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An advanced PI control strategy of Dual-Mode-Operation Resonant Converter for Induction Heating

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ABSTRACT:

Induction heating (IH) technology is nowadays widely present in domestic appliances because of its cleanness, high efficiency, and faster heating process. 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. IH systems are based on dc-link inverters to generate the required alternating current to feed the inductor. Usually, resonant converters are used to achieve higher efficiencies and power densities. As a consequence, in these converters, the efficiency is also reduced in the low-medium output power range. This project presents the use of the half-bridge inverter in two operating modes to achieve higher efficiency in a wide output power range.

INTRODUCTION

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.

Induction heating allows the targeted heating of an applicable item for applications including surface hardening, melting, brazing and soldering and heating to fit. Iron and its alloys respond best to induction heating, due to their ferromagnetic nature. Eddy currents can, however, be generated in any conductor, and magnetic hysteresis can occur in any magnetic material. Induction heating has been used to heat liquid conductors (such as molten metals) and also gaseous conductors (such as a gas plasma - see Induction plasma technology). Induction heating is often used to heat graphite crucibles (containing other materials) and is used extensively in the semiconductor industry for the heating of silicon and other semiconductors. Utility frequency (50/60 Hz) induction heating is used for many lower cost industrial applications as inverters are not required.

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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

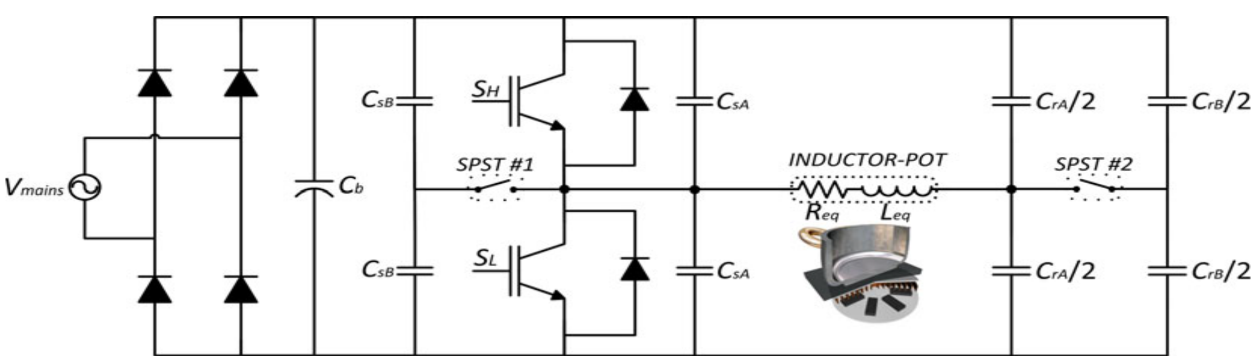

Fig.1

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

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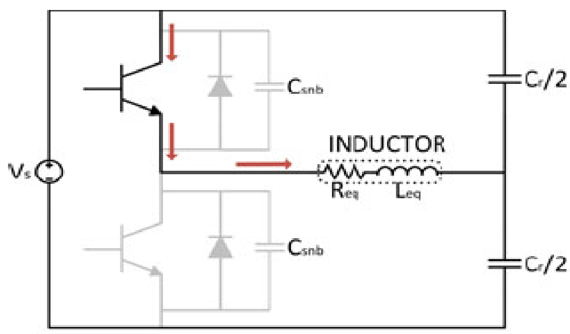
class-E conditions are achieved, i.e., ZVS and zero voltage derivative switching (ZVDS) at the turn-off, the operation mode is known as class DE. This operation mode ensures zero switching losses, but the maximum output power is lower than in class-D operation mode. Considering this, a dual-mode resonant 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

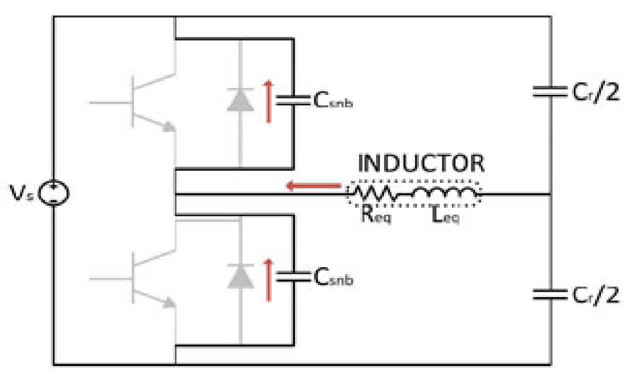
During the first state I, the load current is positive and it is supplied by the high side transistor.



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

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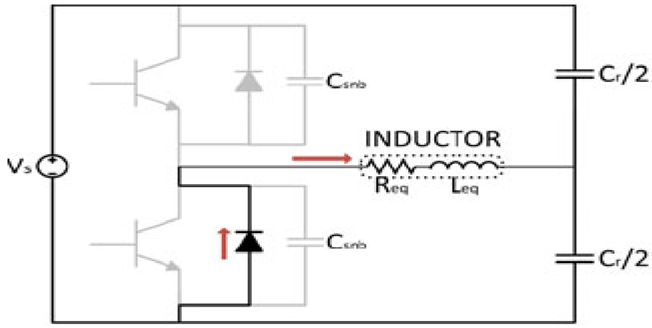
STATE III

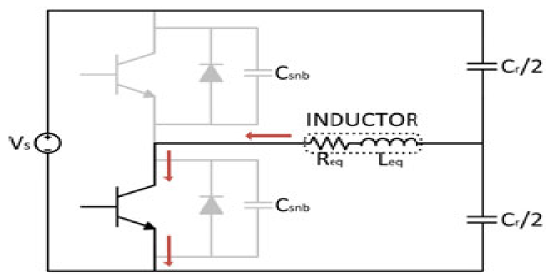
In this state, the load current is also positive, and thus, it is supplied by the low-side diode.



III

STATE IV

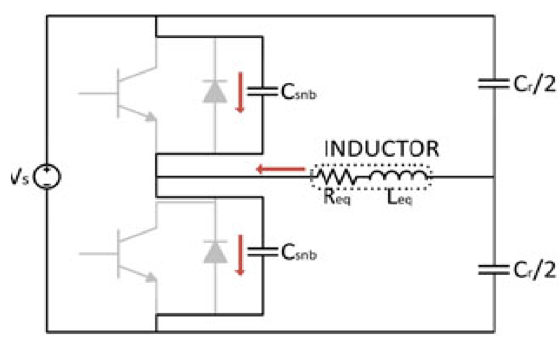
When the load current becomes negative, it is supplied by the low-side transistor.



IV

STATE V

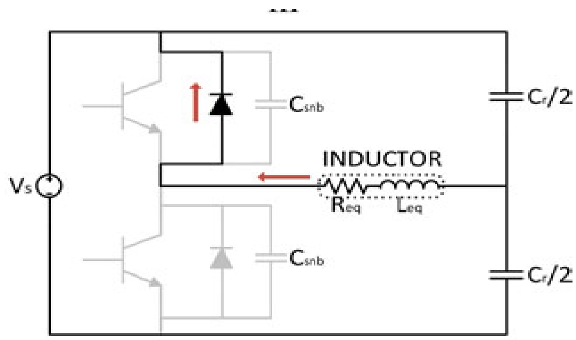
As soon as the low-side transistor is deactivated the load current charges the low-side snubber capacitor to the supply voltage, whereas the high-side snubber capacitor is discharged.



V

STATEVI

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



VI

When the load current reaches zero, the load current is supplied by upper transistor (stateI). Class-D operation mode uses configurations I to VI,

Where as in class-DE operation mode, the configurations II and V, i.e., snubber capacitors charge/discharge, are extended avoiding the use of configurations III and VI, diode conduction.

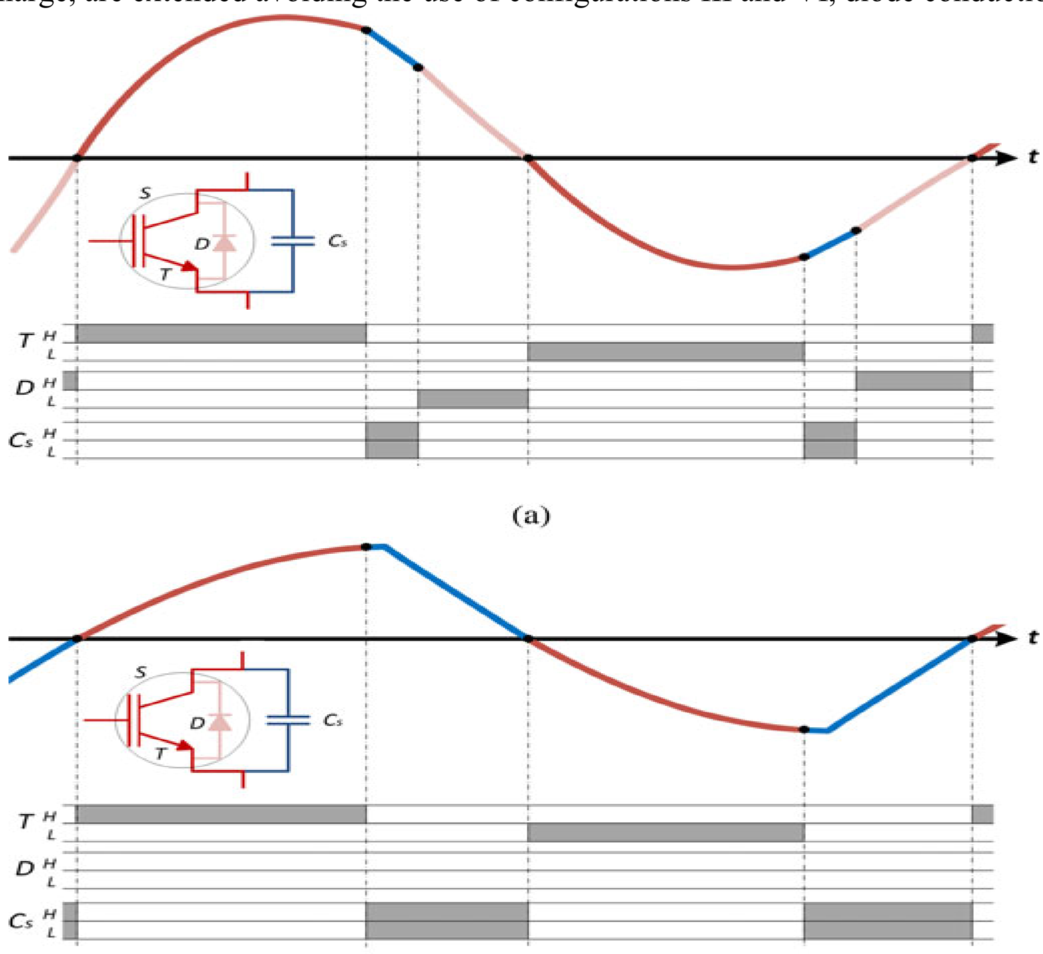


Fig.2 Output current and device activation. (a) Class-D operation mode. (b) Class-DE operation mode.

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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

$$\begin{aligned} v_{\mathrm{CE}}^{\mathrm{DE}}(t) &= \frac{1}{2C_{\mathrm{snb}}^{\mathrm{DE}}}\int i_o(t)dt \\ &= \frac{I_{C,\mathrm{off}}}{2C_{\mathrm{snb}}^{\mathrm{DE}}}\left(t - \frac{t^2}{2T_{\mathrm{snb}}^{\mathrm{DE}}}\right),\ \left(0 \le t \le T_{\mathrm{snb}}^{\mathrm{DE}}\right). \end{aligned}$$

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 *T*DE 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.

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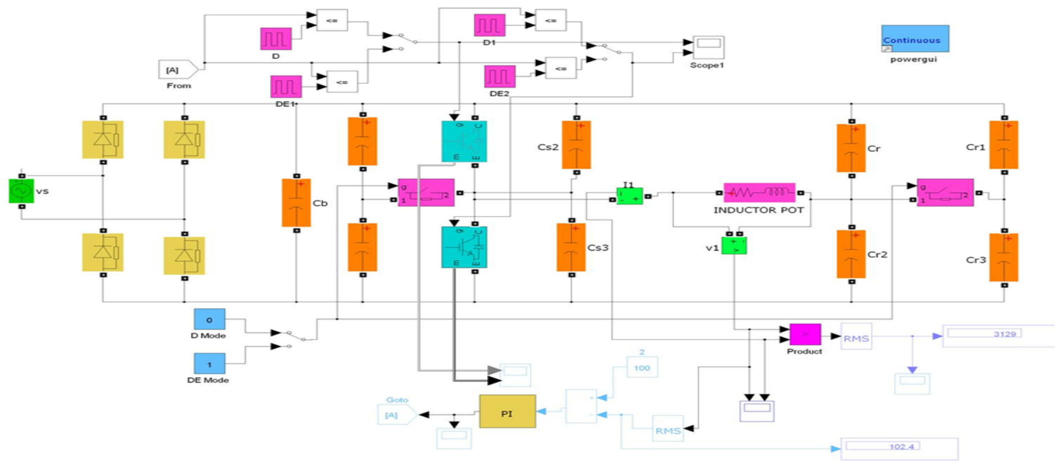

Fig.3 Simulation of a Closed dual loop Class circuit of RESONANT CONVERTER

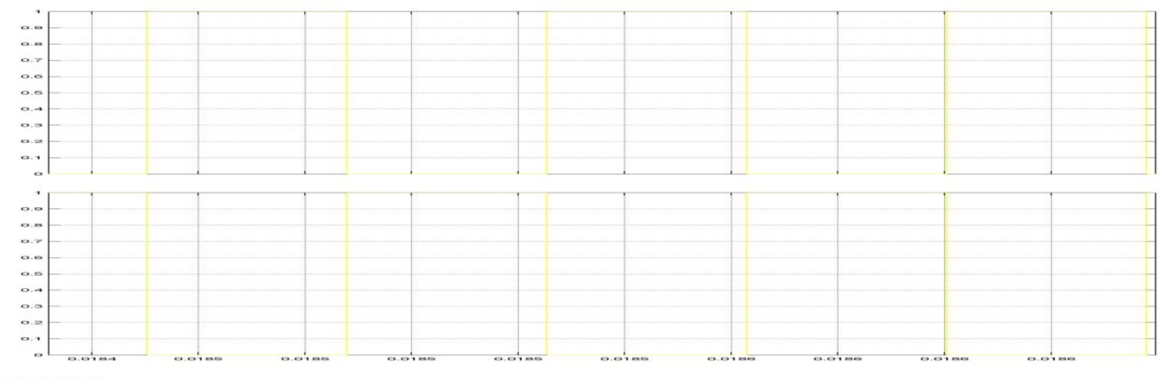

Fig.4 Closed loop dual Class Switching Waveforms

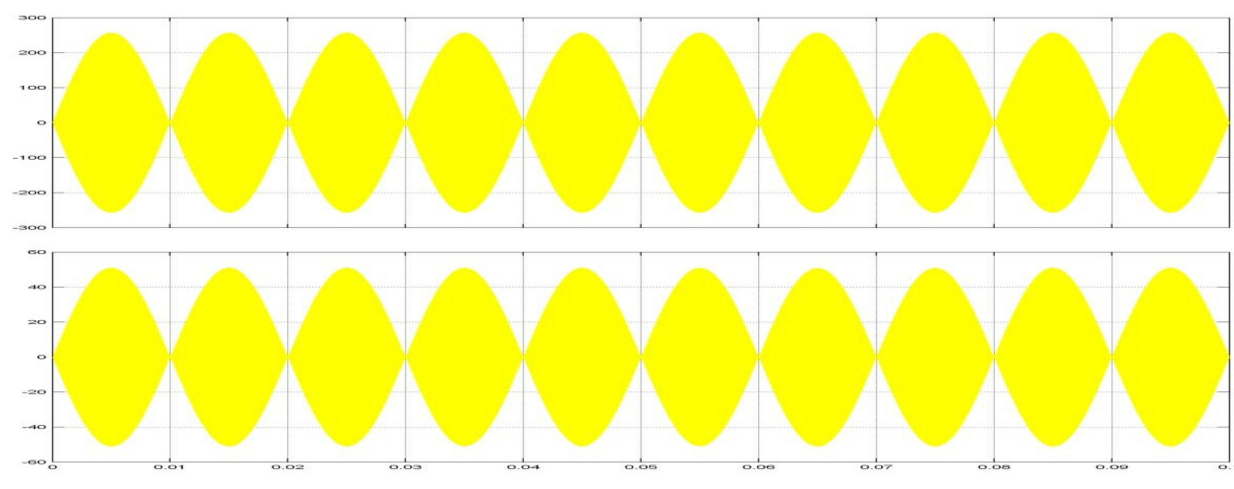

Fig. 4Closed loop dual OUTPUT Voltage and Current Waveform

CONCLUSION

In this paper, a novel reconfigurable series resonant inverter topology is proposed in order to improve the efficiency in the whole operating range. It is based on a dual-mode resonant converter where the class-D and class-DE operation modes are combined to optimize the efficiency. The analytical results have been verified by means of an experimental prototype. As a result, the presented dual-mode topology is proposed as a cost-effective implementation to improve the overall converter efficiency.

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