A Novel Control Design Of An Advanced AC–AC Resonant Boost Converter For Induction Heating Applications

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Abstract: Induction heating technology is leading technical advances in home appliances due to the benefits inherent to the contactless energy transfer including high efficiency, fast heating, safety, cleanness, and accurate control, among others. Recent design trends are focused on developing more versatile cooking appliances for an improved user performance. This paper proposes the use of the half-bridge inverter in two operating modes to achieve higher efficiency in a wide output power range. The power converter topology can be reconfigured by changing the resonant capacitors through electromechanical relays. As a consequence, the entire efficiency of the cooking process is improved with a cost-effective procedure. This paper proposes an optimized modulation strategy to reduce the maximum device voltage, enabling an optimized converter design with improved reliability and performance. All of these advantages are due to its heating process, where the pot is directly heated by the induced currents generated with a varying magnetic field. As a result, the glass where the pot is supported is not directly heated and, consequently, efficiency and heating times are improved. In such systems, the maximum output power and efficiency are achieved at the resonant frequency, and the switching frequency is increased to reduce the output power.

Introduction: Induction heating (IH) technology has become the benchmark heating technology and is leading technical advances in home appliances due to the benefits inherent to the contactless energy transfer, including high efficiency, safety, fast heating, cleanliness, and accurate control, among others. The design of these appliances rely in several key enabling technologies, including power converters inductors, and control electronics. Currently, domestic IH technology are used mainly on hobs, including three or four burners with fixed position and size. Depending on the output power and cooking techniques, the selected power converter topology may change. The series resonant half-bridge inverter is commonly used for high-power IH appliances, up to 4.5 kW, whereas the quasi-resonant single-switch inverter is used up to 2.2 kW. These topologies are, however, not suitable to supply multi coil systems due to the complex multi load control and high cost.

RESONANT CONVERTER

They are combination converter topologies or switching strategies that result in zero voltage and/or zero current switchings. Resonant converters use a resonant circuit for switching the transistors when they are at the zero current or zero voltage point, this reduces the stress on the switching transistors and the radio interference. We distinguish between ZVS- and ZCS-resonant converters (ZVS: Zero Voltage Switching, ZCS: Zero Current Switching).

INDUCTION HEATING

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where eddy currents (also called Foucault currents) are generated within the metal and resistance leads to Joule heating of the metal. An induction heater (for any process) consists of an electromagnet, through which a high-frequency alternating current (AC) is passed. Heat may also be generated by magnetic hysteresis losses in materials that have significant relative permeability. The frequency of AC used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth.

INVERTER :A power inverter, or inverter, is an electrical power converter that changes direct current (DC) to alternating current (AC). The input voltage, output voltage, and frequency are dependent on design. Static inverters do not use moving parts in the conversion process. Some applications for inverters include converting high-voltage direct current electric utility line power to AC, and deriving AC from DC power sources such as batteries.

CIRCUIT DIAGRAM OF THE PROJECT

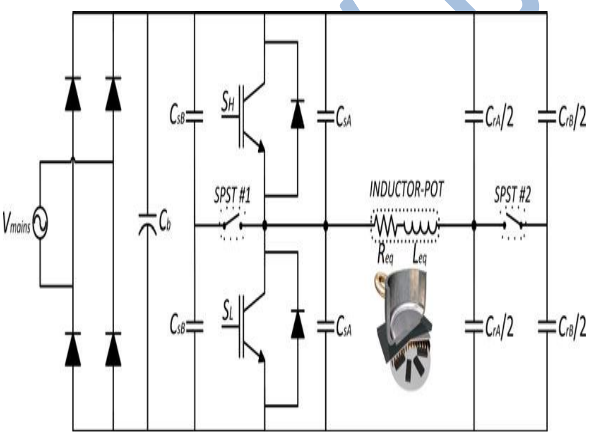
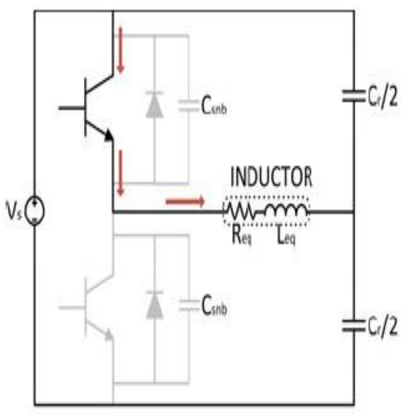


Fig.1

The series resonant half-bridge applied to induction heating operates at switching frequencies higher than the resonant frequency to achieve zero voltage switching (ZVS) conditions. To reduce switch-off switching losses, a lossless snubber network *Cs* is added. Typically, class-D operation mode implies that the snubber capacitor*Cs* is much lower than the resonant capacitor *Cr*. However, if the class-E conditions are achieved, i.e., ZVS and zero voltage derivative switching (ZVDS) at the turn-off, the operation mode is known as class DE. This operation mode ensures zero switching losses, but the maximum output power is lower than in class-D operation mode. Considering this, a dual-mode resonant converter implementation is proposed in order to improve the efficiency in the whole operating range. Fig. 1 shows the proposed implementation scheme, where electromechanical switches SPST 1 and 2 allow varying the snubber and resonant capacitance in order to change the operation mode. The following sections detail the design procedure for both operation modes, where the superscript D denotes the class-D operation mode and the superscript DE is used for the class-DE operation mode. The operation modes of the half bridge inverter, including class-D and class-DE operation.

Operation Modes: The new topology can be effectively broken down into four distinct operating modes, shown in schematic form in **Fig. I-IV**.

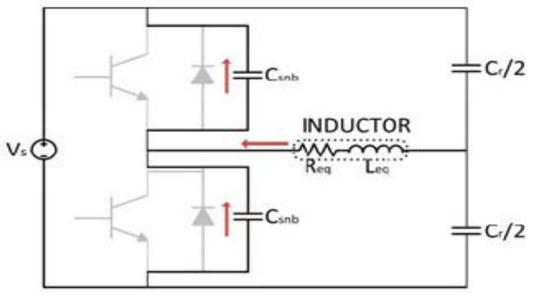
STATE I: During the first state I, the load current is positive and it is supplied by the high side transistor.



I

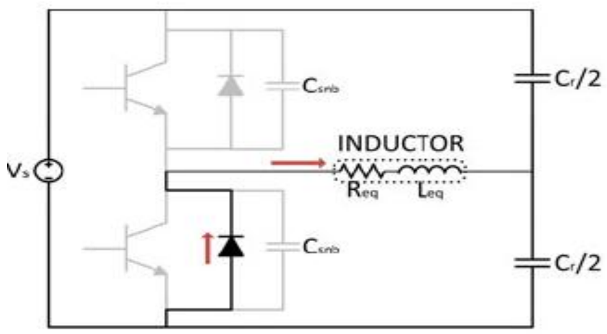
STATE II

When high-side transistor is deactivated, the switch-off current is used to charge/discharge the snubber capacitors, i.e., the high-side snubber capacitor is charged to the supply voltage, whereas the low-side snubber capacitor is discharged.



II

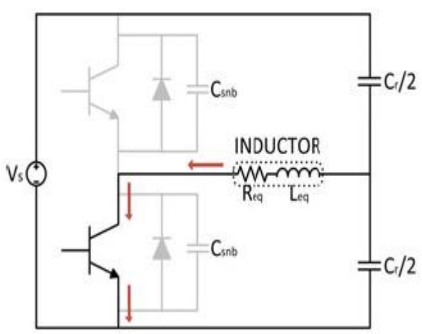
STATE III In this state, the load current is also positive, and thus, it is supplied by the low-side diode.



III

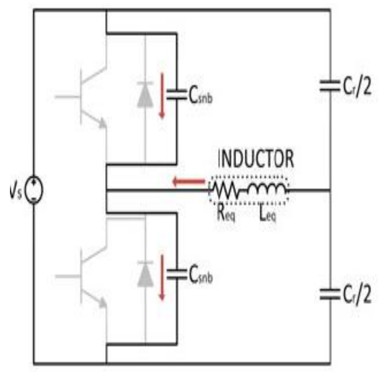
STATE IV

When the load current becomes negative, it is supplied by the low-side transistor.



IV

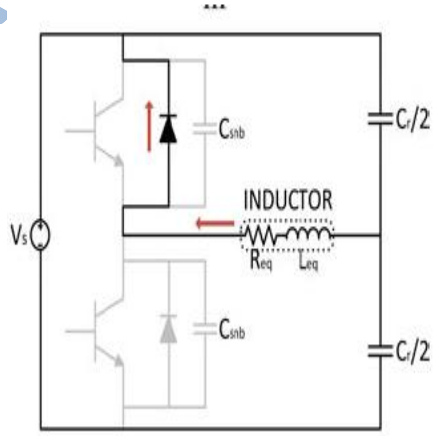
STATE V: As soon as the low-side transistor is deactivated the load current charges the low-side snubber capacitor to the supply voltage, whereas the high-side snubber capacitor is discharged.



V

STATEVI

When both snubber capacitors are charged/discharged, the negative load current flows through the high-side diode. Finally,



VI

EFFICIENCY ANALYSIS

Power losses in the converter can be divided into two terms: conduction and switching losses. Both of them are caused by the non idealities in the switching devices: nonzero switching times and nonzero on resistance. As a result, switching waveforms in the converter have a direct impact in the entire converter losses. As small snubber capacitors are used in the class-D operation mode, the output current can be considered constant during the charge intervals. As a result, the voltage across the device during the switching becomes linear

$$v_{\mathrm{CE}}^{D}(t) = \frac{I_{C,\mathrm{off}}}{2C_{\mathrm{snb}}^{D}} t, \; \left(0 \le t \le T_{\mathrm{snb}}^{D}\right)$$

where *IC* denotes the switch-off current in the switching devices. Moreover, the required time to charge/discharge the snubber capacitance can be calculated as

$$T_{\mathrm{snb}}^{D} = V_S \frac{2C_{\mathrm{snb}}^{D}}{I_{C,\mathrm{off}}}.$$

In the case of the class-DE operation mode, the load current is modeled as a linear function that starts in *IC*, off and ends at zero

$$i_o(t) = I_{C,\mathrm{off}} \left(1 - \frac{t}{T_{\mathrm{snb}}^{\mathrm{DE}}}\right), \; \left(0 \le t \le T_{\mathrm{snb}}^{\mathrm{DE}}\right).$$

As a result, the switch voltage is

$$v_{\mathrm{CE}}^{\mathrm{DE}}(t) = \frac{1}{2C_{\mathrm{snb}}^{\mathrm{DE}}} \int i_o(t)dt$$

$$= \frac{I_{C,\mathrm{off}}}{2C_{\mathrm{snb}}^{\mathrm{DE}}} \left(t - \frac{t^2}{2T_{\mathrm{snb}}^{\mathrm{DE}}}\right), \; \left(0 \le t \le T_{\mathrm{snb}}^{\mathrm{DE}}\right).$$

The class-E switching conditions, i.e., ZVS and ZVDS are achieved in the proposed voltage. The time required to charge/discharge the snubber capacitors *TDE* snb can be directly obtained. yielding

$$T_{\mathrm{snb}}^{\mathrm{DE}} = V_S \frac{4C_{\mathrm{snb}}^{\mathrm{DE}}}{I_{C,\mathrm{off}}}.$$

The proposed analytical model for the switching intervals has been validated with simulation results using SPICE simulation tool. The main simulation results are showing a good agreement with the proposed model. Main differences between the SPICE and the analytical model are due to the linear current assumption. These errors have a reduced impact in the output power and conduction losses computation and provide a useful method to predict the required dead time to ensure the correct snubber charge/discharge with reduced computation effort.

Conduction Losses

Conduction losses can be calculated using the average and rms values of current through the devices. Since a bidirectional switch is used, there are two components in each switch to compute conduction losses, the IGBT (*P*ON, IGBT) and the antiparallel diode (*P*ON, DIODE). The total conduction losses *P*ON therefore results

$$P_{\mathrm{ON}} = 2\left(P_{\mathrm{ON,\,IGBT}} + P_{\mathrm{ON,\,DIODE}}\right).$$

Each conduction term is

$$P_{\mathrm{ON}} = r_{\mathrm{ON}} I_{\mathrm{rms}}^2 + v_{\mathrm{ON}} I_{\mathrm{avg}}$$

where the on-resistance and collector-to-emitter saturation voltage are *r*ON and *v*ON, respectively. The block composed of the switching device, the antiparallel diode, and the snubber capacitance must provide the entire load current (see Fig. 4). As a result, positive current values are supplied by the main transistor, whereas negative current values are supplied by the snubber capacitor and the antiparallel diode. Consequently, higher snubber capacitance implies lower antiparallel diode conduction and, as a result, lower diode conduction losses. Moreover, in the case of class-DE operation mode, the entire negative current is provided by the snubber capacitance, and antiparallel diode does not conduct. In order to compute the average and rms value of current, it is required to obtain the conduction time in each device

$$T_{\mathrm{on}} = T\left(1 - 2T_{\mathrm{snb}}\right).$$

In the case of class-D operation mode, the snubber current can be considered constant, and as a result, switch-on and switch-off currents have the same opposite value, yielding that load current is

$$i_o^D(t) = e^{-\xi t}\left(M_1^D \sin(\omega_n^D t) + M_2^D \cos(\omega_n^D t)\right)$$

where

$$\xi = R/2L_{\text{eq}}, \omega_o^D = 1/\sqrt{L_{\text{eq}}C_r^D}, \omega_n^D = \sqrt{(\omega_o^D)^2 - (\xi)^2}.$$

By applying boundary conditions, load current results

$$\begin{cases} i_o^D(t=0) = -I_{C,\text{off}} \Rightarrow M_2^D = -I_{C,\text{off}} \\ i_o^D(t=T_{\text{on}}) = I_{C,\text{off}} \Rightarrow M_1^D \\ \quad = I_{C,\text{off}}\left(\dfrac{e^{\xi T_{\text{on}}}}{\sin(\omega_n^D T_{\text{on}})} + \dfrac{1}{\tan(\omega_n^D T_{\text{on}})}\right) \end{cases}$$

As a result, the diode on time is

$$i_o^D(t=T_{\text{diode}}) = 0 \Rightarrow T_{\text{diode}} = \frac{1}{\omega_n^D} a\tan\left(\frac{-M}{M_1^D}\right)$$

$$\Leftrightarrow T_{\text{diode}} = \frac{1}{\omega_n^D} a\tan\left(\left(\frac{e^{\xi T_{\text{on}}}}{\sin(\omega_n^D T_{\text{on}})} + \frac{1}{\tan(\omega}\right)^{-1}\right)$$

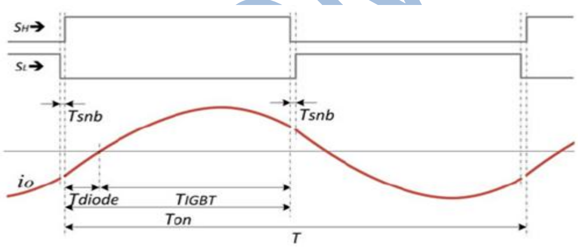
The transistor on time is TIGBT = Ton − Tdiode. Consequently, average currents result

$$I_{\text{avg,diode}}^D = \frac{I_{C,\text{off}}}{T(\omega_o^D)^2}$$
$$\times\left[\omega_n^D\left(\frac{e^{-\xi T_{\text{diode}}}}{\sin(\omega_n^D T_{\text{diode}})} - \frac{1}{\tan(\omega_n^D T_{\text{diode}})}\right.\right.$$

$$I_{\text{avg,IGBT}}^D = \frac{I_{C,\text{off}}}{T(\omega_o^D)^2}$$
$$\times\left[\omega_n^D\left(\frac{e^{\xi T_{\text{IGBT}}}}{\sin(\omega_n^D T_{\text{IGBT}})} - \frac{1}{\tan(\omega_n^D T_{\text{IG}}}\right.\right.$$

and the rms currents. The proposed analytical model has been verified and compared using Spice simulator. The results are for the complete output power range in the class-D operation mode, obtaining a good agreement between analytical and simulation results. In the case of the class-DE operation mode, the diode does not conduct and, therefore, Tdiode = 0, TIGBT = Ton. By applying the same procedure, the average and rms values of current results. Where ωDE o = 1/_Leq$C$DE r , ωDE n = (ωDE o)2 − (ξ)2 . Consequently, the current distribution in the class-DE operation mode is partly derived to the snubber capacitor, reducing conduction losses.

Timing Diagram



Main current waveform and timing in the class-D operation mode.

SIMULATION RESULTS

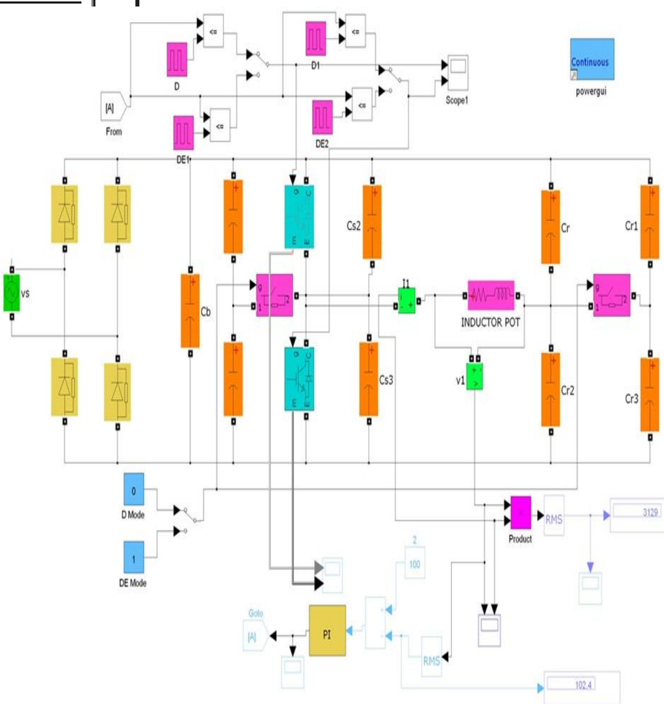


Fig 7: Simulation of a Closed loop circuit of RESONANT CONVERTER

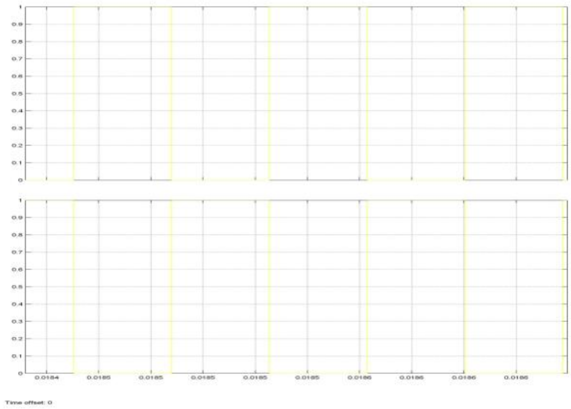


Fig 8: Closed loop Class D Switching Waveforms

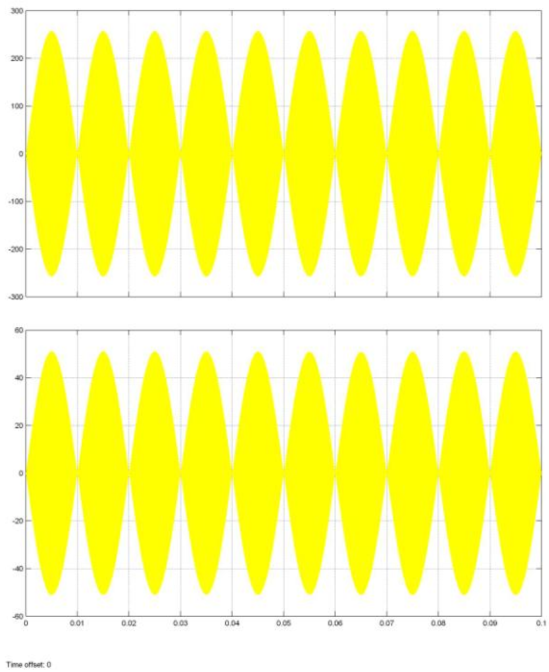


Fig 9: Closed loop OUTPUT Volage and Current Waveform

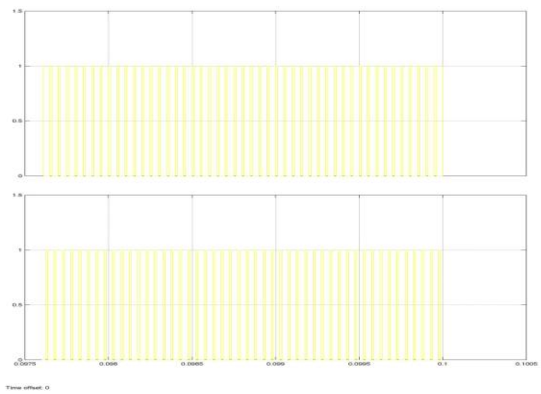


Fig 10: Closed loop Switching Waveforms

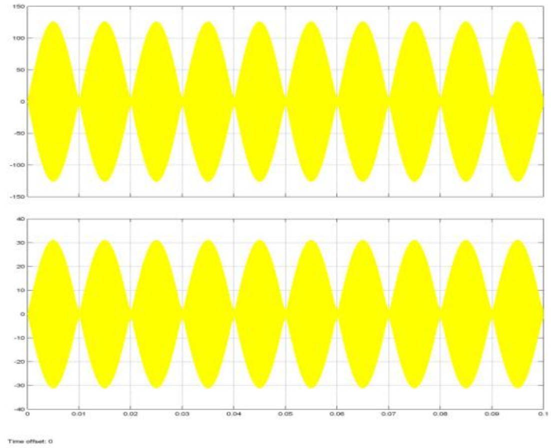


Fig:11 Closed loop OUTPUT Voltage and Current Waveforms

CONCLUSION: In this paper, a novel reconfigurable series resonant inverter topology is proposed in order to improve the efficiency in the whole operating range. This paper has presented a soft-stop modulation strategy that allows reducing the voltage in the resonant capacitor, leading to reduced stress in the power devices and enabling further efficiency optimization. The proposed modulation strategy has been detailed and analyzed. The simulation results have confirmed the expected voltage reduction, proving the feasibility of the proposed soft-stop modulation.

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] H. Sarnago, O. Lucia Gil, A. Mediano, and J. M. Burdio, “Modulation scheme for improved operation of an RB-IGBT-based resonant inverter applied to domestic induction heating,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 5, pp. 2066–2073, May 2013.

[3] O. Luc´ıa, J. M. Burd´ıo, I. Mill´an, 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.

4. R. L. Steigerwald "A comparison of half-bridge resonant converter topologies" Trans. Power Electron., vol. 3, no. 2, pp. 174-182, 1988

5. 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, 2011

6. H. Fujita , N. Uchida and K. Ozaki "A new zone-control induction heating system using multiple inverter units applicable under mutual magnetic coupling conditions" Trans. Power Electron., vol. 26, no. 7, pp. 2009-2017, 2010