2018 Third International Conference on Electrical, Electronics, Communication, Computer Technologies and Optimization Techniques (ICEECCOT) 14-15, December 2018

Dual Frequency Buck-Boost Interleaved Inverter for All Metal Induction Heating Applications

G. Govinda Reddy
Department of Electrical Engineering
National Institute of Technology
Warangal, India.
govindareddy218@gmail.com

S. Porpandiselvi
Department of Electrical Engineering
National Institute of Technology
Warangal, India.
selvi@nitw.ac.in

P. Sharath Kumar
Department of Electrical Engineering
Sreenidhi Institute of Science and Technology
Hyderabad, India.
sharathphd@gmail.com

***Abstract*—Multiple load induction heating applications require good control techniques and high power inverters. A dual frequency buck-boost inverter configuration for different loads operating at different frequencies is proposed in this paper. Each load uses one half-bridge series resonant inverter. Effective input voltage to each half-bridge becomes $2V_{DC}$ in this configuration and hence it handles same power as that of full-bridge topology. Through buck-boost converter half of the load power is supplied to each load and remaining half load power is transferred directly from the source. With ADC control, each load power is controlled independently. This topology uses less number of components. The presented inverter configuration is simulated with two loads and can be extended to multiple loads also.**

Keywords—Dual frequency, Induction heating, Buck-boost converter, ADC Control.

I. INTRODUCTION

Due to unique features of induction heating (IH), this technology is showing rapid growth in several areas like medical, industrial and domestic applications over conventional heating methods. Induction cooking is one of the applications of induction heating. The main principle behind induction heating is heating a material by high frequency eddy currents produced due to electro-magnetic induction. When an alternating magnetic field is applied to the material to be heated from high frequency inverter, the magnetic field penetrates through it and generates an electric current inside it called eddy current. The resistance of materials helps in heating due to eddy currents produced. If it is a ferromagnetic material, heat will be produced by both eddy current and hysteresis losses. The depth of penetration of magnetic field inside the material depends on the frequency (f_s) of the current, resistivity (ρ) and relative permeability (μ_r) of the material as given by

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f_s}} \quad (1)$$

where (δ) is the penetration depth or skin depth.

For induction cooking 20 kHz to 150 kHz frequency is used. The switching devices used in converters operate in hard switching mode. As high frequency is adopted in induction heating, there will be considerable amount of switching losses present which will affect the overall efficiency. Soft switching is the better solution to reduce the switching losses. In this method either current or voltage is forced to become zero at the instant of each switching with the use of passive elements like L or C to create resonance condition. Hence resonant converters are the apt choice to be used in high frequency induction heating (IH) applications as they reduce switching losses. Generally MOSFETs are used as switches in inverter configurations. Zero voltage switching (ZVS) and Zero current switching (ZCS) are the two methods of soft switching. In ZVS, voltage is made zero before turning ON the switch which reduces turn on losses where as in ZCS, current is made zero before turning the switch OFF which reduces turn off losses.

Induction heating load can be modelled as a resistor, R_{eq} and an inductor L_{eq}, connected in series which is analogous to the transformer primary with secondary short circuited. R_{eq} and L_{eq} represent the equivalent resistance and inductance of heating material respectively. Due to the inductance of the coil, power factor of the induction heating (IH) systems will be poor. The power factor can be improved using resonance by connecting a resonant capacitor, C_r in series with the coil. Various topologies have been proposed based on number of switches used and regarding resonant inverters such as single switch resonant converter [1], half-bridge series resonant inverter(SRI) [2] and full bridge SRI [3-4]. Half bridge SRI is generally used for domestic and industrial heating applications. For resonant or conventional inverters appropriate power control technique is needed to improve the quality of heating. Basically power control is done by two methods either by input voltage source (V_{DC}) which is called Pulse Amplitude Modulation (PAM) or by switching frequency (f_s) that is called Pulse Frequency Modulation (PFM). In first method, variable DC voltage is required which increases size and cost due to various stages involved. In second method due to variable frequency [5], efficiency is low when f_s is high and large filter components required when f_s is low and also the range of frequencies to ensure ZVS operation is less. To fix this problem, duty cycle is varied by keeping frequency fixed. A good and wide range of power modulation techniques have been introduced to control the power. In [6], Phase shift (PS) control technique is used in a high frequency full bridge inverter to control output power. The phase shift is maintained between the pulses S_1, S_2, and S_3, S_4 in this technique. Another technique called Asymmetrical duty cycle (ADC) control was proposed in [7] where switches S_1-S_2 and S_3-S_4 operates on a different duty cycle. In most of the domestic induction cooking appliances Asymmetric Voltage Cancellation (AVC) [8] is used. Another popular control technique is Pulse density modulation (PDM) [9] in which

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power is controlled by controlling the ratio between continuous T_{on} pulses and continuous T_{off} pulses.

As per the traditional approach of inverter topologies one inverter is required per IH load or one inverter for multiple loads. In the first case multiple inverters are required for multiple IH loads which increase component count, cost and size. Hence one inverter for powering multiple loads i.e., multi-output inverter is the alternative available which offers clear benefits for multiple loads like less component count as some of them are shared and higher utilisation of electronics. So there is scope for development of various topologies and control techniques for multi-output inverters. In the past several topologies have been presented for multiple load induction heating systems [10-12].

In [13], a buck-boost interleaved inverter configuration has been proposed for multiple load induction cooking applications. In this two conventional loads are used operating at same frequency and are independently controlled. However the frequencies of this inverter and of induction cookers available in the market are suitable for vessels made of ferromagnetic materials. This is the well-known limitations of induction cooking method which prevents the use of aluminium and copper vessels. Hence this paper proposes dual frequency operation and independent control of buck-boost interleaved inverter. This configuration is suitable for vessels made of both ferromagnetic and non-ferromagnetic materials. The operation of proposed circuit is presented in Section II. Section III describes the design procedure. Simulation results are presented in Section IV. Section V and Section VI explains independent control of load and conclusion respectively.

II. PROPOSED INVERTER CONFIGURATION

The proposed circuit shown in Fig. 1 is a dual frequency interleaved buck-boost inverter supplying power to two half bridges.

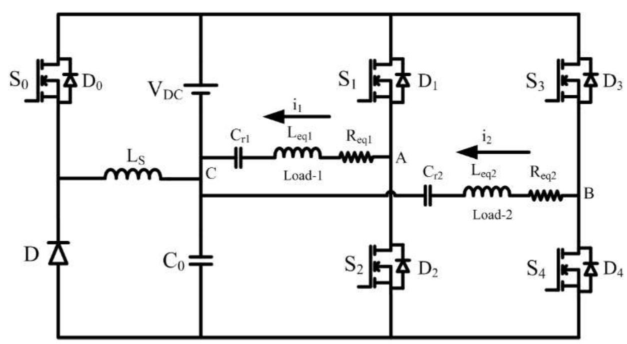


Fig. 1. Proposed inverter configuration for two different loads

Here two different loads i.e., iron (ferromagnetic) and aluminium (non-ferromagnetic) are considered. Each half bridge is switched at a different frequency. V_{DC} is the supply voltage and from buck-boost converter output another V_{DC} across C_0 is obtained which is in series with source voltage. Due to the voltage reversal nature of buck-boost converter the voltage across C_0 is maintained constant at V_{DC} equal to that of source voltage by suitable duty cycle of the converter. Hence a total voltage of $2V_{DC}$ is available as input to each half-bridge inverter.

As the two loads are connected between the midpoint of total input voltage $2V_{DC}$ which acts like a split capacitor and respective half-bridge inverter, the voltage across each load changes from $+V_{DC}$ to $-V_{DC}$ which is same as in the case of full-bridge inverter with input voltage of V_{DC}. Hence by using this configuration, with the half-bridges, the power supplied to each load is same as the full-bridge configuration. For the independent control of power to each load, ADC control technique is used for both half-bridges. Load-1 is connected between A and C terminals and its output voltage is represented as V_{AC}. Load-2 is connected between the terminals B and C and its output voltage is represented as V_{BC}.

The admittance characteristics of the two loads considered are shown in Fig. 2. Generally the induction cooking appliances are designed for ferromagnetic materials. For non-ferromagnetic materials resistance is low compared to ferromagnetic materials. Hence the same IH system designed for ferromagnetic loads cannot be used for non-ferromagnetic loads directly because high currents will flow through the switches. Hence in order to increase the effective resistance due to the skin effect, frequency needs to be increased for non-ferromagnetic loads.

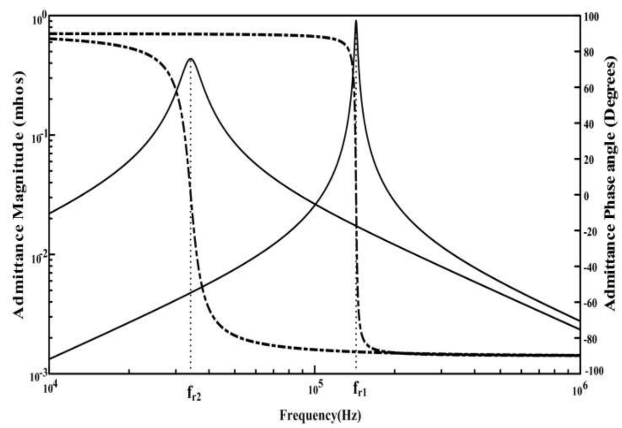
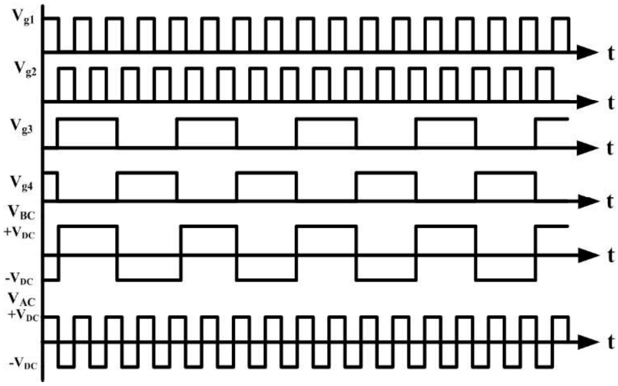


Fig. 2. Admittance characteristics of two IH loads

In the proposed circuit aluminium load is placed across A and C terminals which is operating at high frequency (150 kHz). Iron load is placed across the terminals B and C which is operating at low frequency (40 kHz). Hence the resonant capacitor C_r should be selected such that switching frequency (f_s) of each half bridge is 5-10% higher than resonant frequency (f_r) of respective load to ensure ZVS.

The parameter values of two loads are shown in Table I. One half bridge is operated at high frequency of 150 kHz and the other at low frequency of 40 kHz. For the source voltage of 115V the rated power of load-1 is 865 W and for load-2 it is 1795 W. During ADC control of power for two loads the gate pulses V_{g1}-V_{g4} and the output voltages of respective loads are depicted below in Fig. 3 for various combinations of duty cycles. With ADC control, the duty ratio of each half-bridge is given by

$$\text{Duty Cycle, } D = \frac{T_{on}}{T/2} \tag{2}$$



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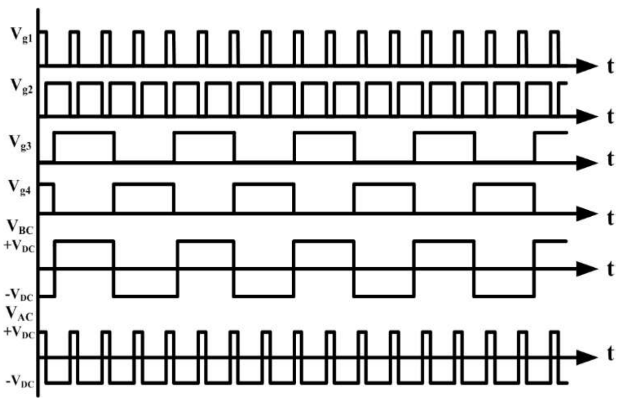

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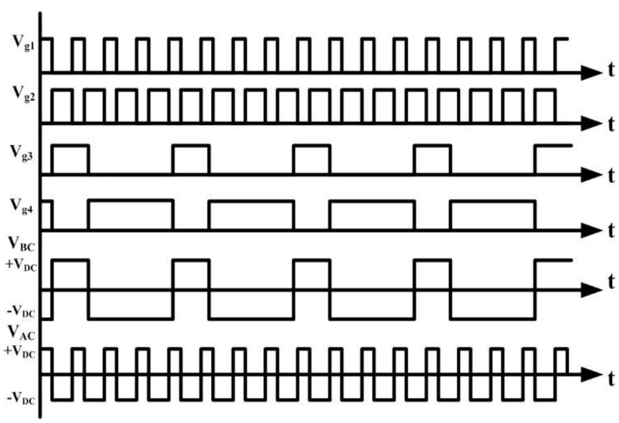

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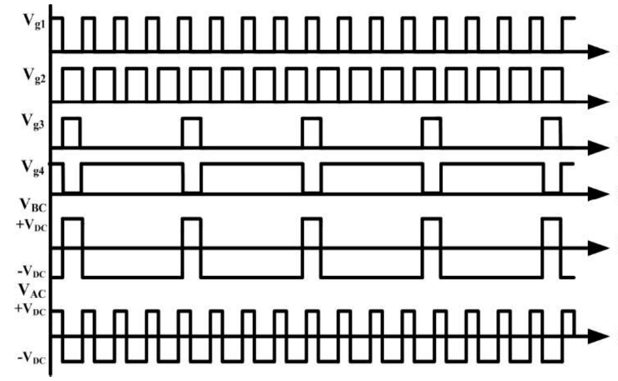


(d)

Fig. 3. Gate pulses and output voltages of V_{BC} and V_{AC} for various duty cycle combination.

a) $D_1 = 0.93$ and $D_2 = 0.98$

b) $D_1 = 0.5$ and $D_2 = 0.98$

c) $D_1 = 0.7$ and $D_2 = 0.6$

d) $D_1 = 0.7$ and $D_2 = 0.3$

III. DESIGN PROCEDURE

The quality factor and resonant frequency of the series resonant loads are expressed as

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{3}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

As the parameter values of both the loads are mentioned in Table I and by using equation (4), the value of resonant capacitors of each load is calculated.

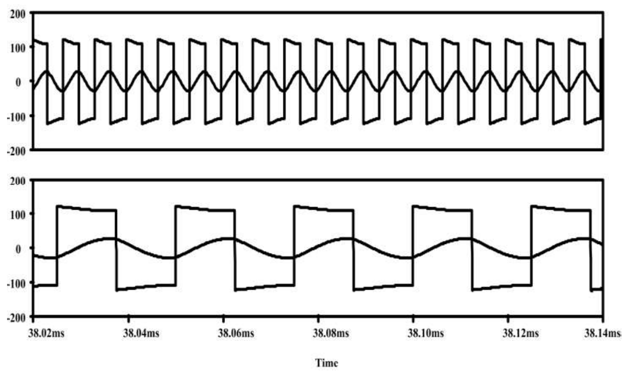
TABLE I. INVERTER PARAMETERS AND THEIR VALUES

Parameter	**Value**
DC input voltage (V_{DC})	115 V
Load 1 resistance (R_{eq1})	1.1 Ω
Load 2 resistance (R_{eq2})	2.3 Ω
Load 1 inductance (L_{eq1})	58.87 µH
Load 2 inductance (L_{eq2})	68 µH
Load 1 resonant capacitor (C_{r1})	0.021 µF
Load 2 resonant capacitor (C_{r2})	0.32 µF
Switching frequency of bridge-1 (f_1)	150 kHz
Switching frequency of bridge-2 (f_2)	40 kHz

IV. SIMULATION RESULTS

The proposed circuit is simulated by using ORCAD PSPICE software for two different material loads. The input voltage to buck-boost converter is taken as 115 V and the frequencies of two half-bridges are taken as 150 kHz and 40 kHz respectively.

Fig. 4 to Fig. 7 shows the simulation waveforms of output voltages and output currents for both the loads operating at different frequencies. FFTs of both the load currents are also shown for various duty cycles. In Fig 4(a) the simulated waveforms of load voltages V_{AC}, V_{BC} and load currents i_1, i_2 are shown for duty cycles of D_1=0.93 and D_2=0.98. The corresponding FFTs of load currents is shown in Fig 4(b). The above mentioned waveforms and FFTs are shown in Fig. 5, Fig. 6 and Fig. 7 for duty cycle combinations of D_1=0.5 & D_2=0.98, D_1=0.7 & D_2=0.6 and D_1=0.7 & D_2=0.3 respectively.



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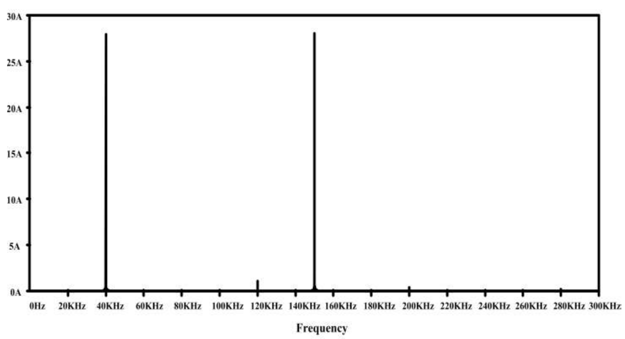

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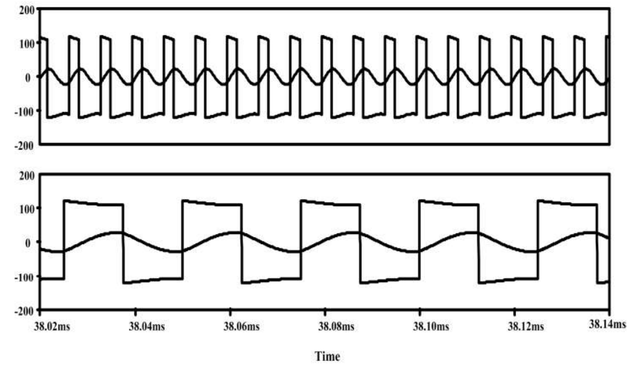
Fig. 4. Simulation waveforms for D_1 = 0.93 and D_2 = 0.98
a. Load voltages V_{AC}, V_{BC} and load currents i_1, i_2
b. FFT of output currents



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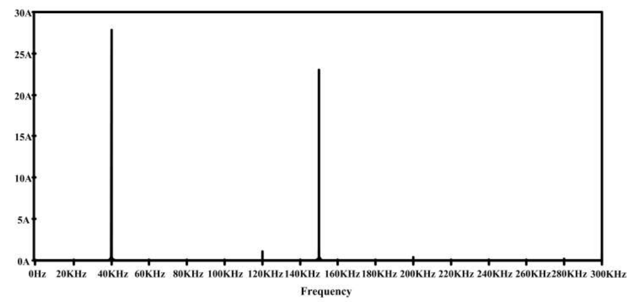

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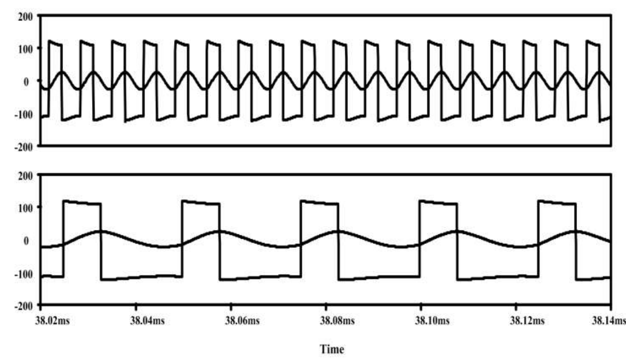
Fig. 5. Simulation waveforms for D_1 = 0.5 and D_2 = 0.98
a. Load voltages V_{AC}, V_{BC} and load currents i_1, i_2
b. FFT of output currents



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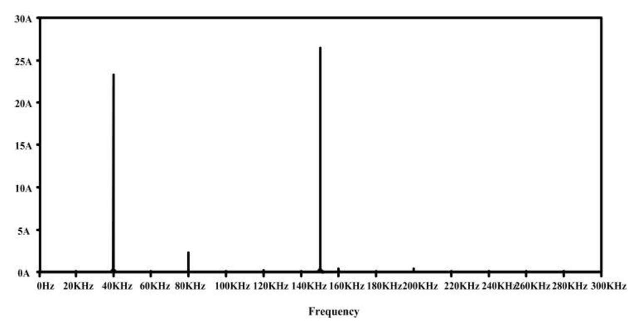
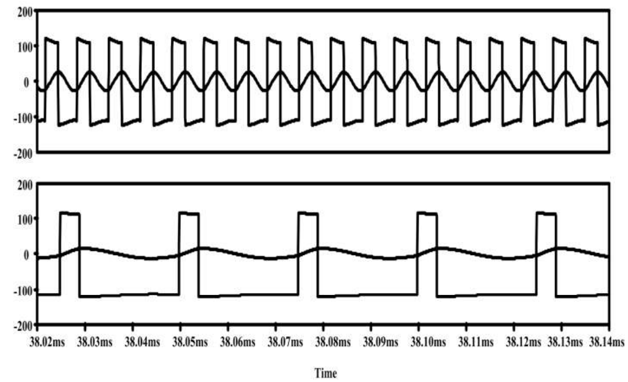


(b)

Fig. 6. Simulation waveforms for D_1 = 0.7 and D_2 = 0.6
a. Load voltages V_{AC}, V_{BC} and load currents i_1, i_2
b. FFT of output currents



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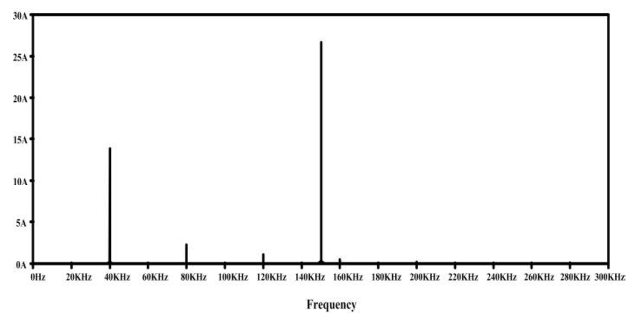

(b)

Fig. 7. Simulation waveforms for $D_1 = 0.7$ and $D_2 = 0.3$
a. Load voltages V_{AC}, V_{BC} and load currents i_1, i_2
b. FFT of output currents

V. INDEPENDENT CONTROL OF LOAD POWER

By using ADC control technique, load power is controlled independently. By keeping duty cycle of load-1 constant and varying duty cycle of load-2 i.e., D_2 only load-2 current changes and load-1 current is constant as shown in Fig.8. Similarly if load-1 duty cycle changes by keeping D_2 constant, only current of load-1 changes while current of load-2 is constant as shown in Fig. 9. Hence independent control is achieved. In Table II, the load-2 current remains constant as duty cycle, D_2 = 0.98 is fixed while current of load-1 is controlled by varying D_1. The variation of output powers of the two loads with respective duty cycle is shown in Fig. 10 and Fig. 11 respectively.

TABLE II. VARIATION OF LOAD-1 CURRENT WITH D_1

Duty cycle, D_1	Load-1 (A)	Load-2 (A)
0.93	28.03	27.93
0.8	27.54	27.93
0.7	26.75	27.93
0.6	25.18	27.93
0.5	22.91	27.93
0.4	20.16	27.93
0.3	16.82	27.93
0.2	12.78	27.93
0.1	6.98	27.93

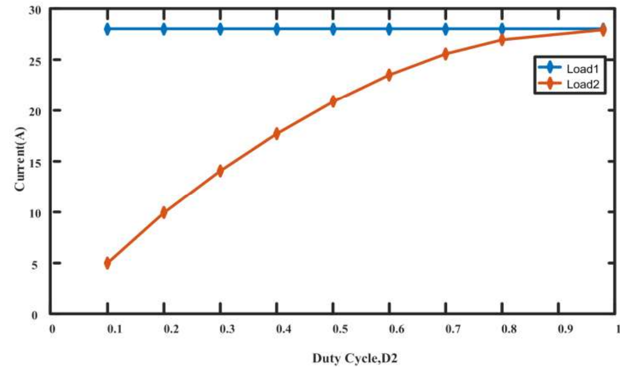

Fig. 8. Output currents vs D_2 ($D_1 = 0.93$)

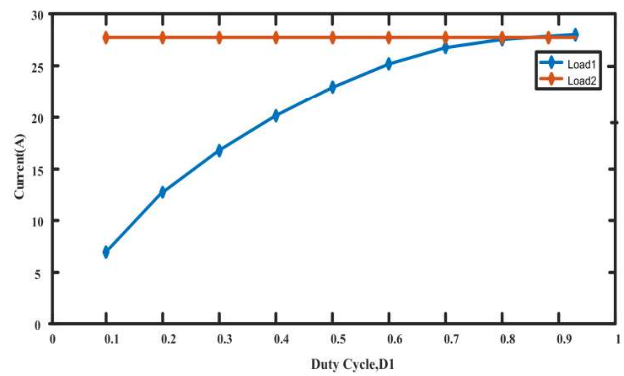

Fig. 9. Output currents vs D_1 ($D_2 = 0.98$)

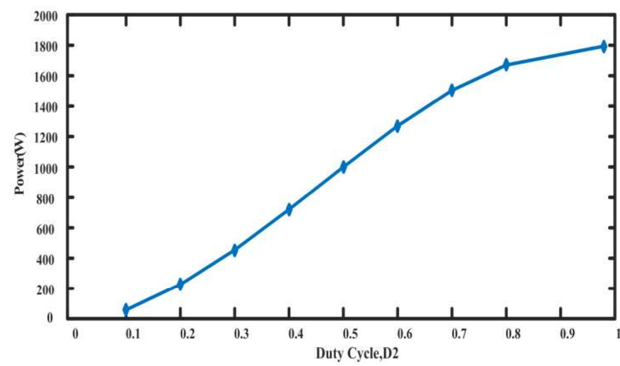

Fig. 10. Load-2 output power vs D_2

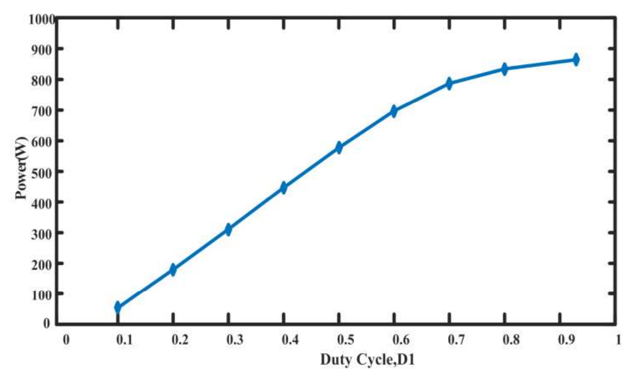

Fig. 11. Load-1 output power vs D_1

VI. CONCLUSION

A dual frequency buck-boost interleaved inverter topology suitable for different material IH loads is proposed in this paper. It uses one half-bridge for each load and supplies same power as that of full-bridge inverter. One half-bridge is operated at high frequency and the other at low frequency. The load power is independently controlled for both loads using Asymmetric Duty Cycle (ADC) control. From the FFTs of load currents it is observed that only currents of desired frequencies (40 kHz and 150 kHz) are flowing through the respective loads. This configuration uses less number of components and suitable for all metal IH applications ensuring reliability. As the future work, this configuration can be extended to multiple loads.

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