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High Frequency Soft Switching Dual Mode Resonant Converter with SW / PDM Control for Improved Efficiency of Domestic IH Applications

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Abstract: ***Domestic Induction Heating (IH) systems are based on a dc-link resonant converter which supplies high frequency currents (20-100 kHz) to an inductor, which heats up the pan. In resonant converters, maximum output power and efficiency occurs at the resonant frequency, and the switching frequency is increased to reduce the output power. It results in increased switching losses and lower efficiency in the low-medium-output power range. Thus class-D/DE dual-mode-operation resonant converter is proposed to achieve higher efficiency in a wide output power range. In such converters, resonant capacitors are replaced with electromechanical relays in order to change the operation mode. Class-D half bridge converter with square wave(SW) control is used in the high output power range, whereas class-DE half-bridge converter with pulse density modulation (PDM) is used in the low to medium output power range. The combination of these operation modes achieves high efficiency levels in a wider range of output power levels. The dual-mode resonant converter is simulated using MATLAB/SIMULINK. Class D/DE dual mode resonant converter operation is a cost-effective procedure for the entire improved efficiency of the cooking process.***

Keywords: induction heating (IH), resonant converter, square wave control (SW), pulse density modulation (PDM)

1. Introduction

With tremendous advances of power semiconductor switching devices, the electromagnetic induction eddy current based direct heat energy processing products and applications using high frequency power conversion circuits; inverters, cyclo-inverters and cyclo-converters have attracted special interest for consumer food cooking and processing appliances [1]. Thus domestic induction heating has become a leading technology owing to its benefits such as increased efficiency and safety, cost effectiveness, reduced cooking times, high reliability, high power density and low electromagnetic noise. Domestic induction hobs are now becoming a standard option, especially in Asia and Europe [2].

Induction cookers constitute the domestic application of the induction heating phenomena. Figure 1 shows the basic components of an induction cooker. In an induction cooker, initially an AC supply of 50 Hz is applied. It is then rectified to DC and subsequently back to a high frequency AC source through an inverter. This high frequency current produces a high frequency alternating magnetic field through an induction coil. Therefore, placing a cooking pan / utensil close to the induction coil will induce eddy current in the pan. As a result of which, heat energy will be produced on the surface of the pan. The internal resistance of the pan causes heat to be dissipated according to Joules effect. Thus, it is the pan itself and not the heater that heats up and cooks the food.

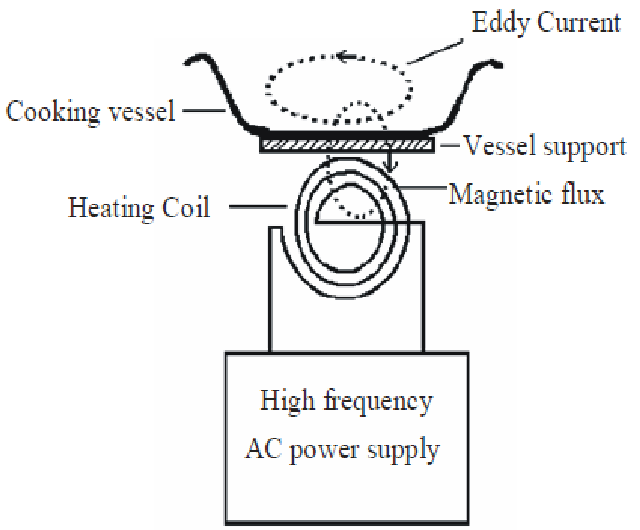


Figure 1: Principle of induction cooking

Basically, a domestic induction arrangement consists of a planar turn winding situated below a metallic vessel and supplied by a high-frequency power source. The usual operating frequency is higher than 20 kHz to avoid the audible range and lower than 100 kHz to reduce switching losses [2]. The most used device is the insulated gate bipolar transistor (IGBT) because of the operating frequency range and the output power range, up to 3 kW.

Basic requirements of an induction cooker can be summarized as: switching in the radio frequency range, power factor close to unity, and wide power range and reliability. Hence selection of inverter topology is the first step in the design of a high efficient induction cooker. Now-a-days, resonant inverter topologies are commonly used to supply the inductor-pot-system. The most used topologies have been the full bridge [3][4], half-bridge[5][6] and two single-switch inverter topologies[7] with zero voltage switching and zero current switching operations. For low-cost appliances and low output power levels, the one-switch topology is the most used. The half-bridge inverter is the most used topology, for medium-high output power levels due to its high efficiency and low voltage stress across the switching devices. Finally, for higher output power levels, the full-bridge inverter is used. The half-bridge series resonant inverter is the most employed topology due to its simplicity, its cost-effectiveness, and the electrical requirements of its components. The resonant tank consists of the pan, the induction coil, and the resonance capacitor. Induction-coil-and-pan coupling is modeled as a series connection of an inductor and a resistor, based on the analogy of a transformer, and it is defined by the values of L_{eq} and R_{eq} [8]. These values change mainly with excitation frequency ω, pan material, temperature, and inductor–pan coupling.

Zero Voltage Switching (ZVS) series resonant converter which uses Pulse Density Modulation (PDM) [8], [4] is normally used in the commercial purpose domestic induction heating system due to its robustness and control simplicity. Usually, PDM is applied to keep high efficiency in the low output power range [9]. However it increases flicker emissions, which can compromise the appliance electro-magnetic compatibility. Thus PDM is usually applied at high switching frequencies and results in lower output power and increased switching losses. Since PDM is applied at high switching frequencies, it results in increased switching losses and lower efficiency in the low-medium-output power range. In this paper, a dual-mode-operation resonant converter is proposed which further improves efficiency in the low output power range due to the reduced switching losses. The proposed resonant converter operates as Class-D half bridge converter [10] in the high output power range and class-DE half bridge converter [10] in the low to medium output power range. The combination of these operation modes achieves high efficiency levels in a wider range of output power levels.

This paper is organized as follows. The proposed class D/DE resonant converter is presented in section 2, describing its operation modes and the modulation strategies used in the converter. The detailed analysis of class D and class DE operation mode is performed in section 3. Simulation results of the resonant converter are shown in section 4. Finally, the main conclusions of this paper are outlined in section 5.

2. Dual Mode Resonant Converter

In order to achieve improved efficiency domestic induction heating system, dual mode resonant converter can be implemented in which half bridge converter is used in two operating modes.

2.1 Block Diagram

A schematic diagram of the power stage of a domestic induction apparatus is shown in Figure 2. Induction appliances take the energy from the mains voltage, which is rectified by a bridge of diodes. A bus filter is designed to allow a high voltage ripple, getting a resultant input power factor close to one. Then, an inverter topology supplies the alternating current (between 20 kHz to 100 kHz) to the induction coil. Nowadays, burners of domestic induction appliances are designed to deliver up to 5.5 kW.

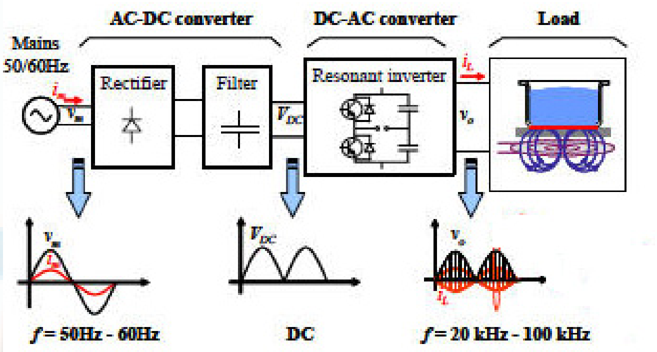


Figure 2: Schematic diagram of the induction cooker

2.2 Circuit Operation

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. Figure 3 shows the dual-mode resonant converter. Typically, class-D operation mode implies that the snubber capacitor C_s is much lower than the resonant capacitor C_r. However, if the class-E conditions are achieved, i.e zero voltage switching 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 can be used in order to improve the efficiency in the whole operating range. In dual-mode resonant converter, electromechanical switches SPST 1 and 2 allow varying the snubber and resonant capacitance in order to change the operation mode. There are six operation modes for the converter.

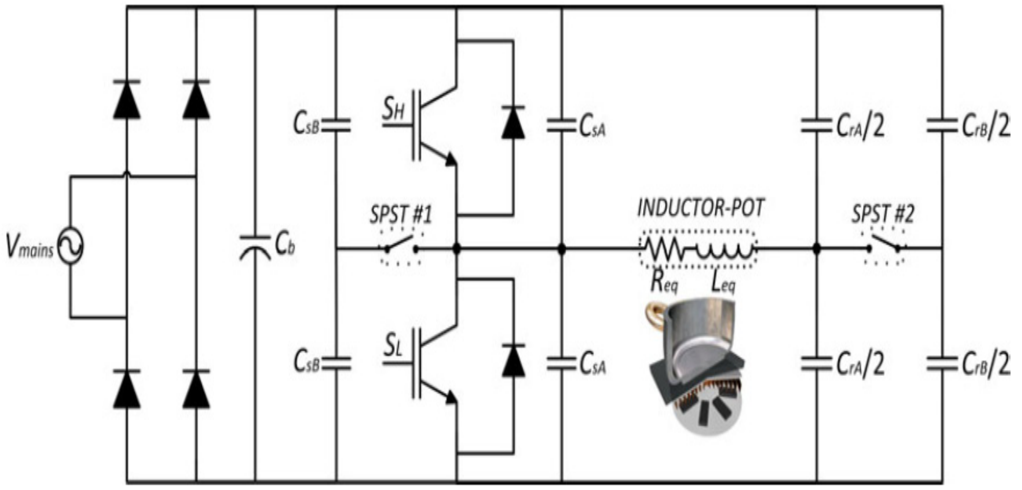
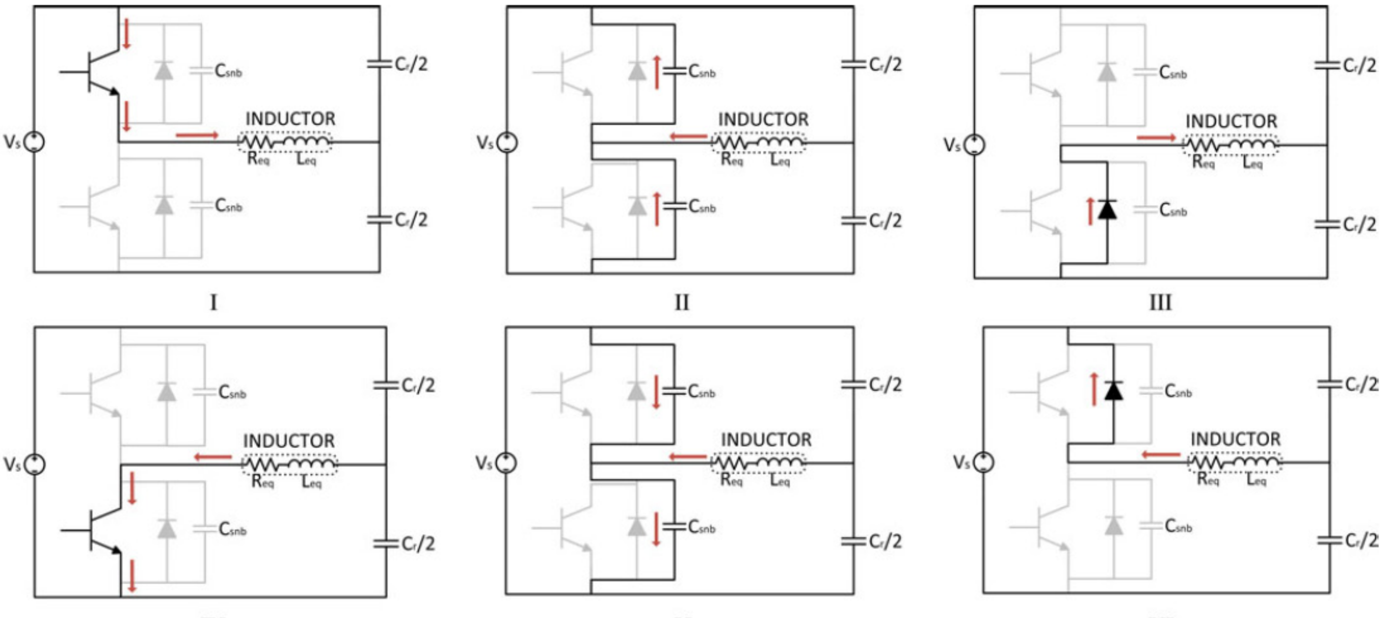


Figure 3: Dual-mode series resonant half bridge converter



I
II
III
IV
V
VI

Figure 4: Main circuit states of the dual mode resonant converter

During the first state I, the load current is positive and it is supplied by the high-side transistor. When high side transistor, S_H is on, low side transistor S_L and both diodes are off, voltage across upper switch is nearly zero, and the voltage across bottom switch is approximately equal to dc-link capacitor voltage. When high-side transistor is deactivated, the switch-off current is used to charge/discharge the snubber capacitors (state II), i.e., the high-side snubber capacitor is charged to the supply voltage, whereas the low-side snubber capacitor is discharged. During state II diodes are reverse biased and voltage across S_H increases and voltage across S_L decreases. The current through high side transistor falls rapidly to zero while the voltage across this transistor remains close to zero. Since the voltage and current waveforms of transistor do not overlap, the turn-off switching loss in transistor is approximately zero. When the voltage across S_L reaches -0.7V, low-side diode turns on and supplies positive load current during state III. Again voltage across low-side transistor increases and when voltage becomes positive S_L gets turned on. Thus during state IV, the load current becomes negative, it is supplied by the low-side transistor. As soon as the low-side transistor is deactivated (state V), the load current charges the low-side snubber capacitor to the supply voltage, whereas the high-side snubber capacitor is discharged. When both snubber capacitors are charged/discharged, the negative load current flows through the high-side diode (state VI). Finally, when the load current reaches zero, the load current is supplied by upper transistor (state I).Class-D operation mode uses configurations I to VI, whereas in class-DE operation mode, the configurations II and V, snubber capacitors charge/discharge, are extended avoiding the use of configurations III and VI, diode conduction. Moreover, in the case of class-DE operation mode, the entire negative current is provided by the snubber capacitance, and anti-parallel diode does not conduct. Therefore, $T_{diode}=0$, T_{IGBT} =Ton. Consequently, the current distribution in the class-DE operation mode is partly derived to the snubber capacitor, reducing conduction losses. As small snubber capacitors are used in the class-D operation mode, the output current can be considered constant during the charge intervals.

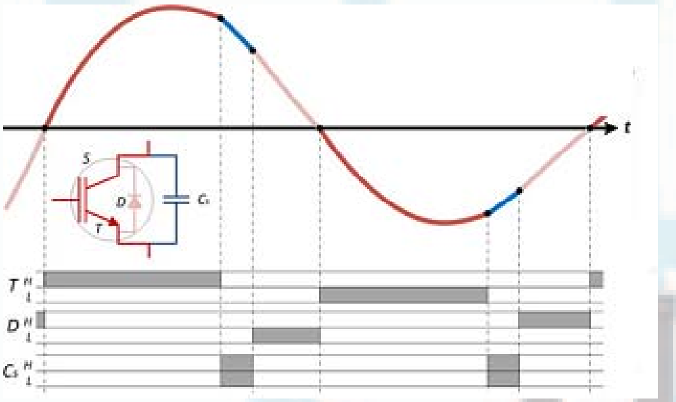


Figure 5: Output current waveform and device activation of class D operation mode

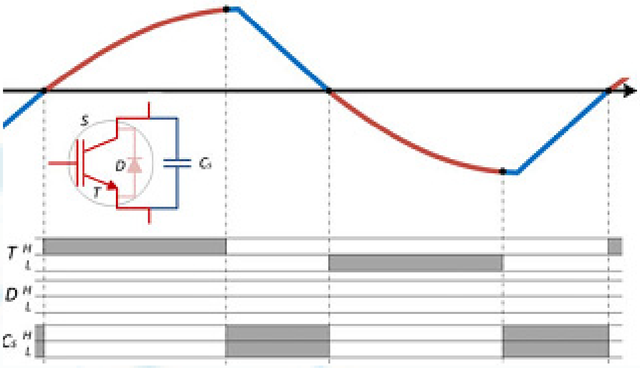


Figure 6: Output current waveform and device activation of class DE operation mode

2.3 Modulation strategies

In the class DE operation mode, the snubber capacitors conduct the cut-off current instead of the anti-parallel diodes for the class D. As a result, the conduction losses are lower. Moreover, the voltage slope for the class DE operation mode is lower than the class-D. The main disadvantage of the class DE operation mode is that output power cannot be varied using switching frequency. On the other hand, the output power in the class D operation mode can be modified using switching frequency or duty cycle. According to the selected operation mode, the hybrid converter uses two modulation strategies. On the one hand, the class-D operation mode supplies the high output power range and, therefore, the square wave modulation (SW) is used [9].Consequently, the maximum output power is achieved at the resonant frequency, and lower power levels can be obtained by increasing the switching frequency. As a result, the ZVS switching-on condition is achieved in the entire power range for this operation mode. When lower output powers are required, the system changes resonant and snubber capacitors to operate in the class-DE operation mode. For a given load, that is, for a given inductor-pot system, the class-DE optimal switching conditions are only achieved for a single operation point, i.e., a switching frequency, a duty cycle, and a phase lag. In the case of class DE inverter, the output power level is controlled by using Pulse Density Modulation (PDM) [9].In the PDM, the output power is controlled by varying the duration for which pulses are applied. The switching period for the pulse density modulation, $T_{PDM,}$ must be designed to fulfill the EMC requirements and the input power flicker requirements. Flicker increases when output power increases, and therefore the PDM control strategy cannot be used in the wide output power range. Using this control strategy, the average output power can be defined as

$$P_o^{DE} = \frac{T_{on}}{T_{PDM}} P_{o,max}^{DE} \tag{1}$$

where T_{on} is the total on time and T_{PDM} is the total switching period.

3. Analysis of Class D & Class DE Mode

As the class DE operation mode is used to achieve the lower output power levels, both resonant and snubber capacitor use higher values than in the class-D operation mode. Therefore, the electromechanical relays SPST 1 and 2 are used to increase this capacitance for the class-DE operation mode.

3.1 Class-D operation mode

The output power in the class-D inverter can be determined using Fourier transform as expressed in the following expression [6]:

$$\begin{aligned} P_o^D &= \sum_{h=1}^{\infty} R_{eq} I_{o,rms}^2 \\ &= \sum_{h=1}^{\infty} R_{eq} \frac{V_{o,rms}^2}{R_{eq}^2 + (h2\pi f_{sw} L_{eq} - \frac{1}{h2\pi f_{sw} C_r^D})^2} \\ &= \sum_{h=1}^{\infty} \frac{2R_{eq} V_{mains}^2 / (h\pi)^2}{R_{eq}^2 + (h2\pi f_{sw} L_{eq} - \frac{1}{h2\pi f_{sw} C_r^D})^2} \end{aligned} \tag{2}$$

where R_{eq} and L_{eq} are the inductor-pot system electrical equivalent, f_{sw} is the switching frequency, and h is the harmonic number. The maximum output power occurs at resonant frequency. As a consequence, the first harmonic approximation can be assumed and the load resistance is given by

$$R_{eq} \le \frac{2V_{mains}^2}{\pi^2 P_{o,max}^D} \tag{3}$$

The resonant capacitor can be determined as

$$C_r^D = \frac{1}{L_{eq}(2\pi\, f_{sw})^2} \tag{4}$$

The snubber capacitance is charged/discharged during dead time between transistor activation with the output current to achieve ZVS in a wide range of operating conditions.

3.2 Class DE operation mode

The resonant inverter under class-DE operation mode is designed to supply the required low-medium output power for the same R_{eq}, L_{eq}. Resonant and snubber capacitors are therefore modified as

$$C_r^{DE} = C_{rA} + C_{rB} \tag{5}$$

$$C_s^{DE} = C_{sA} + C_{sB} \tag{6}$$

The load resistance is determined by the maximum output power required in the class-D operation mode. As a consequence, he maximum output power when operating in class-DE operation mode is strongly dependent of the duty cycle, D.

$$P_{o,max}^{DE} = \frac{V_{mains}^2}{2\pi^2 R_{eq}}(1 - cos(2\pi D)) \tag{7}$$

The snubber capacitance can be calculated as follows:

$$C_{snb}^{DE} = \frac{1 + cos(2\pi D)}{(2\pi)^2 R_{eq} f_{sw}} \tag{8}$$

α is the phase lag between current and voltage and is given by

$$tan(\alpha) = \frac{\pi(1 - 2D) + sin(2\pi D)cos(2\pi D)}{sin^2(2\pi D)} \tag{9}$$

The resonant frequency in the class DE operation mode is determined by the inductor and the resonant capacitors.

$$f_r^{DE} = \frac{f_{sw}}{2}\left(\sqrt{\left(\frac{tan(\alpha)}{Q_{eq}}\right)^2 + 4} - \frac{tan(\alpha)}{Q_{eq}}\right) \tag{10}$$

where $Q_{eq} = 2\pi\, f_{sw} L_{eq} / R_{eq}$ is the inductor power quality factor at the switching frequency. Consequently, the resonant capacitor for the class-DE operation mode is given by

$$C_r^{DE} = \frac{1}{\left(2\pi f_r^{DE}\right)^2 L_{eq}} \tag{11}$$

4. Simulation Results

Single phase 230 V, 50Hz AC supply is applied as input to the diode bridge rectifier. The circuit components are selected in according to the relation (2)-(11) and are listed in the table I and table II for class D and class DE operation modes. The simulation diagram of class D and class DE resonant converter is shown in Figure 7 and Figure 8. The dc link voltage across the smoothing capacitor is measured using scope. PWM signal is used for switching two IGBTs. PWM signal is generated from a ramp signal using integrator, comparator, sign and saturation blocks. One of the two IGBTs is directly fed with PWM signal from saturation block and the other is fed with inverted PWM signal output from the NOT logical operator. Series RL branch is the representation of equivalent inductance and resistance of inductor-pot system. The output voltage across the series RL branch is measured with the help of voltage measurement block and the output current is measured with the help of current measurement block and scope is used for observing the output voltage waveform and output current waveform.

Table 1: Simulation parameters of class D converter

Switching Frequency(f_{sw})	(20-40)kHz
Resonant Capacitor(C_r)	2.14 µF
Snubber Capacitor(C_s)	15 nF
DC-Link Capacitor(C_b)	6.6 µF
Inductor-pot Equivalent Resistance(R_{eq})	2.89 Ω
Inductor-pot Equivalent Inductance(L_{eq})	29.6 µH

Table 2: Simulation parameters of class DE converter

Switching Frequency(f_{sw})	20kHz
Resonant Capacitor(C_r)	7.35 µF
Snubber Capacitor(C_s)	464 nF
DC-Link Capacitor(C_b)	6.6 µF
Inductor-pot Equivalent Resistance(R_{eq})	2.89 Ω
Inductor-pot Equivalent Inductance(L_{eq})	29.6 µH

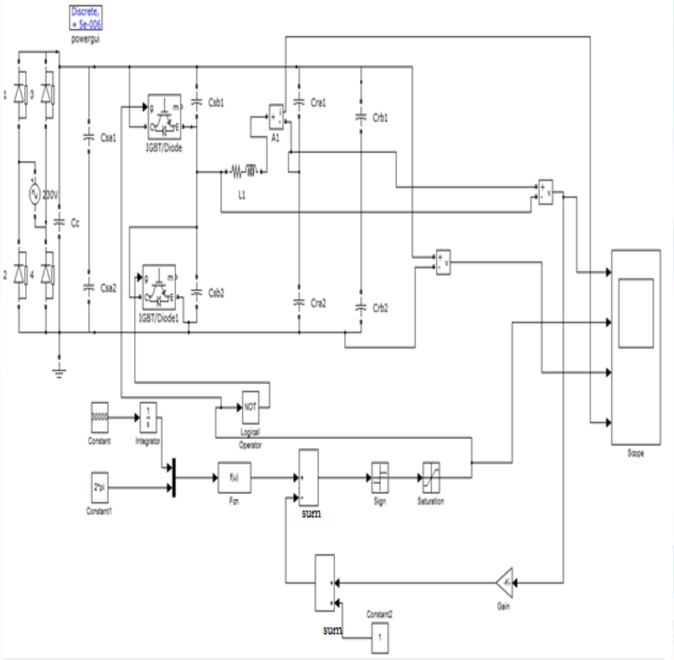


Figure 7: Simulation model of class D converter

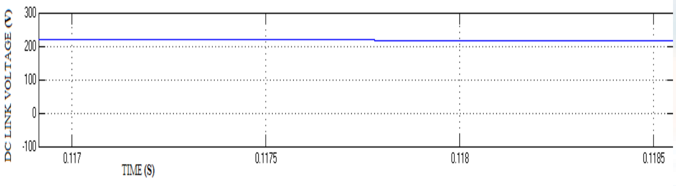


Figure 8: DC link voltage waveform of class D converter

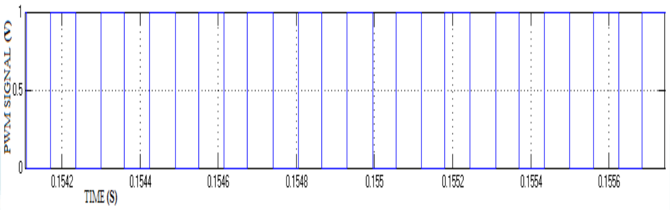


Figure 9: PWM signal

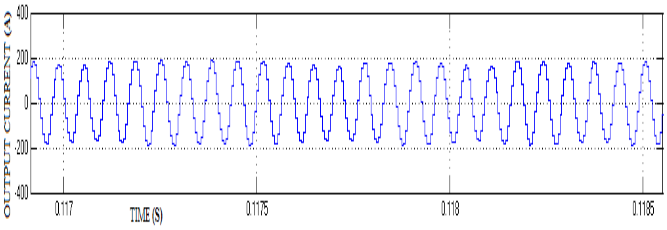


Figure 10: Output current waveform of class D converter

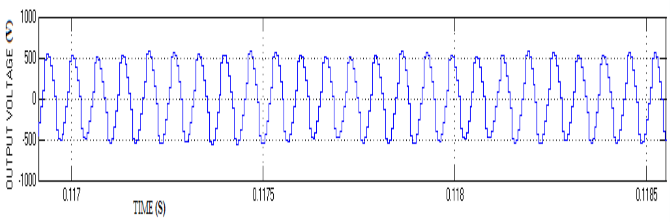


Figure 11: Output voltage waveform of class DE converter

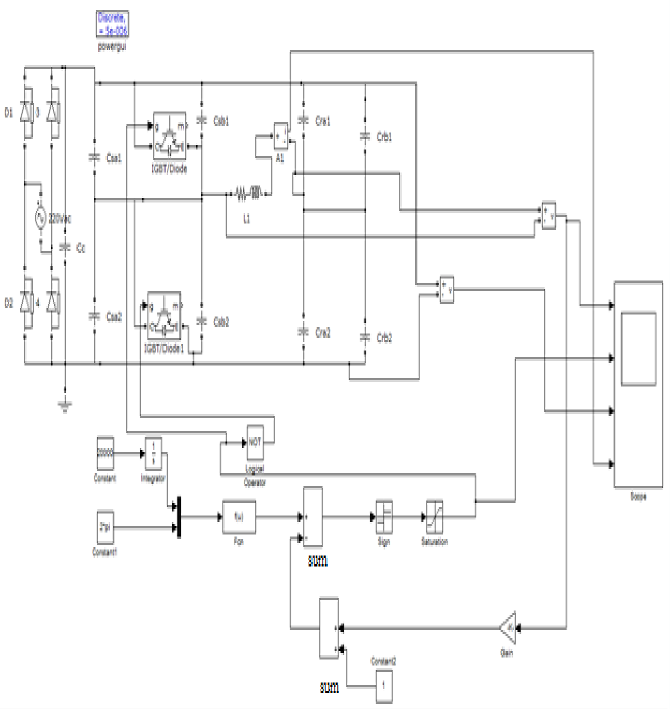


Figure 12: Simulation model of class DE Converter

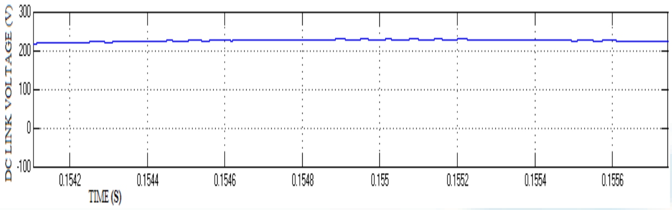


Figure 13: DC link voltage waveform of class DE converter

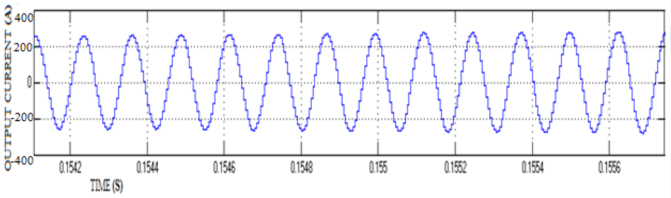


Figure 14: Output current waveform of class DE converter

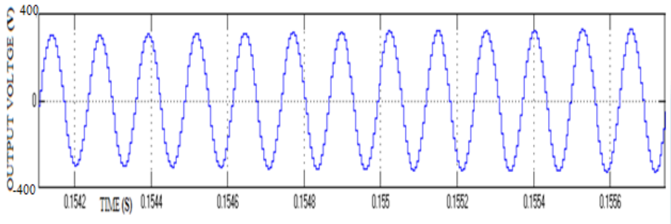


Figure 15: Output voltage waveform of class DE converter

From the simulation diagrams, the dc-link voltage is found to be almost 210V which is same for both class D and class DE operation modes. The output current waveform and output voltage waveform is almost sinusoidal for class D and class DE converter. The time period for one cycle of waveform is very small and hence frequency of output current and voltage is also very high. Class DE operation mode achieves lower output voltage levels than in the class D operation mode. Moreover, there is some phase shift between the output voltage and current waveforms of the dual mode converter in both class D and class DE operation modes.

5. Conclusion

Domestic Induction Heating (IH) systems are based on a dc-link resonant converter which supplies high frequency currents (20-100 kHz) to an inductor, which heats up the pan. The dual-mode resonant half bridge converter has been simulated using MATLAB/SIMULINK. The dual-mode-operation resonant converter improves efficiency in the low output power range due to the reduced switching losses. Class-D half bridge converter with SW control is used in the high output power range, whereas class-DE half-bridge converter with PWM is used in the low to medium output power range. The combination of these operation modes achieves high efficiency levels in a wider range of output power levels. In the dual-mode resonant converter, class-D and class-DE operation modes are combined to optimize the efficiency in wide range of output power levels. Thus, the presented dual-mode resonant converter topology is a cost-effective implementation for domestic induction heating appliances.

Future implications of this research would be micro-controller based hardware implementation for production on a large scale basis. Power factor correction and selection of heating temperature according to different cooking purposes, would make the proposed induction heating system a success in market production.

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