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Dual Frequency Full-Bridge Inverter for All Metal Induction Heating Cooking Applications

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***Abstract*— In this paper, a dual frequency full-bridge series resonant inverter topology is proposed for induction heating applications. ADC method is employed for power regulation. Each leg of the proposed full-bridge inverter operates at different frequency making it suitable for all metal induction heating applications. The proposed inverter resonates automatically for magnetic and non-magnetic vessel and thereby transferring maximum heating to the vessel. The component count is less. The detailed description, circuit analysis and simulation results of the proposed converter are presented.**

Keywords—Induction heating, ADC, dual frequency

I. INTRODUCTION

Now-a-days, compared to various heating technologies, induction heating gains popularity as it facilitates contactless, fast dynamic, high efficient heating. Due to advancements in power semiconductor devices, these induction heating elements are widely used in domestic cooking applications. Induction cooker uses an induction heating coil, driven by high frequency inverters. The high frequency output current from inverter produces high frequency magnetic flux in the heating coil. This high frequency flux induces eddy currents in the pan kept over the coil and produces heat in it. Once the pan is removed, induction heating stops. This is a flameless method of cooking. The efficiency is about 90% as less heat is lost in the air [1]. The heat generation in case of non-magnetic material is due to only eddy current losses. In case of magnetic material heat generation is due to eddy current losses as well as hysteresis losses.

The electrical equivalent circuit of induction cooker consists of a series connection of a resistor, R_{eq} and an inductor, L_{eq} based on transformer analogy. R_{eq} and L_{eq} are the equivalent resistance and inductance respectively of heating coil and pan. Due to the inductive nature, the induction heating load power factor is poor (< 0.3 lag) [2]. In order to improve power factor and to minimize switching losses using resonance, a resonant capacitor, C_r is used in series with the equivalent circuit. Due to reduced component count and simplicity, half-bridge series resonant inverters are mostly employed in induction cooking applications. The load is operated slightly above resonance frequency in order to obtain ZVS. Two types of controls are generally employed in induction heating. One is square wave (SW) control [3] and other is asymmetrical duty cycle (ADC) control [4]. In SW control switching frequency, f_s is the control parameter where as in ADC control, parameters are switching frequency, f_s and duty ratio, d.

The conventional induction heaters are designed to operate at only one resonant frequency which is in the range of suitable for ferromagnetic materials. Thereby conventional induction heaters can only heat ferromagnetic vessels like iron or stainless steel. These induction heaters are unable to heat non-ferromagnetic vessels like aluminum or copper which are mostly used in kitchen. The pans or vessels used have different properties such as permeability and resistivity which affects the loading of induction heating. Based on particular type of vessel, the equivalent inductance and resistance will change which affects the resonance frequency. As ferromagnetic materials have high permeability and high resistivity, these can be easily operated at low frequency to generate required heat. Non-ferromagnetic materials have low permeability and low resistivity and they should be operated at very high frequency to generate required heat. Thereby the resonant inverters must be able to operate at two different frequencies in order to drive both ferromagnetic and non-ferromagnetic vessels. Therefore, there is a requirement of advanced inverter topology which can heat both ferromagnetic and non-ferromagnetic vessels called as all metal domestic induction heating.

Various inverter topologies are proposed in the past for all metal domestic induction heating. In [5], half-bridge series resonant inverter based topology is proposed by modifying half bridge by one relay and resonant capacitor. In [6], quasi variable capacitor is used in soft switched inverter for induction heating applications with PWM control. In [7], time sharing high frequency resonant inverter is discussed for all metal induction heating application. Here two selective capacitors are used which is based on particular type of load. Power regulation is carried out by phasor angle control scheme with phase shifted PWM scheme.

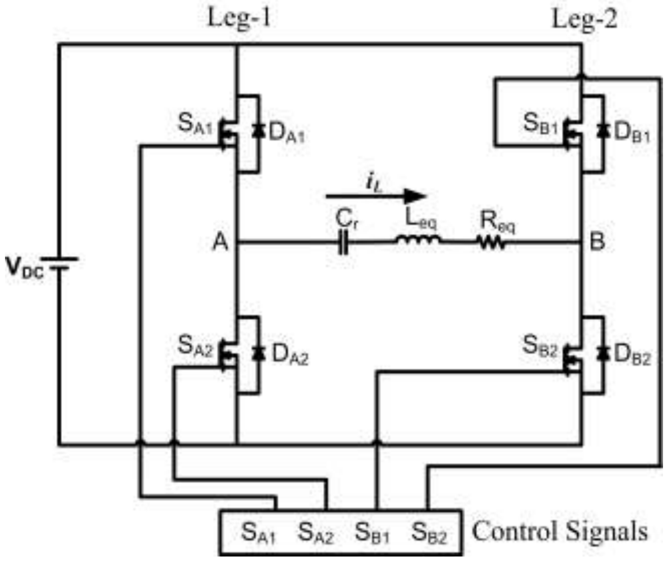


Fig. 1 Schematic diagram of proposed Inverter

In [8], a transformer coupled, series-resonant topology for induction heating of aluminum cookware is discussed based on impedance matching in order to efficiently deliver the desired amount of power to low impedance induction heating loads. Boost half-bridge series load resonant inverter is proposed in [9] and [10]. Here currents in the devices are minimized for a particular output power. Two selective resonant capacitors are used.

This paper proposes a dual frequency operated full-bridge based series resonant inverter topology for induction heating applications. The proposed topology is capable of heating both ferromagnetic and non-ferromagnetic vessels effectively. ADC control scheme is employed for power regulation. The proposed topology uses single resonant capacitor which is common for both types of vessels. This circuit automatically transfers maximum power to particular type of vessel based on series resonance without using any selective switching of elements and with reduced component count. Thereby the proposed inverter can be employed in all metal induction heating applications. Principle of operation of the proposed circuit is explained in section II. Analysis of proposed inverter is discussed in section III. In section IV, design procedure is described. In section V, simulation results are discussed. Section VI states the conclusions of the proposed dual frequency inverter.

II. PRINCIPLE OF OPERATION

The proposed ADC controlled full-bridge series resonant inverter based induction heater is shown in Fig.1. The proposed circuit is driven by DC source, V_{DC}. The full-bridge inverter consists of switches S_{A1} and S_{A2} of leg-A operated complementary to each other and switches S_{B1} and S_{B2} of leg-B operated complementary to each other. Ferromagnetic (iron) and non-ferromagnetic (aluminum) vessels are considered here for induction heating. The non-ferromagnetic induction heating load is represented by series combination of L_{eq1} and R_{eq1} and ferromagnetic induction heating load is represented by L_{eq2} in series with $R_{eq2.}$ A resonant capacitor, C_r is connected in series with induction heating load. For operating the inverter in series resonance, with two types of induction heating loads, two resonant frequencies i.e., f_{r1} corresponding to non-ferromagnetic material and f_{r2} corresponding to ferromagnetic material must be considered. The resistivity and permeability of non-magnetic materials will be less compared with ferromagnetic materials. Here the values of inductance and resistance are considered such that L_{eq2} = 6 L_{eq1} and R_{eq2} = 4 R_{eq1}. With these values the admittance characteristics of induction heating tank is shown in Fig. 2.

In order to heat two types of vessels, the two legs of the full-bridge inverter are operated with two different switching frequencies. Inverter leg-A is operated at high switching frequency, f_{s1} (120 kHz) above resonant frequency f_{r1} of non-ferromagnetic material and leg-B is operated at low switching frequency, f_{s2} (50 kHz) above resonant frequency f_{r2} of ferromagnetic material. When operating with non-ferromagnetic vessel, i.e., with L_{eq1} and R_{eq1} the circuit is automatically tuned to resonant frequency f_{r1}. As shown in Fig. 2, this f_{r1} is far away from ferromagnetic frequency curve, making it possible to heat non-ferromagnetic vessel effectively.

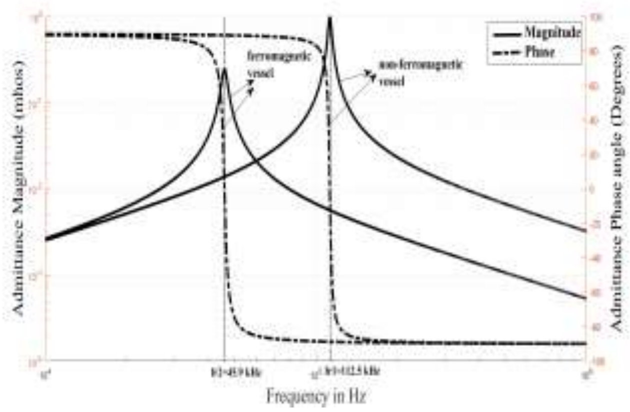
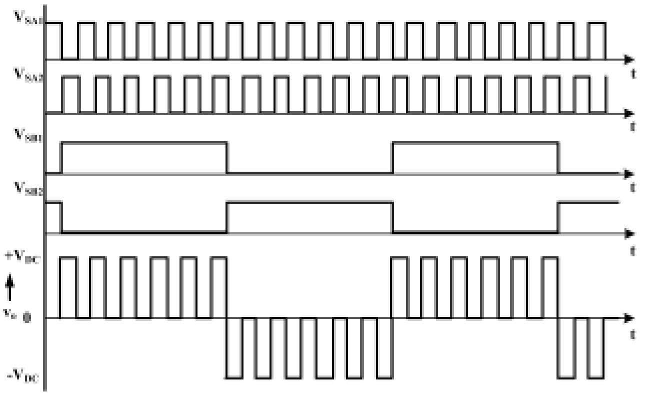


Fig. 2 Admittance characteristics of two loads considered

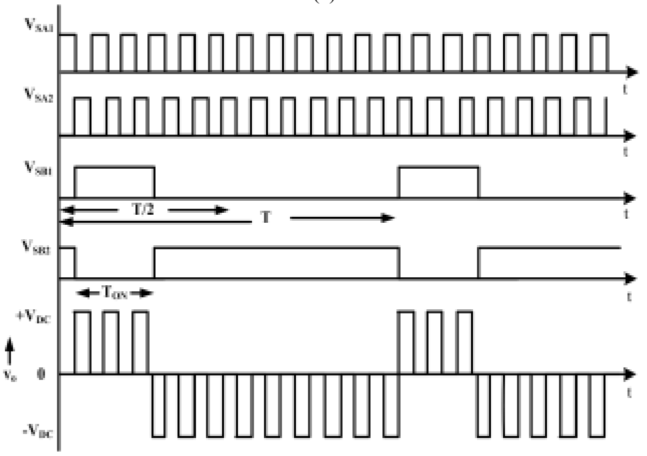
Similarly when ferromagnetic vessel is used i.e., with L_{eq2} and R_{eq2}, the circuit is automatically tuned to resonance frequency f_{r2}. This f_{r2}, as shown in Fig. 2, is far away from non-ferromagnetic frequency response making possible to heat ferromagnetic vessel effectively. Hence, the proposed circuit automatically tunes for particular load resonant frequency corresponding to that particular vessel and heats it effectively. Thereby the proposed circuit is able to heat ferromagnetic and non-ferromagnetic vessels without any external modifications to the circuit.

III. CIRCUIT ANALYSIS

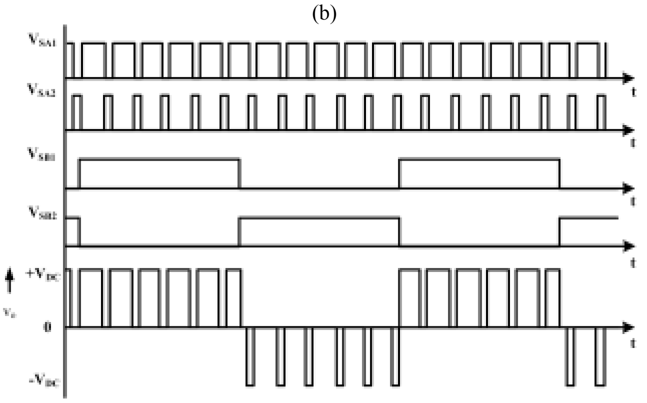
The instantaneous value of inverter output voltage is v_o and i_o is the load current. v_o depends on the switching states of leg-A and leg-B devices. When S_{B1} is ON, v_o can be zero or V_{DC} depending on whether S_{A1} or S_{A2} is ON respectively. When S_{B2} is ON, v_o is $-V_{DC}$ or zero depending on whether S_{A1} or S_{A2} is ON respectively. Thus output voltages v_o can be at any one of the three levels, $+V_{DC}$, 0 or $-V_{DC}$ depending on the switching states of the devices. Gate pulses of switching devices S_{A1}, S_{A2}, S_{B1} and S_{B2} and output voltage v_o are shown in Fig. 3 for different duty cycle combinations. D_1 and D_2 are duty cycles



(a)



(b)



(c)

Fig. 3 Gate pulses and output voltage v_o for different duty cycle combinations
a. $D_1 = 1$ and $D_2 = 1$
b. $D_1 = 1$ and $D_2 = 0.5$
c. $D_1 = 0.5$ and $D_2 = 1$

of leg-A and leg-B devices respectively. Here, duty cycle is defined as,

$$D = \frac{T_{ON}}{(T/2)} \quad (1)$$

T_{ON} and T are indicated in Fig. 3(b) for leg-A control pulses. The same definition of duty cycle is also applicable to leg-B devices. Proposed load resonant circuit equivalent circuit is shown in Fig. 4. This circuit can be considered as either ferromagnetic or non-ferromagnetic series resonance circuit based on type of vessel used.

Here L_{eq} can be either L_{eq1} or L_{eq2} and R_{eq} can be either R_{eq1} or R_{eq2} depending on whether vessel used is non-ferromagnetic or ferromagnetic type. The resonance frequency developed in the circuit depends on the type of vessel used.

When S_{A1} and S_{B2} are on, the loop equation of low frequency resonant load circuit can be written as

$$\left(L_{eq}\right)\frac{di_{L_{eq}}(t)}{dt}+\frac{1}{C_r}\int i_{L_{eq}}(t)dt + v_{C_r}(t=0)+R_{eq}i_{L_{eq}}(t) = v_o \quad (2)$$

With initial values of $i_{Leq} = I_{Leqo}$ and $v_{cr} = V_{Cro}$, the solution of this equation is

$$i_{L_{eq}}(t) = \left(\frac{v_o - V_{Cro}}{\omega_n L_{eq}}\right)e^{-\alpha t}\sin\omega_n t + \left(I_{Leqo}e^{-\alpha t}\left(\cos\omega_n t - \frac{\alpha}{\omega_n}\sin\omega_n t\right)\right) \quad (3)$$

and

$$v_{C_r}(t) = V_{Cro} + (v_o - V_{Cro})\left(1 - e^{-\alpha t}\left(\cos\omega_n t + \frac{\alpha}{\omega_n}\sin\omega_n t\right)\right) + \frac{I_{L_{eqo}}}{\omega_n C_r}e^{-\alpha t}\sin\omega_n t \quad (4)$$

where

$$\alpha = \frac{R_{eq}}{2L_{eq}} \quad (5)$$

and

$$\omega_n = \sqrt{\frac{1}{L_{eq}C_r} - \left(\frac{R_{eq}}{2L_{eq}}\right)^2} \quad (6)$$

Thus during each output voltage levels, by substituting the corresponding value of v_o and initial conditions, equations for resonant currents and resonant capacitor voltages can be obtained using the above equations.

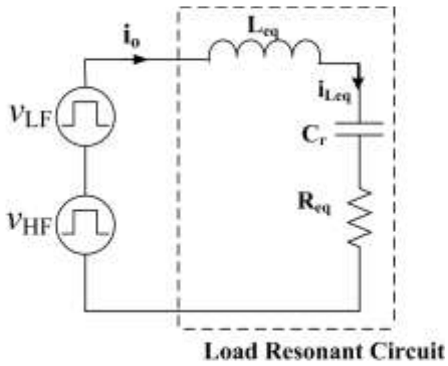


Fig. 4 Equivalent circuit of dual frequency operated inverter

The output power with non-ferromagnetic vessel can be expressed as $P_{o1}= I_{o1}^2 R_{eq1}$ (7)

The output power with ferromagnetic vessel can be expressed as $P_{o2}= I_{o2}^2 R_{eq2}$ (8)

where I_{o1} and I_{o2} are the rms values of the fundamental components of load current respectively with non-ferromagnetic and ferromagnetic vessels.

IV. DESIGN PROCEDURE

The quality factor and resonant frequency of the series resonance circuit can be expressed as

$$Q = \frac{1}{R_{eq}}\sqrt{\frac{L_{eq}}{C_r}} \quad (9)$$

$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C_r}} \quad (10)$$

The parameters corresponding to non-ferromagnetic vessel are L_{eq1} = 50 µH and R_{eq1} = 1 Ω. Values corresponding to ferromagnetic vessel are L_{eq2} = 300 µH and R_{eq2} = 4 Ω.

Using equation (10), the value of resonant capacitor, C_r is calculated as 40 nF.

Table 1 Parameters of proposed dual frequency inverter

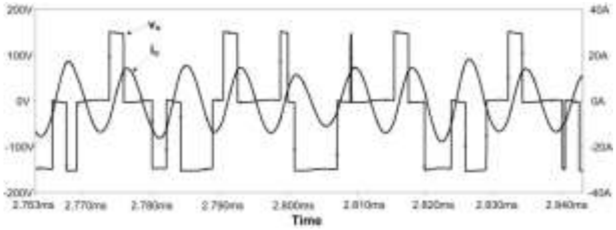
DC voltage (V_{dc})	150 V
High frequency equivalent inductance (L_{eq1})	50 µH
High frequency equivalent resistance (R_{eq1})	1 Ω
Low frequency equivalent inductance (L_{eq2})	300 µH
Low frequency equivalent resistance (R_{eq2})	4 Ω
Resonant capacitor (C_r)	40 nF
High switching frequency (f_1)	120 kHz
Low switching frequency (f_2)	50 kHz

V. SIMULATION RESULTS

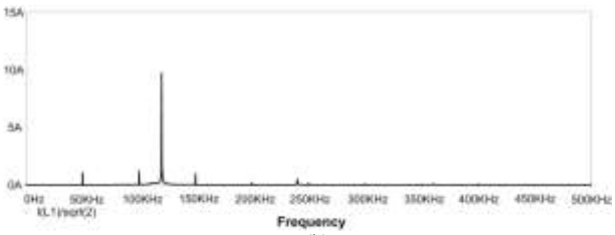
The circuit parameters of the converter are listed in Table 1. The proposed induction heater has been simulated using ORCAD PSpice software. The input voltage to the converter V_{DC} is chosen as 150 V. Low and high frequency output power is controlled by asymmetric duty cycle control of the corresponding legs of the inverter.

Figs. 5 to 7 show simulation waveforms of output voltage, current and its FFT for different duty cycle combinations. Fig. 5(a) shows simulation waveforms of v_o and i_o and Fig. 5(b) shows load current FFT at D_1=0.5 with D_2=0.5. Fig. 6(a) shows simulation waveforms of v_o and i_o and Fig. 6(b) shows load current FFT at D_1=0.8 with D_2=0.5. Similarly, Fig. 7(a) shows simulation waveforms of v_o and i_o and Fig. 7(b) shows load current FFT at D_2=0.5 with D_1=0.5. Fig. 8(a) shows simulation waveforms of v_o and i_o and Fig. 8(b) shows load current FFT at D_2=0.8 with D_1=0.5.

Fig. 9(a) and (b) shows variation of load powers with respect to duty cycle for non-ferromagnetic and ferromagnetic loads. Fig. 9(a) shows variation of output



(a)

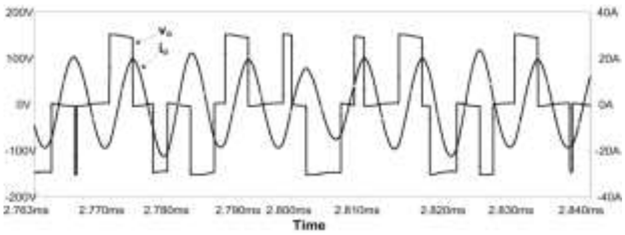


(b)

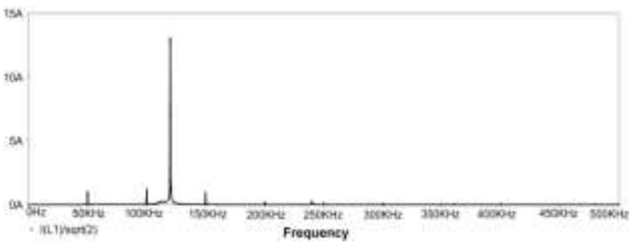
Fig. 5 Simulation waveforms at D_1=0.5 and D_2=0.9 for non-ferromagnetic vessel

a. Output voltage and current waveforms

b. FFT of output current



(a)



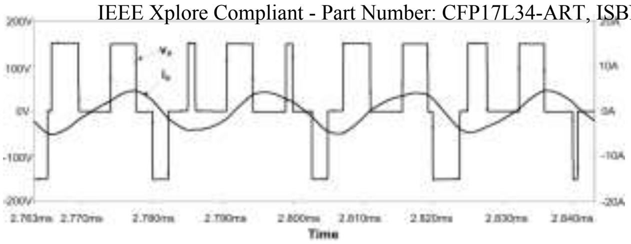
(b)

Fig. 6 Simulation waveforms at D_1=0.8 and D_2=0.9 for non-ferromagnetic vessel

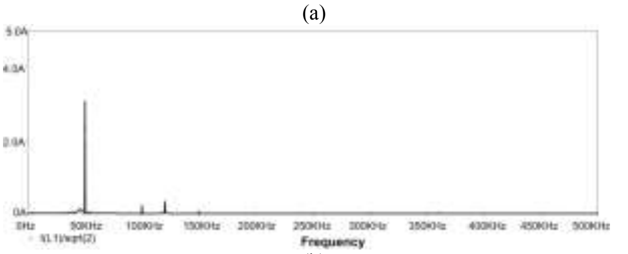
a. Output voltage and current waveforms

b. FFT of output current

power of load with non-ferromagnetic vessel with respect to variation of D_1 with D_2=0.9. Fig. 9(b) shows variation of output power of load with ferromagnetic vessel with respect to variation of D_2 with D_1=0.9.



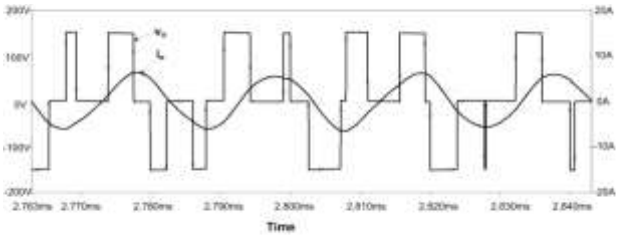
(a)



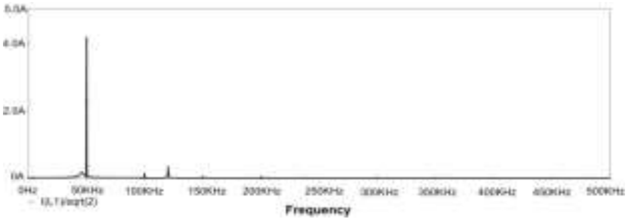
(b)

Fig.7 Simulation waveforms at D_1=0.9 and D_2=0.5 for ferromagnetic vessel

a. Output voltage and current waveforms
b. FFT of output current



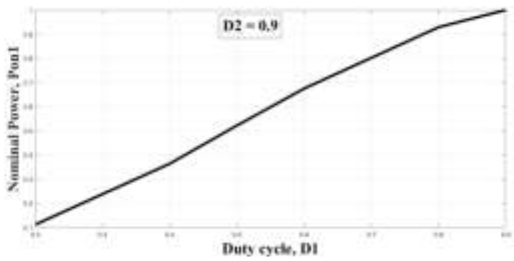
(a)



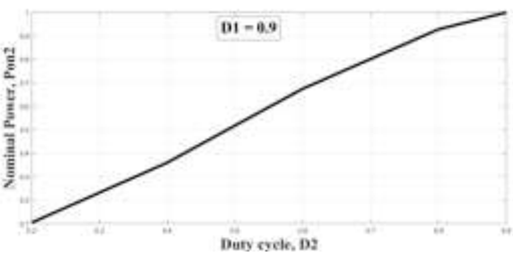
(b)

Fig. 8 Simulation waveforms at D_1=0.9 and D_2=0.8 for ferromagnetic vessel

a. Output voltage and current waveforms
b. FFT of output current



(a)



(b)

Fig. 9 Nominal power vs duty cycle plot

a. Non-ferromagnetic load
b. Ferromagnetic load

VI. CONCLUSION

In this paper ADC controlled dual frequency operated full-bridge based series resonance inverter topology is proposed for induction heating applications. This configuration is suitable for ferromagnetic as well as non-ferromagnetic vessel applications. First leg devices are switched at a low frequency. Second leg devices are switched at a high frequency. Both, low and high frequency legs are controlled with asymmetric duty cycle control. The inverter output is applied to the load resonant circuit. This configuration is analyzed in detail for its performance. Principle of operation and design of this inverter are explained. This inverter automatically provides maximum power output to particular vessel using series resonance principle. FFTs of load currents show that magnitudes of frequency components other than the desired values (50 kHz and 120 kHz) are negligible with corresponding loads. Control logic is simple. Number of components used is less.

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