control (α_+, α_-, β and switching frequency, fs) output voltage or power. As a generalized controller, if $\alpha_+ = \alpha_-$ variable and β are taken as 180° then condition of phase shift control comes into the picture and for the condition of asymmetrical duty cycle α_+, and α_- should be equal to zero and β should be variable.

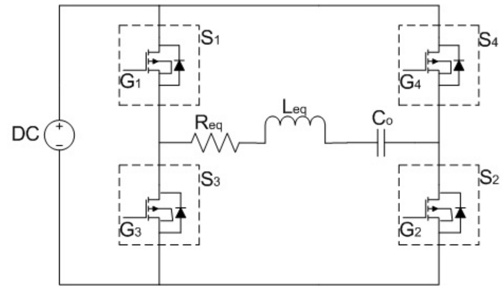

Figure 20: Full bridge series resonant inverter

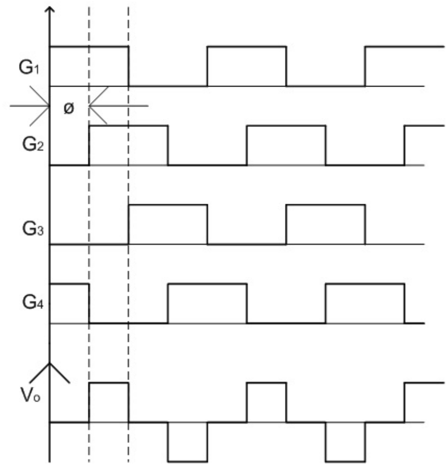

Figure 21: Waveform of PS control technique

Pulse density modulation is another very popular power control technique which is presented by various authors [21, 29, 35, 72–74]. In the normal PWM, output power is controlled by controlling the duty cycle of pulse width modulation. In the resonant inverter, the PWM method is not able to maintain the ZVS condition under variable load due to the increase in switching losses. In the PDM technique, by adjusting the ratio between continuous T_{on} pulses and continuous Toff pulses, output power could be controlled. It can be better understood through Fig. 24. By controlling the time period of the pulse density modulation T_{PDM}, the transfer of output power to the load can be controlled. Power is transmitted to the load by the inverter in T_A time and in $(T_{PDM} - T_A)$ time it stops working. So it can be concluded that output power can be controlled by changing pulse density. Thus the duty cycle of PDM (D_{PDM}) can be defined as the ratio of T_A to T_{PDM}. So here D_{PDM} is the variable which controls output power. Fig. 22, Fig. 23, Fig. 24 show the theoretical waveforms of

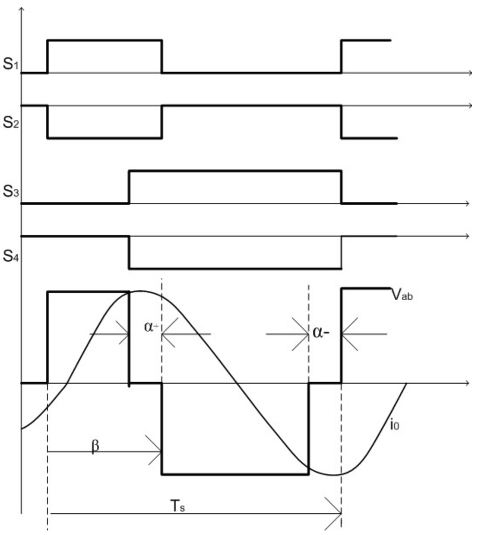

Figure 22:

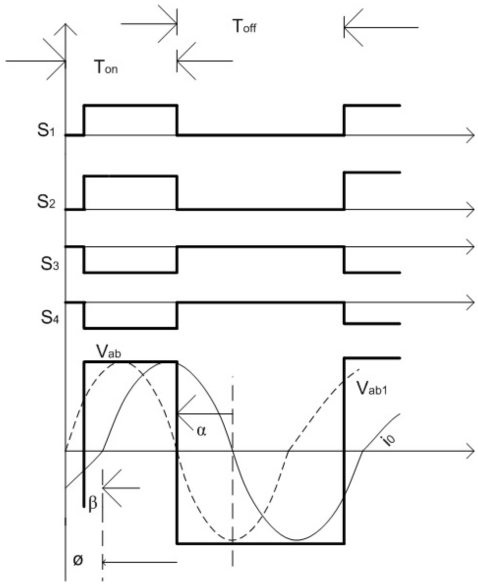

Figure 23:

ADC, AVC, and PWM.

Research is also ongoing into discontinuous mode control [75–77] in which dead time of the switches in the same leg is used as a control variable. The main advantages of this method are transient switching losses become zero and a smaller resonant component is required, meaning the converter can operate at very high frequency.

In modern induction heating, the methods which were discussed earlier are not used in isolation. To improve efficiency and achieve accurate output power and better current control, these methods are used in combination with PLL, fuzzy logic, PID controller, FPGA etc. In [78], the asymmetrical pulse width modulation technique was introduced in the de-

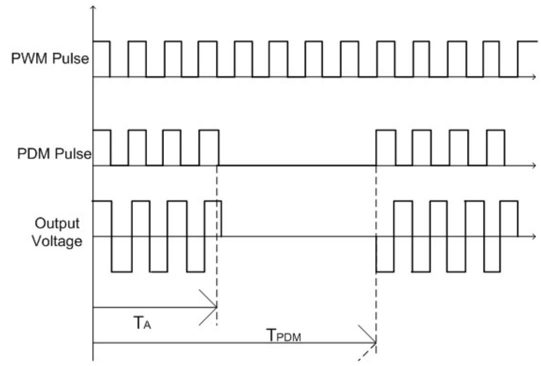

Figure 24:

sign of HBSRI (for induction cooking) using FPGA and PLL. Also, the logic for the generation of pulses for switches inside FPGA was discussed. Within the FPGA, two control loops were used, one is PLL, which is used to track the load frequency, and the second loop is the duty cycle loop, which is used to control output power. In addition to these, control techniques have also been developed for multiple inverters for multiple zones induction heating (ZCIH) [61, 79]. H. Pham et. al presented a paper in which the researchers tried to control the phase angle of high-frequency resonant current for multiple inverters in a zone control induction heating system. It controls the magnitude of each coil current for uniform temperature distribution. Fig. 26 shows a block diagram of a controller for multiple inverter units in zone control induction heating. There are two loops in the controller. One loop controls the amplitude and other loop controls the phase angle of each coil current. In this proposed system, a buck converter was used to provide input voltage for the inverter. Here D^* is used to control the duty cycle of the buck converter and 'θ' is used to control the phase angle of the inverter. In [79] by the same author (H. Pham), a method was proposed in which a real and imaginary part of inverter voltage/current is detected and controlled instead of the phase angle and the current amplitude control technique from the author's own previous work. In this paper, two decoupling techniques were used (a) manipulated input decoupling (MID) and (b) state feedback decoupling. As a result, this method is able to control the each coil current for 0 to 100%. A 6 coil ZCIH experimental setup was also developed.

Load adaptive capabilities is the another issue for modern induction heating and various solutions have been proposed [80, 81]. In [82], adaptive simmering control was proposed for modern induction cookers, which are based on an infrared sensor, instead of a negative temperature coefficient (NTC) sensor, whose parameters are updated online with the help of a multiple models reset observer (MMReO). Fig. 26 shows the block diagram of MMReO, which consists of multiple fixed identification models and of a ReO. Also in this paper a QFT based controller has been designed and compared. This method can be used for achieving good temperature control and quick heating.

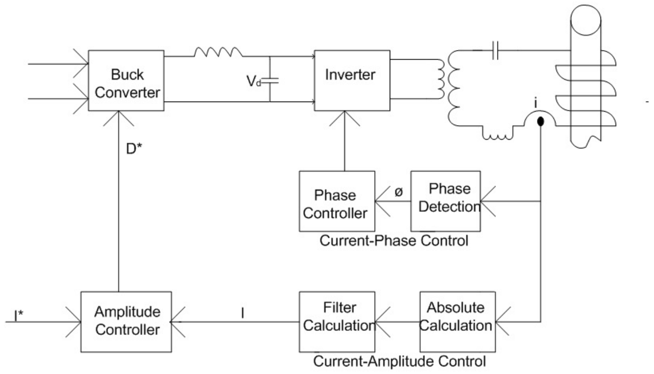

Figure 25: Block diagram of controller for multiple inverter units in ZCIH

To obtain dynamics control, resonant control has been proposed for induction heating systems [83]. In this paper, modeling of a multi-phase induction heating system has been proposed. An attempt has been made to control the amplitude and phase of the inductor current in a current source inverter, consisting of a multi-coil induction heating system in a transverse flux configuration. It can be used in the application of temperature control for the working of metals. In this paper, it is concluded that when the number of coils is increased, a better temperature profile can be achieved. But tuning methodology is still an issue due to the coupling arms and its complex system.
Also, it has been seen that it is difficult to deliver induction heating control at variable load. Due to this, good power control, system stability, and ZVS are not achievable. In order to describe/solve this problem, Inverse-based control strategy [84] was proposed by Alberto Dominguez et. al., which is a combination of different modulation strategies to deal with load uncertainty. This method achieves a faster settling time.
All these control strategies which are discussed above can either be designed by using an analog circuit or a digital method [85]. In an analog circuit, input current and voltage and output voltage and current are measured through the current transformer, and gating signals are generated. But in the digital controller, these parameters are sampled and converted from analog to digital by using advanced controllers such as a digital signal processor (DSPs), microprocessor, and field programmable gate array (FPGA). Various digital implementations have been proposed, using DSPs (Digital Signal Processor) and FPGA (Field Programmable Gate Arrays). Various power converters and design methodologies have been proposed for the induction heating application which harnesses the advantages of Field Programmable Gate Array (FPGA) [86–89].

4. Future scope and challenges

From the discussion above it can be seen that various converters and control strategies have been developed to enhance the efficiency and performance of modern induction heating. But there are still some issues which have to be eliminated to further upgrade performance. The continuous development of power electronics, digital control and advanced software are opening up new areas of research in the field of induction heating. Some of them are given below:

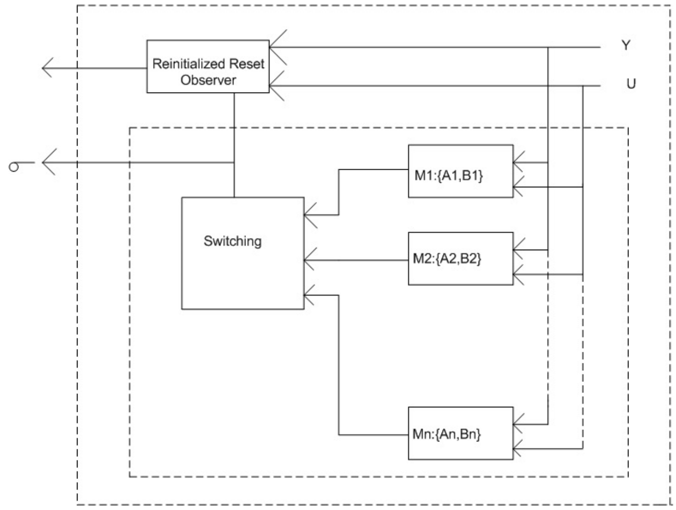

Figure 26: A block diagram of MMRe

- Induction High-Performance Heating System: With the development of improved semiconductor technology and wideband devices, it is possible to design an IH system with higher efficiency. This type of system enjoys high efficiency and stability, reliability, and performance can also be improved.
- Advanced Modulation Technique: The control system of IH is designed in such a way that it can adapt the operation of the power converter at different induction heating loads and operating points. Research is ongoing into the use of a real-time identification system and load adaptive algorithms. Research can also be done on smart pot recognition for domestic induction heating.
- User-Friendly pot: At present, in induction heating systems, the user places a pot in a specified region. But future research can also be done in the field of total active surface concept in which the user can place a pot anywhere on the cooking surface. This could lead to very high efficiency and performance.
- Advanced Converter System: Converters currently used in induction heating systems consist of two stages. First AC to DC conversion and then again DC to high-frequency AC conversion. These two stages increase losses and decrease efficiency. To rectify these problems, research is going into direct AC to AC conversion. A matrix converter might be a better solution for direct AC to AC conversion. But very few works have been done on matrix converter-based induction heating systems. Also in a matrix converter, a large number of switches (bidirectional switches) are used in the

converter, which increases switching losses and creates a problem in terms of ZVS and ZCS.

Another line of research, which is eyeing the development of an advanced converter, is the multilevel converter for IH application. But the capacitor voltage imbalance problem is still an issue in this converter. Once this problem is solved, this converter will be a very good option for industrial and domestic induction heating applications at higher rated power.

5. Conclusion

This paper presents a review of current research in the field of high-frequency inverters and trelated power control techniques. Two main technologies are involved in modern induction heating technology, driving the design process: (a) the high-frequency power inverter and (b) power control techniques (modulation techniques) for the high-frequency power inverter. The intense research done in recent years in this field has led to significant gains in efficiency. Consequently, the use of induction heating has increased in many fields such as medical, domestic and industrial applications and with sustained research this trend should continue.

References

[1] A. Arteconi, C. Brandoni, F. Polonara, Distributed generation and trigeneration: Energy saving opportunities in italian supermarket sector, Applied Thermal Engineering 29 (8) (2009) 1735–1743.

[2] P. R. Stauffer, T. C. Cetas, R. C. Jones, Magnetic induction heating of ferromagnetic implants for inducing localized hyperthermia in deep-seated tumors, IEEE Transactions on Biomedical Engineering (2) (1984) 235–251.

[3] W. Moreland, The induction range: Its performance and its development problems, IEEE Transactions on Industry Applications (1) (1973) 81–85.

[4] A. Chakraborty, D. Roy, P. K. Sadhu, A. Ganguly, A. Banerjee, (0549) an interference of high frequency series resonant inverter in domestic induction heater estimation in emission control using fem, Journal of Power Technologies.

[5] D. Roy, A. Naskar, P. K. Sadhu, A mathematical analysis of two dimensional steady state heat conduction in the coil of an induction heater using finite element method, J. Power Technol.

[6] A. MÜHLBAUER, History of induction heating and melting. essen: Vulkan, c2008, x, 202 p, Tech. rep., ISBN 38-027-2946-3.

[7] O. Lucía, P. Maussion, E. J. Dede, J. M. Burdío, Induction heating technology and its applications: past developments, current technology, and future challenges, IEEE Transactions on Industrial Electronics 61 (5) (2014) 2509–2520.

[8] F. P. Dawson, P. Jain, A comparison of load commutated inverter systems for induction heating and melting applications, IEEE Transactions on Power Electronics 6 (3) (1991) 430–441.

[9] H. W. Koertzen, J. D. Van Wyk, J. A. Ferreira, Design of the half-bridge, series resonant converter for induction cooking, in: Power Electronics Specialists Conference, 1995. PESC'95 Record., 26th Annual IEEE, Vol. 2, IEEE, 1995, pp. 729–735.

[10] M. Kamli, S. Yamamoto, M. Abe, A 50-150 khz half-bridge inverter for induction heating applications, IEEE Transactions on Industrial Electronics 43 (1) (1996) 163–172.

[11] Y.-S. Kwon, S.-B. Yoo, D.-S. Hyun, Half-bridge series resonant inverter for induction heating applications with load-adaptive pfm control strategy, in: Applied Power Electronics Conference and Exposition, 1999. APEC'99. Fourteenth Annual, Vol. 1, IEEE, 1999, pp. 575–581.

[12] H. Koertzen, J. Ferreria, J. Van Wyk, A comparative study of single switch induction heating converters using novel component effectivity concepts, in: Power Electronics Specialists Conference, 1992. PESC'92 Record., 23rd Annual IEEE, IEEE, 1992, pp. 298–305.

[13] J. M. Burdio, L. A. Barragan, F. Monterde, D. Navarro, J. Acero, Asymmetrical voltage-cancellation control for full-bridge series resonant inverters, IEEE Transactions on Power Electronics 19 (2) (2004) 461–469.

[14] J. Davies, P. Simpson, Induction heating handbook, McGraw-Hill Companies, 1979.

[15] H. Sarnago, Ó. Lucía, M. Pérez-Tarragona, J. M. Burdío, Dual-output boost resonant full-bridge topology and its modulation strategies for high-performance induction heating applications, IEEE Transactions on Industrial Electronics 63 (6) (2016) 3554–3561.

[16] H. Sarnago, O. Lucia, A. Mediano, J. M. Burdio, Direct ac–ac resonant boost converter for efficient domestic induction heating applications, IEEE Transactions on Power Electronics 29 (3) (2014) 1128–1139.

[17] P. P. Roy, S. Doradla, S. Deb, Analysis of the series resonant converter using a frequency domain model, in: Power Electronics Specialists Conference, 1991. PESC'91 Record., 22nd Annual IEEE, IEEE, 1991, pp. 482–489.

[18] A. Bhat, Fixed frequency pwm series-parallel resonant converter, in: Industry Applications Society Annual Meeting, 1989., Conference Record of the 1989 IEEE, IEEE, 1989, pp. 1115–1121.

[19] L. Grajales, J. Sabate, K. Wang, W. Tabisz, F. Lee, Design of a 10 kw, 500 khz phase-shift controlled series-resonant inverter for induction heating, in: Industry Applications Society Annual Meeting, 1993., Conference Record of the 1993 IEEE, IEEE, 1993, pp. 843–849.

[20] J. Milewski, W. Bujalski, M. Wolowicz, K. Futyma, J. Kucowski, Off-design operation of an 900 mw-class power plant with utilization of low temperature heat of flue gases, Journal of Power Technologies 95 (3) (2015) 221.

[21] M. Wolowicz, J. Milewski, K. Badyda, Feedwater repowering of 800 mw supercritical steam power plant, Journal of Power Technologies 92 (2) (2012) 127.

[22] M. Hediehloo, M. Akhbari, New approach in design of planar coil of induction cooker based on skin and proximity effects analysis, in: Industrial Technology, 2009. ICIT 2009. IEEE International Conference on, IEEE, 2009, pp. 1–6.

[23] 'Induction Heating System Topology Review', http://www.induksiyonx.com/FileUpload/bs736485/File/an-9012.pdf.

[24] O. Fernandez, J. Delgado, F. Martinez, J. Correa, M. Heras, Design and implementation of a 120a resonant inverter for induction furnace, in: Power, Electronics and Computing (ROPEC), 2013 IEEE International Autumn Meeting on, IEEE, 2013, pp. 1–6.

[25] A. Shenkman, B. Axelrod, Y. Berkovich, Single-switch ac–ac converter with high power factor and soft commutation for induction heating applications, IEE Proceedings-Electric Power Applications 148 (6) (2001) 469–474.

[26] A. Shenkman, B. Axelrod, Y. Berkovich, Improved modification of the single-switch ac-ac converter for induction heating applications, IEE Proceedings-Electric Power Applications 151 (1) (2004) 1–4.

[27] N. Yongyuth, P. Viriya, K. Matsuse, Analysis of a full-bridge inverter for induction heating using asymmetrical phase-shift control under zvs and non-zvs operation, in: Power Electronics and Drive Systems, 2007. PEDS'07. 7th International Conference on, IEEE, 2007, pp. 476–482.

[28] C.-M. Wang, H.-J. Chiu, D.-R. Chen, Novel zero-current-switching (zcs) pwm converters, IEE Proceedings-Electric Power Applications 152 (2) (2005) 407–415.

[29] N.-J. Park, D.-Y. Lee, D.-S. Hyun, A power-control scheme with constant switching frequency in class-d inverter for induction-heating jar application, IEEE Transactions on Industrial Electronics 54 (3) (2007) 1252–1260.

[30] F. Forest, S. Faucher, J.-Y. Gaspard, D. Montloup, J.-J. Huselstein, C. Joubert, Frequency-synchronized resonant converters for the supply of multiwinding coils in induction cooking appliances, IEEE Transactions on Industrial Electronics 54 (1) (2007) 441–452.

[31] P. Savary, M. Nakaoka, T. Maruhashi, A high-frequency resonant inverter using current-vector control scheme and its performance evaluations, IEEE Transactions on Industrial Electronics (2) (1987) 247–256.

[32] A. L. Shenkman, B. Axelrod, V. Chudnovsky, A new simplified model of the dynamics of the current-fed parallel resonant inverter, IEEE Transactions on Industrial Electronics 47 (2) (2000) 282–286.

[33] A. Shenkman, B. Axelrod, V. Chudnovsky, Assuring continuous input current using a smoothing reactor in a thyristor frequency converter for induction metal melting and heating applications, IEEE Transactions on Industrial Electronics 48 (6) (2001) 1290–1292.
[34] R. L. Steigerwald, A comparison of half-bridge resonant converter topologies, IEEE transactions on Power Electronics 3 (2) (1988) 174–182.
[35] V. Esteve, E. Sanchis-Kilders, J. Jordán, E. J. Dede, C. Cases, E. Maset, J. B. Ejea, A. Ferreres, Improving the efficiency of igbt series-resonant inverters using pulse density modulation, IEEE transactions on industrial electronics 58 (3) (2011) 979–987.
[36] O. Lucia, J. M. Burdio, I. Millán, J. Acero, L. A. Barragán, Efficiency-oriented design of zvs half-bridge series resonant inverter with variable frequency duty cycle control, IEEE Transactions on Power Electronics 25 (7) (2010) 1671–1674.
[37] J. Espi, E. Dede, E. Navarro, E. Sanchis, A. Ferreres, Features and design of the voltage-fed l-lc resonant inverter for induction heating, in: Power Electronics Specialists Conference, 1999. PESC 99. 30th Annual IEEE, Vol. 2, IEEE, 1999, pp. 1126–1131.
[38] J. Espi, E. Dede, Design considerations for three element l-lc resonant inverters for induction heating, International journal of electronics 86 (10) (1999) 1205–1216.
[39] J. Espi, A. Navarro, J. Maicas, J. Ejea, S. Casans, Control circuit design of the l-lc resonant inverter for induction heating, in: Power Electronics Specialists Conference, 2000. PESC 00. 2000 IEEE 31st Annual, Vol. 3, IEEE, 2000, pp. 1430–1435.
[40] J. Espi, E. Dede, A. Ferreres, R. Garcia, Steady-state frequency analysis of the" llc" resonant inverter for induction heating, in: Power Electronics Congress, 1996. Technical Proceedings. CIEP'96., v IEEE International, IEEE, 1996, pp. 22–28.
[41] J. M. Espi-Huerta, E. J. D. G. Santamaria, R. G. Gil, J. Castello-Moreno, Design of the l-lc resonant inverter for induction heating based on its equivalent sri, IEEE Transactions on Industrial Electronics 54 (6) (2007) 3178–3187.
[42] L. Szablowski, J. Milewski, Dynamic analysis of compressed air energy storage in the car, Journal of Power Technologies 91 (1) (2011) 23.
[43] J. Milewski, K. Badyda, L. Szablowski, Compressed air energy storage systems, Journal of Power Technologies 96 (4) (2016) 245.
[44] O. Lucia, J. M. Burdio, L. A. Barragan, J. Acero, I. Millán, Series-resonant multiinverter for multiple induction heaters, IEEE Transactions on Power Electronics 25 (11) (2010) 2860–2868.
[45] J. M. Burdio, F. Monterde, J. R. Garcia, L. A. Barragan, A. Martinez, A two-output series-resonant inverter for induction-heating cooking appliances, IEEE Transactions on Power Electronics 20 (4) (2005) 815–822.
[46] M. Pérez-Tarragona, H. Sarnago, Ó. Lucia, J. M. Burdío, Series resonant multi-inverter prototype for domestic induction heating, in: Industrial Electronics Society, IECON 2015-41st Annual Conference of the IEEE, IEEE, 2015, pp. 005444–005449.
[47] Y.-C. Jung, Dual half bridge series resonant inverter for induction heating appliance with two loads, Electronics letters 35 (16) (1999) 1345–1346.
[48] F. Forest, E. Laboure, F. Costa, J. Y. Gaspard, Principle of a multi-load/single converter system for low power induction heating, IEEE Transactions on Power Electronics 15 (2) (2000) 223–230.
[49] N. Nguyen-Quang, D. Stone, C. Bingham, M. Foster, Single phase matrix converter for radio frequency induction heating, in: Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006. International Symposium on, IEEE, 2006, pp. 614–618.
[50] H. Sugimura, S.-P. Mun, S.-K. Kwon, T. Mishima, M. Nakaoka, High-frequency resonant matrix converter using one-chip reverse blocking igbt-based bidirectional switches for induction heating, in: Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, IEEE, 2008, pp. 3960–3966.
[51] H. Sarnago, A. Mediano, O. Lucia, High efficiency ac–ac power electronic converter applied to domestic induction heating, IEEE Transactions on Power Electronics 27 (8) (2012) 3676–3684.
[52] J. Rodriguez, J.-S. Lai, F. Z. Peng, Multilevel inverters: a survey of topologies, controls, and applications, IEEE Transactions on industrial electronics 49 (4) (2002) 724–738.
[53] J.-S. Lai, F. Z. Peng, Multilevel converters-a new breed of power converters, IEEE Transactions on industry applications 32 (3) (1996) 509–517.
[54] G. P. Adam, S. J. Finney, A. M. Massoud, B. W. Williams, Capacitor balance issues of the diode-clamped multilevel inverter operated in a quasi two-state mode, IEEE Transactions on Industrial Electronics 55 (8) (2008) 3088–3099.
[55] L. Qingfeng, W. Huamin, L. Zhaoxia, Discuss on the application of multilevel inverter in high frequency induction heating power supply, in: TENCON 2006. 2006 IEEE Region 10 Conference, IEEE, 2006, pp. 1–4.
[56] J. I. Rodriguez, S. B. Leeb, A multilevel inverter topology for inductively coupled power transfer, IEEE Transactions on Power Electronics 21 (6) (2006) 1607–1617.
[57] B. Nagarajan, R. R. Sathi, Phase locked loop based pulse density modulation scheme for the power control of induction heating applications, Journal of Power Electronics 15 (1) (2015) 65–77.
[58] O. Lucia, C. Carretero, D. Palacios, D. Valeau, J. Burdío, Configurable snubber network for efficiency optimisation of resonant converters applied to multi-load induction heating, Electronics letters 47 (17) (2011) 989–991.
[59] N. A. Ahmed, M. Nakaoka, Boost-half-bridge edge resonant soft switching pwm high-frequency inverter for consumer induction heating appliances, IEE Proceedings-Electric Power Applications 153 (6) (2006) 932–938.
[60] H. Sarnago, O. Lucia, A. Mediano, J. M. Burdío, Class-d/de dual-mode-operation resonant converter for improved-efficiency domestic induction heating system, IEEE Transactions on Power Electronics 28 (3) (2013) 1274–1285.
[61] H. P. Ngoc, H. Fujita, K. Ozaki, N. Uchida, Phase angle control of high-frequency resonant currents in a multiple inverter system for zone-control induction heating, IEEE Transactions on power electronics 26 (11) (2011) 3357–3366.
[62] C. Carretero, O. Luc, J. Acero, J. Burd, et al., Phase-shift control of dual half-bridge inverter feeding coupled loads for induction heating purposes, Electronics Letters 47 (11) (2011) 670–671.
[63] M. K. Kazimierczuk, M. K. Jutty, Fixed-frequency phase-controlled full-bridge resonant converter with a series load, IEEE transactions on power electronics 10 (1) (1995) 9–18.
[64] H. Kifune, Y. Hatanaka, M. Nakaoka, Cost effective phase shifted pulse modulation soft switching high frequency inverter for induction heating applications, IEE Proceedings-Electric Power Applications 151 (1) (2004) 19–25.
[65] B.-Y. Chen, Y.-S. Lai, Switching control technique of phase-shift-controlled full-bridge converter to improve efficiency under light-load and standby conditions without additional auxiliary components, IEEE transactions on power electronics 25 (4) (2010) 1001–1012.
[66] P. Imbertson, N. Mohan, Asymmetrical duty cycle permits zero switching loss in pwm circuits with no conduction loss penalty, IEEE transactions on industry applications 29 (1) (1993) 121–125.
[67] P. Imbertson, N. Mohan, New pwm converter circuits combining zero switching loss with low conduction loss, in: Telecommunications Energy Conference, 1990. INTELEC'90., 12th International, IEEE, 1990, pp. 179–185.
[68] S. Yachiangkam, A. Sangswang, S. Naetiladdanon, C. Koompai, S. Chudjuarjeen, Resonant inverter with a variable-frequency asymmetrical voltage-cancellation control for low q-factor loads in induction cooking, in: Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on, IEEE, 2011, pp. 1–10.
[69] S. Hosseini, A. Y. Goharrizi, E. Karimi, A multi-output series resonant inverter with asymmetrical voltage-cancellation control for induction-heating cooking appliances, in: Power Electronics and Motion Control Conference, 2006. IPEMC 2006. CES/IEEE 5th International, Vol. 3, IEEE, 2006, pp. 1–6.
[70] J. Jittakort, S. Chudjuarjeen, A. Sangswang, S. Naetiladdanon, C. Koompai, A dual output series resonant inverter with improved asymmetrical voltage-cancellation control for induction cooking appliance, in: IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society, IEEE, 2011, pp. 2520–2525.
[71] L. A. Barragán, J. M. Burdío, J. I. Artigas, D. Navarro, J. Acero, D. Puyal, Efficiency optimization in zvs series resonant inverters with asymmetrical voltage-cancellation control, IEEE transactions on power

electronics 20 (5) (2005) 1036–1044.
[72] N. A. Ahmed, High-frequency soft-switching ac conversion circuit with dual-mode pwm/pdm control strategy for high-power ih applications, IEEE transactions on industrial electronics 58 (4) (2011) 1440–1448.
[73] H. Fujita, H. Akagi, Control and performance of a pulse-density-modulated series-resonant inverter for corona discharge processes, IEEE Transactions on Industry Applications 35 (3) (1999) 621–627.
[74] O. Lucia, J. M. Burdio, I. Millan, J. Acero, D. Puyal, Load-adaptive control algorithm of half-bridge series resonant inverter for domestic induction heating, IEEE Transactions on Industrial Electronics 56 (8) (2009) 3106–3116.
[75] S. Shah, A. K. Upadhyay, Analysis and design of a half-bridge series-parallel resonant converter operating in discontinuous conduction mode, in: Applied Power Electronics Conference and Exposition, 1990. APEC'90, Conference Proceedings 1990., Fifth Annual, IEEE, 1990, pp. 165–174.
[76] V. Belaguli, A. K. Bhat, Series-parallel resonant converter operating in discontinuous current mode. analysis, design, simulation, and experimental results, IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications 47 (4) (2000) 433–442.
[77] I. Millan, D. Puyal, J. Burdio, C. Bemal, J. Acero, Improved performance of half-bridge series resonant inverter for induction heating with discontinuous mode control, in: Applied Power Electronics Conference, APEC 2007-Twenty Second Annual IEEE, IEEE, 2007, pp. 1293–1298.
[78] J. Tian, G. Berger, T. Reimann, M. Scherf, J. Petzoldt, A half-bridge series resonant inverter for induction cookers using a novel fpga-based control strategy, in: Power Electronics and Applications, 2005 European Conference on, IEEE, 2005, pp. 1–9.
[79] H. N. Pham, H. Fujita, K. Ozaki, N. Uchida, Dynamic analysis and control for resonant currents in a zone-control induction heating system, IEEE Transactions on Power Electronics 28 (3) (2013) 1297–1307.
[80] J. Egalon, S. Caux, P. Maussion, M. Souley, O. Pateau, Multiphase system for metal disc induction heating: Modeling and rms current control, IEEE Transactions on industry applications 48 (5) (2012) 1692–1699.
[81] M. Cano, A. Barrera, J. Estrada, A. Hernandez, T. Cordova, An induction heater device for studies of magnetic hyperthermia and specific absorption ratio measurements, Review of Scientific Instruments 82 (11) (2011) 114904.
[82] D. Paesa, C. Franco, S. Llorente, G. Lopez-Nicolas, C. Sagues, Adaptive simmering control for domestic induction cookers, IEEE Transactions on Industry Applications 47 (5) (2011) 2257–2267.
[83] N. K. Long, S. Caux, X. Kestelyn, O. Pateau, P. Maussion, Resonant control of multi-phase induction heating systems, in: IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, IEEE, 2012, pp. 3293–3298.
[84] A. Dominguez, L. A. Barragan, A. Otin, D. Navarro, D. Puyal, Inverse-based power control in domestic induction-heating applications, IEEE transactions on industrial electronics 61 (5) (2014) 2612–2621.
[85] J. I. Artigas, I. Urriza, J. Acero, L. A. Barragan, D. Navarro, J. M. Burdio, Power measurement by output-current integration in series resonant inverters, IEEE Transactions on Industrial Electronics 56 (2) (2009) 559–567.
[86] D. Navarro, Ó. Lucı, L. A. Barragán, I. Urriza, Ó. Jiménez, et al., High-level synthesis for accelerating the fpga implementation of computationally demanding control algorithms for power converters, IEEE Transactions on Industrial Informatics 9 (3) (2013) 1371–1379.
[87] O. Lucia, L. A. Barragan, J. M. Burdio, O. Jimenez, D. Navarro, I. Urriza, A versatile power electronics test-bench architecture applied to domestic induction heating, IEEE Transactions on Industrial Electronics 58 (3) (2011) 998–1007.
[88] D. Navarro, Ó. Lucía, L. A. Barragan, J. I. Artigas, I. Urriza, O. Jimenez, Synchronous fpga-based high-resolution implementations of digital pulse-width modulators, IEEE transactions on power electronics 27 (5) (2012) 2515–2525.
[89] O. Jimenez, O. Lucia, I. Urriza, L. A. Barragan, P. Mattavelli, D. Boroyevich, An fpga-based gain-scheduled controller for resonant converters applied to induction cooktops, IEEE Transactions on Power Electronics 29 (4) (2014) 2143–2152.