IMPROVED AC-AC CONVERTER FOR INDUCTION HEATING APPLICATIONS

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Abstract —Induction heating applications require high frequency currents which are obtained using resonant converters viz., Series and Parallel resonant inverters. The resonance frequency in these converters will be tuned to a high value. In this paper a single-switch parallel resonant converter for induction heating is simulated. It is compared with the existing inverter topologies; half bridge and full bridge. The circuit consists of input LC-filter, bridge rectifier and one controlled power switch. The switch operates in soft commutation mode and serves as a high frequency generator. Output power is controlled via switching frequency.

Keywords — High frequency, induction heating, Resonant converters

I. INTRODUCTION

Induction heating is a non-contact heating process. It uses high frequency electricity to heat materials that are electrically conductive. Since it is non-contact, the heating process does not contaminate the material being heated. It is also very efficient since the heat is actually generated inside the work-piece. This can be contrasted with other heating methods where heat is generated in a flame or heating element, which is then applied to the work-piece. For these reasons Induction heating lends itself to some unique applications in industry. Static frequency converters have been extensively applied in industry as a medium –frequency power supply for induction heating and melting installations. They are applied in all branches of the military, machine-building industries, domestic heating cooking [1] devices and other purposes.

Increasing the frequency of operation of power converters is desirable, as it allows the size of circuit magnetics and capacitors to be reduced, leading to cheaper and more compact circuits. However, increasing the frequency of operation also increases switching losses and hence reduces system efficiency. One solution to this problem is to replace the "chopper" switch of a standard SMPS topology (Buck, Boost etc.) with a "resonant" switch, which uses the resonances of circuit capacitances and inductances to shape the waveform of either the current or the voltage across the switching element, such that when switching takes place, there is no current through or voltage across it, and hence no power dissipation.

Because they require a substantial drive current, Bipolar transistors are not generally used in resonant converters, unless the base drive is provided by the resonant circuit itself (for example in TV deflection circuits and fluorescent lamp ballasts). Power MOSFETs and IGBTs, with their effectively capacitive inputs and low drive energy requirements, are the most frequently used types.

The power converter generally implemented in domestic IH appliances is a resonant inverter due to its improved efficiency and lower size , which allows developing compact appliances. Inverter topologies commonly used for IH are the full-bridge and half-bridge[2]-[4] operations Some deviations of these topologies are used often to achieve multiple-output converters. The modulation strategies commonly applied to control output power are based on modifying either switching frequency or duty cycle to achieve the desired output power. Each power-converter topology offers different performance features with specific requirements in terms of costs, and hardware and control complexity.

The full-bridge[5]-[6] topology can offer the higher output power (up to 5 kW) and control flexibility, and its efficiency can be significantly optimized through the proper control strategy. However, its higher cost makes it unfeasible for the mean IH appliance. The half-bridge series resonant inverter is the most used topology due to its appropriate balance between performance, complexity, and cost. It is used to design converters with up to 3.5-kW output power. The decision has to be made considering the proper balance between cost and performance.

This paper presents circuit of an AC-AC converter[7] for induction heating .It typically includes a controlled rectifier and a frequency controlled current source or a voltage source inverter. It is a fact that the input rectifier does not ensure a sine wave input current, and is characterized by a low power. Recently many studies of high power factor rectifiers [8] with a single switch have been made. These schemes are also characterized by a close to sine wave input current. The input circuit of the converter is constructed similarly to the input circuit in, which also ensures a high power factor. The present problem aims to minimize the cost of induction heater system by using an embedded controller.

II. IH TECHNOLOGY

The main blocks of an induction cooking appliance are shown in Fig. 1.

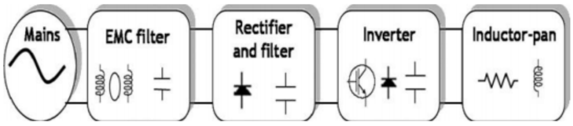


Fig 1. Induction cooking appliance block diagram.

The energy taken from the mains is filtered by an electromagnetic compatibility (EMC) filter, which prevents the device from inserting interferences and provides immunity to voltage transients. Then it is converted to DC using a rectifier. Then, connect this DC current to a high frequency switching circuit to administer high frequency current to the heating coil. According to Ampere's Law, a high frequency magnetic field is created around the heated coil. A low value of filter capacitor is taken to get a high power factor, and as a consequence, a high-ripple dc bus is obtained. Then, the resonant inverter supplies variable frequency current (20–100 kHz) to the induction coil. This current produces an alternating magnetic field, which causes eddy currents and magnetic hysteresis heating up the pan. The inductor-pan system is modeled as the series connection of an equivalent resistance *R*eq and an equivalent inductance *L*eq. This model shows proper results to analyze power-converter operation.
At the resonance frequency, the inductive reactance and the capacitive reactance become the same, i.e. the voltage of the power source and the current in the circuit stay at the same level. The current in the circuit reaches its peak when the source frequency becomes identical to the resonance frequency. It decrements when the source frequency gets higher or lower than the resonance frequency. The current and output energy reaches its maximum value at resonance frequency.

III. HALF BRIDGE SERIES RESONANT INVERTER

The main power circuit employs a half-bridge series converter switching at a high frequency as shown in Fig. 2. The switching circuit consists of an IGBT. Zero voltage/current turn-on switching is enabled by turning on the IGBT while the diode is in turn on period. The resonant circuit comprises of resonant inductance (Lr) and resonant capacitance (Cr). The capacitors, C1 and C2, are the lossless turn-off snubbers for the switches, S1 and S2. The resonant frequency fr of the converter is mainly determined by the inductance Lr and the capacitance Cr of the series capacitor.

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$$

The switching frequency of the system is set higher than the resonance frequency, in order to avoid noise generated within the audio frequency band.
The resonant load consists of the pan, the induction coil and the resonant capacitor. Induction coil and pan coupling is modelled as the series connection of an inductor and a resistor, based on its analogy with respect to a transformer. The basic circuit of a half bridge series resonant circuit is shown in Fig. 2

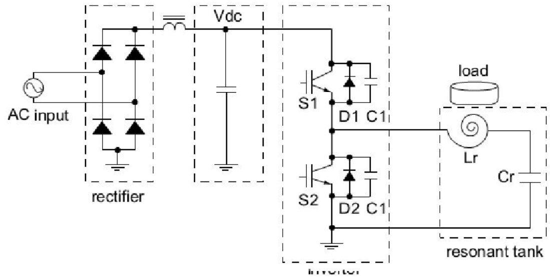


Fig 2. Half bridge series resonant inverter

By connecting the IGBT switching circuit, S1 and S2 in parallel to diodes D1 and D2, current loss is minimized. When S1 is turned-off, D2 helps S2 stay on zero voltage/current before being turned on, thereby substantially reducing current loss (the same is the case with S1). There is no reverse- recovery problem as the voltage on both sides remains zero after the diode is turned off. However, as the switching circuit is turned off at around the upper limit of voltage and current, some switching loss results on turn-off. The capacitors C1 and C2, acting as turn-off snubbers connected in parallel to S1 and S2, keep this loss to a minimum. Upon turn-on the switching circuit starts from zero voltage/current, so these turn-off snubbers operate as lossless turn-off snubbers. This has been simulated using MATLAB/ SIMULINK with the circuit diagram shown in Fig. 3.

This system does not require a big capacitor to make DC more leveled, as the primary purpose of the system is to generate heat energy. Rather, the rugged form of DC helps improve the power factor of the system. In this system, the leveling capacitor serves as a filter preventing the high frequency current from flowing toward the inverter and from entering the input part. Input current becomes the average of the inverter current, and the ripples flow to the leveling capacitor. The voltage passing the leveling capacitor is turned into a square wave in the process of high frequency switching in the inverter. The high frequency harmonics contained in the square wave are eliminated by the L_r, C_r filter. The square wave enables resonance in the resonant circuit, which in turn, creates a magnetic field around the resonant inductor affecting the load. Eddy currents are formed around the surface of the object, generating heat energy.

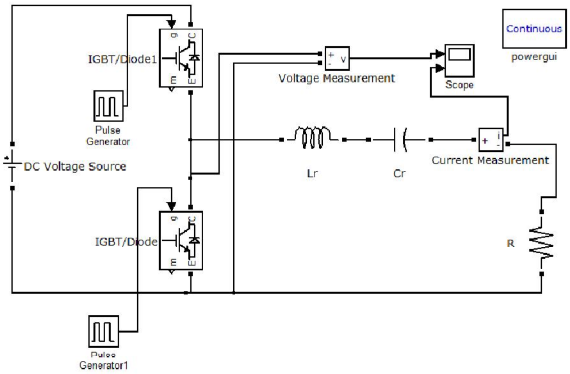
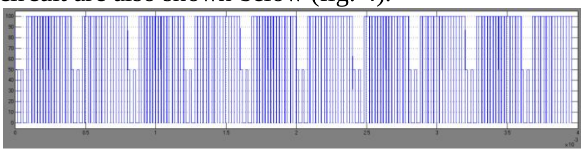
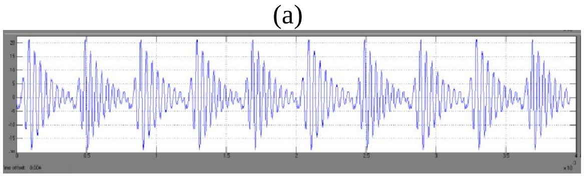


Fig 3 . SIMULINK model of Half bridge inverter

The voltage and current waveforms of the simulated circuit are also shown below (fig. 4).



(a)



(b)

Fig. 4. (a) The voltage waveform and (b) current waveform

Since it is a voltage- source inverter voltage waveform is having square pulses and the current waveform is oscillatory as is seen in figure 4(a),(b).

SIMULATION PARAMETERS:
Lr=52.7uH and Cr=0.8uF, resonant frequency=24.5kHz

IV. FULL BRIDGE HYBRID RESONANT INVERTER

Another commonly used inverter topology with 4 semiconductor switches is described in this section. This high frequency full bridge hybrid resonant inverter supplies more power when compared to half bridge seies resonant inverter.

One hybrid resonant inverter consists of four semiconductor switches (IGBT's) for each heating-range. The switching frequency lies between 25 to 35 kHz. It can be considered as a combination of both series and parallel resonant circuits where the switching is made at zero current cross over (ZCS). An advantage of the series circuit is that both zero current and zero voltage switching are possible. Different diameters of induction coils can be chosen for different diameters of flat bed pans. For getting maximum efficiency (with induction system, about 88%) of the system, the coil diameter and the diameter of the utensils must be equal.

The full resonant current passes through the switches resulting in ON losses. Depending on the converter design there will be reactive power consumption or more complexity. In a parallel load, there would be low ON losses in the switches but turn-on / turn-off losses would be more as the switching takes place at high voltage and current. So, a hybrid inverter, (i.e. by using combined series and parallel circuit) can be used to reduce the losses in the switches. Fig. 5 shows a resonant inverter system for one cooking zone. Here the energy is transferred from the series resonant circuit to the parallel resonant circuit. By turning on one of the switch pairs S1, S4 or S2, S3 a resonant current starts flowing through L1 to CR and when this current is zero, the switches are turned off. After that the series resonant circuit is disconnected and the energy transferred to resonant capacitor is dissipated as heat in RL by the current flowing through the parallel resonant circuit. RL is the equivalent resistance for the magnetic loss in the induction heating system.

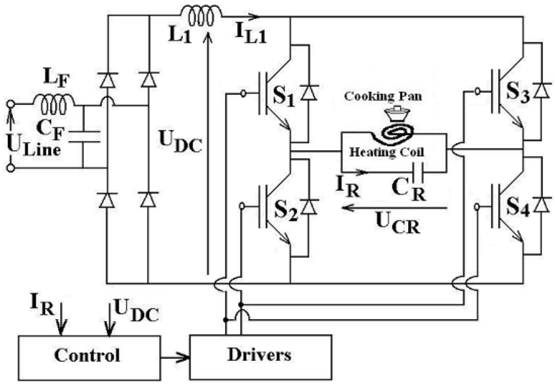


Fig. 5 Full bridge Hybrid resonant inverter system for one cooking zone

This is simulated and the SIMULINK block is shown in Fig. 6 and the corresponding voltage waveform is shown in Fig.7

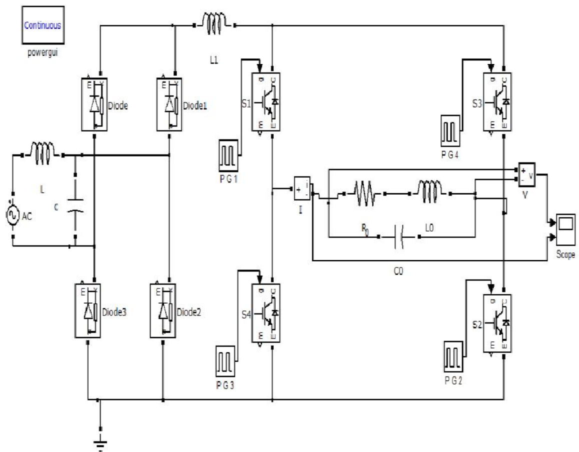


Fig. 6 SIMULINK model of hybrid resonant inverter using IGBT

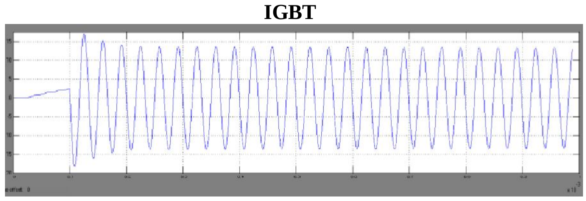


Fig. 7 voltage waveform of hybrid resonant inverter

Filter circuit Components	L1=50uH, L2=100µH, C1=5uf
Heating coil parameters	L3=150µH, R1=0.0025Ω
Parallel capacitors (C2):	0.15µF
Switching frequency	30 kHz

TABLE1: INPUT PARAMETERS OF SIMULATION

V. AC TO AC CONVERTER

In the proposed scheme of the AC-AC converter there are two main advantages: It is having a high power factor and a sine wave input current. Also the inverter circuit is composed with only a single controlled switch, which serves as a high-frequency generator for induction heating. Fig.8 shows the circuit diagram.

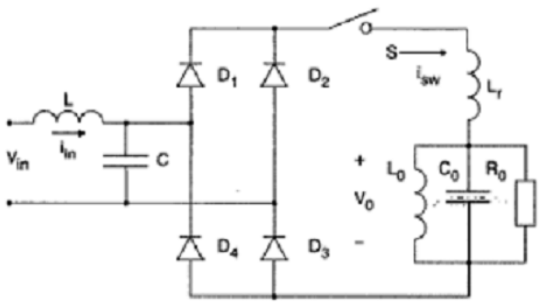


Fig. 8 Circuit diagram of AC- AC converter

The operating principles of the circuit are illustrated by Fig. 9

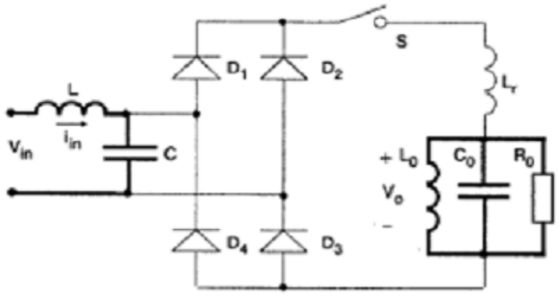


Fig.9a. Mode 1 (to-t1)

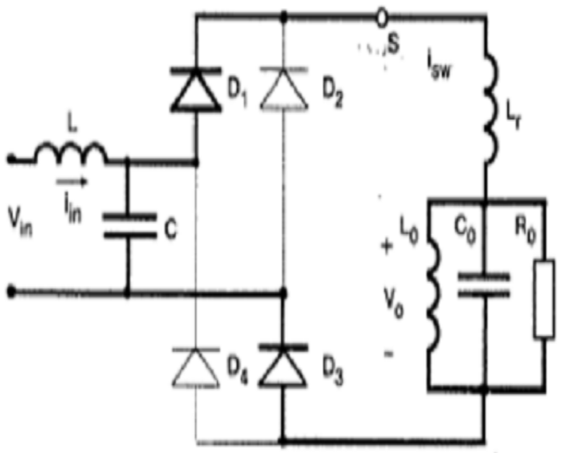


Fig.9b. Mode 1I (t1-t2)

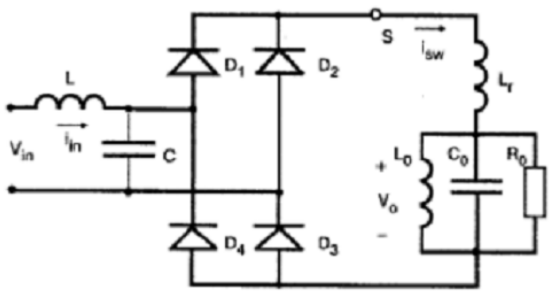


Fig.9c. Mode 1II (t2-t3)

Fig.9 Equivalent Circuits

Interval 1: t0**<t<t**1

The equivalent circuit is shown in Fig.9a. Four diodes D**1**-D**4** and the switch S are off. In this interval the capacitor C charges up linearly at a rate and a polarity corresponding to the instantaneous input voltage **V**in**.**

Interval 2: t1**<t<t**2

The equivalent circuit is shown in Fig.9b. Two diodes D**1,** D3 and the switch S are on. In this interval the capacitor C is discharging via the circuit C-D**1**-S-L**r**-load-D**3.** This interval ends when the capacitor voltage reduces to zero.

Interval 3: t2**<t<t**3

The equivalent circuit is shown in Fig.9c. All the diodes and the switch S are on. In this interval the current through switch S flows via two parallel bridge branches. This interval ends when this switch current decreases to zero. At this moment the switch turns off and the process starts from the beginning.

The theoretical waveforms are shown in fig.10

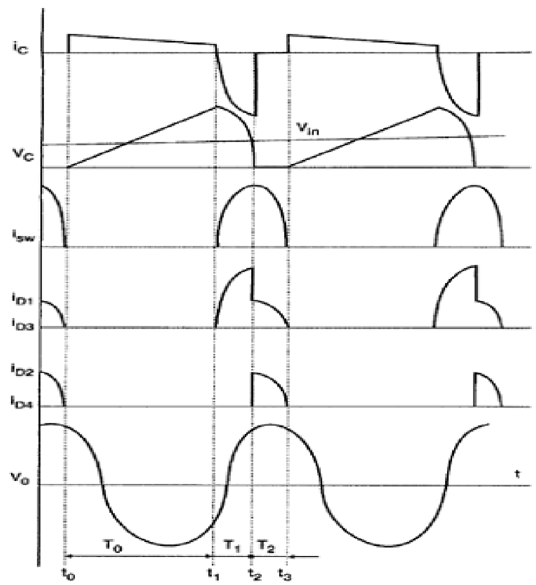


Fig.10 Ideal Switching Waveforms

Before the analysis it is assumed that all the circuit components are ideal. The analytical calculations are based on two more assumptions: the switch current can be assumed as semi sinusoidal, and the load power is determined by the first harmonic of the load voltage.. Evaluation of the relationship between input and output voltages Mg = Vo/Vin

$$A_1 = \frac{I_{sw.max}}{i_{in}} = \frac{\pi}{D} \cdot \frac{(1 - D + D_1)}{1 - \cos(\pi \frac{D_1}{D})}$$

$$A_2 = \frac{I_{sw1.max}}{I_{sw.max}} = \frac{2D}{\pi(1 - 4D^4)} \cdot \cos(2\pi D)$$

$$A_3 = \frac{I_{R1.max}}{I_{sw1.max}} = \frac{1}{\sqrt{(1 + R_0^{*2}(\omega_s^* - 1/_{w_s^*})^2}}$$

$$M_g = \frac{V_{o.max}}{V_{in\,rms}} = \frac{\sqrt{2}}{A_1 A_2 A_3}$$

The AC to AC converter fed induction heater is simulated using Matlab/Simulink and their results are presented here. The SIMULINK model of AC-AC converter is shown in Fig 11 and its corresponding waveform is also shown (fig. 12)

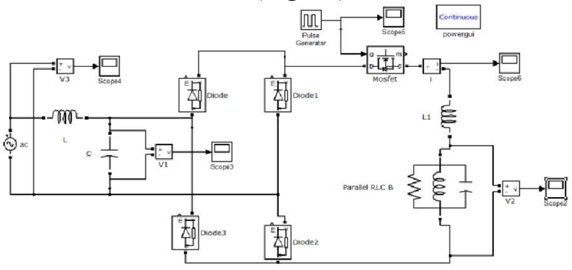


Fig.11 SIMULINK model of AC-AC converter

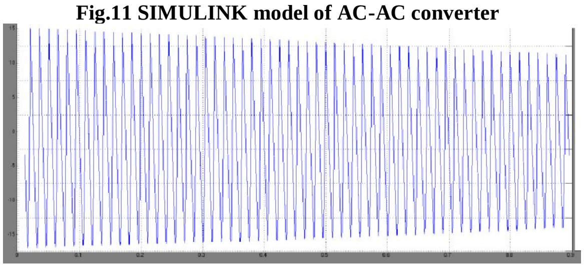


Fig.12 Voltage Waveform of AC- AC converter

Filter circuit Components	Lr=24µH; Li=9.0mH; Cin=0.96Mf
Heating coil parameters	R0=55Ω; L0=160µH; C0=2.25µF;
Switching frequency	65 kHz

TABLE 2: SIMULATION PARAMETERS

CONCLUSION

Different inverter topologies are used in induction heating applications. Of that the basic half- bridge and full bridge inverter topologies have been compared. A new topology have been proposed. The AC-AC converter circuit for induction heating has been simulated. Its power factor is close to unity. The circuit topology is very simple since includes only one power switch. This switch operates in a soft commutation mode. The converter provides a wide-range power control. This converter has advantages like reduced hardware, reduced stresses and high power density.

FUTURE SCOPE

The proposed topology have been done in open loop manner. It can be made closed loop using a PI controller and applied.
This can improve steady state stability.

REFERENCES

[1] J.Acero, J. M. Burdio, L.A. Barragan, D. Navarro, R.Alonso, J. R. Garcia, F. Monterde, P. Hernandez, S. Llorente, and I. Garde, "Domestic induction appliances," *IEEE Ind. Appl. Mag.*, vol. 16, no. 2, pp. 39–47, Mar./Apr. 2010.

[2] I. Mill´an, J. M. Burd´ıo, J. Acero, O. Luc´ıa, and S. Llorente, "Series resonant inverter with selective harmonic operation applied to all-metal domestic induction heating," *IET Power Electron.*, vol. 4, pp. 587–592, May 2011.

[3] R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies," *IEEE Trans. Power Electron.*, vol. 3, no. 2, pp. 174–182, Apr. 1988

[4] H. W. Koertzen, J. D. van Wyk, and J. A. Ferreira, "Design of the halfbridge series resonant converters for induction cooking," *Proc. IEEE Power Electron. Spec. Conf. Records*, 1995, pp. 729–735

[5] Nitai Pal, Pradip Kumar Sadhu, Dola Sinha and Atanu Bandyopadhyay," Selection of Power Semiconductor Switches – a Tool to Reduce Switching & Conduction Losses of High Frequency Hybrid Resonant Inverter fed Induction Cooker", *International Journal of Computer and Electrical Engineering, Vol. 3, No. 2, April, 2011 1793-8163*

[6] P. K. Sadhu, N. Jana, R. Chakrabarti, and D. K. Mittra "A Unique Induction Heated Cooking Appliances Range Using Hybrid Resonant Converter" – *Int. J. of Circuits, Systems and Computers, World Scientific, Volume 14, Number 3, June 2005, pp. 619-630*

[7] Bayindir, N.S.; Kukrer, O.; Yakup, M (May 2003).: "DSP based PLL controlled 50–100 kHz 20 kW high-frequency induction heating system for surface hardening and welding applications". *IEE Proc.-Electr. Power Appl., Vol. 150, No.3, pp. 365-371*.

[8] Mollov, S.V.; Theodoridis, M.; Forsyth, A.J. (January 2004): "High frequency voltage-fed inverter with phase-shiftcontrol for induction heating", *IEE Proc.-Electr. Power Appl., Vol. 151, No. 1, pp. 12-18.*

[9] 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.

[10] I. Millán, D. Puyal, J. M. Burdío, C. Bemal, and J. Acero, "Improved performance of half-bridge series resonant inverter for induction heating with discontinuous mode control," in Proc. IEEE Appl. Power Electron. Conf. Expo., 2007, pp. 1293–1298.

[11] F. P. Dawson and P. Jain, "A comparison of load commutated inverter systems for induction heating and melting applications," IEEE Trans. Power Electron., vol. 6, no. 3, pp. 430–441, Jul. 1991.

[12] 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.

[13] N. J. Park, D. Y. Lee, and D. S. Hyun, "A power-control scheme with constant switching frequency in class-D inverter for induction-heating jar application," IEEE Trans. Ind. Electron., vol. 54, no. 3, pp. 1252–1260, Jun. 2007.

[14] J. M. Burdío, F. Monterde, J. R. García, L. A. Barragán, and A. Martínez, "A two-output series-resonant inverter for induction-heating cooking appliances,"IEEE Trans. Power Electron., vol. 20, no. 4, pp. 815–822, Jul. 2005.