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Pulse Frequency Controlled Resonant Inverter for Different Material Induction Cooking Loads

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***Abstract* - Existent induction cooking application requires high frequency and high efficiency multiple load resonant inverter configuration with independent control that suits for multiple vessels. In this paper, a multiple frequency resonant inverter is proposed for induction cooking application suitable for different material vessels. The proposed inverter is using half bridge configuration and is supplying the loads with power as that of full bridge circuit using a buck boost converter. Pulse Frequency control (PFC) technique is used for output power control. This configuration offers advantages like reduced component count and also improved efficiency. It also provides independent control. This new configuration is simulated with two different vessels and the simulation results prove the benefits of this converter.**

Keywords - Resonant Inverter, Buck-Boost, Pulse Frequency control

I INTRODUCTION

Induction heating (IH) is a highly efficient technology with economic and social impact due to its benefits like safety performance, high efficiency, cleanliness, reduced heating time and controllability. Induction heating needs a high-frequency (HF) AC source. The schematic diagram of an induction heating system is shown in Fig. 1. The high frequency currents through the induction coil can be supplied by different types of inverter topologies. The various inverter topologies existing in the literature are resonant inverters [1], half-bridge topologies [2]–[3], full-bridge topologies [4] etc. The output power control of these inverters can be accomplished by techniques such as Asymmetric Duty Cycle (ADC) control, Phase- Shifted PWM control, Load-Adaptive pulse frequency modulation control, Asymmetric Voltage Cancellation (AVC) control, hybrid control and Load Adaptive Frequency Tracking control [5-7] etc. All these proposed controls have their specific merits and demerits. In [8], full bridge inverter configuration has been proposed for multiple-load domestic induction cooking application which can control multiple-loads independently using fixed frequency control. In [9], half bridge inverter with buck boost converter is proposed for multi vessel induction cooking. In this configuration, both half-bridges are operated with fixed switching frequency and the two similar loads are controlled using ADC control technique. The existing inverter topologies are suitable for induction cooking with vessels of ferromagnetic material. However, it would be cost effective and efficient if the inverter topologies are made compatible with non-ferromagnetic vessels also like aluminum and copper. In the literature, reported work is less on this application. Few number of multi-frequency multi-load inverter topologies are available for different metal induction cooking application. The desirable features of these inverters are cost effectiveness, reduced losses, reduced component count, simple structure and also high conversion efficiency. In [10], an inverter topology with two loads is proposed and tested with aluminum and steel vessels. It uses several resonant capacitors connected in parallel with electro-mechanical switches. In [11], a dual frequency full-bridge inverter for all metal induction cooking is proposed, in which asymmetric voltage cancellation control technique is adopted for power control.

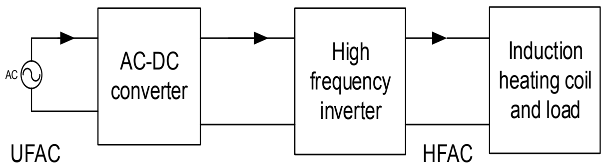

Fig. 1. Schematic representation of HFAC induction heating system

This paper proposes a half bridge based inverter topology with buck-boost converter with independent control of multiple different metal induction cooking loads. It uses pulse frequency control technique and independent load control is achieved. Two loads are supplied by two half bridges whose output is same as that of full bridge topology. Each half bridge supplies a voltage of $2V_{DC}$ to respective resonant load with two different frequencies which is suitable for different metal cooking appliances (ferromagnetic and non-ferro magnetic).

This paper is structured as follows. In section II proposed inverter configuration is described. Pulse frequency control technique is described in section III. In section IV & V, simulation results of proposed resonant inverter configuration and independent control of the loads are presented. Conclusion is presented in section VI.

II. PROPOSED INVERTER CONFIGURATION

Circuit diagram of the proposed inverter configuration is shown in Fig. 2. Among the two legs of the inverter configuration proposed, each leg operates as one half-bridge inverter for particular induction vessel. One half-bridge is used for low frequency material (ferromagnetic) vessel and another half bridge for high frequency (non-ferromagnetic) material vessel. The High frequency half bridge inverter comprises of switches S_1 and S_2 that are operated complementary to each other and low frequency half bridge inverter comprises of switches S_3 and S_4 that are operated complementary to each other. Ferromagnetic (steel) and non-ferromagnetic (aluminum) vessels are used here for induction cooking. High frequency current is used for non-ferromagnetic vessels and low frequency is used for ferromagnetic vessel. From a given dc input of V_{DC}, a voltage with same magnitude of V_{DC} is derived by using buck-boost converter, operated at 50 % duty cycle. The two equal voltages, one from DC source and other from buck-boost converter are used just similar to divided capacitor configuration of half-bridge inverter. Buck-boost converter is used in this configuration to get a total voltage of $2V_{DC}$ across dc link as shown in Fig. 2. The buck-boost converter is operated at low frequency.

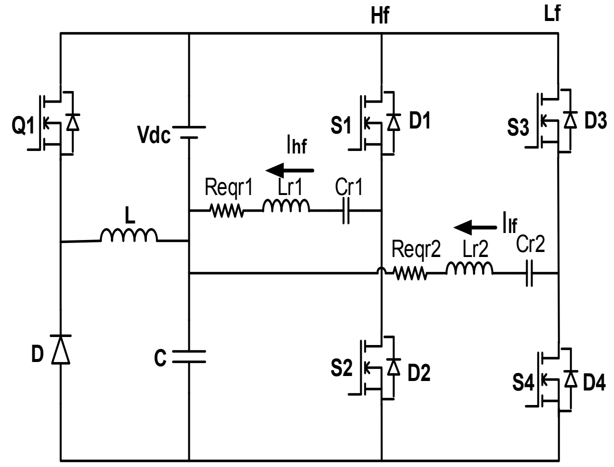

Fig. 2. Proposed dual frequency multi load resonant inverter

Square wave voltages with a magnitude of V_{DC} are generated at the output of two half-bridge inverters and are applied to the two different vessel loads. High frequency load consists of inductance (L_{r1}), equivalent load resistance (R_{eqr1}) and resonant capacitance (C_{r1}), making series resonant tank and is supplied from inverter output voltage V_{ohf}. Similarly, low frequency load consists of inductance (L_{r2}), equivalent load resistance (R_{eqr2}) and resonant capacitance (C_{r2}) respectively making series resonant tank which is supplied from inverter output voltage V_{olf}. Hence in this proposal, both low frequency and high frequency loads are supplied with different powers. The power supplied are as that of full bridge inverter. Each half-bridge works with its own switching frequency with pulse frequency control (PFC) technique. Using PFC, output power of low and high frequency loads are independently controlled

The resonant circuit quality factor and voltage conversion ratio G_{dc} can be expressed as

$$Q = \frac{\sqrt{Lr/Cr}}{R_{eq}} \quad (1)$$

$$G_{dc} = V_O/V_{DC} = \frac{1}{\sqrt{1+Q^2\left(\left(\frac{\omega_s}{\omega_r}\right)-\left(\frac{\omega_r}{\omega_s}\right)\right)2}} \quad (2)$$

Where ω_s represents switching frequency and ω_r represents resonant frequency

$$\omega_r = 2\pi f_o \quad (3)$$

III. PULSE FREQUENCY CONTROL TECHNIQUE

The proposed topology is controlled using pulse frequency control. To control the load power, frequency of that particular leg is varied with maintaining duty cycle constant. In this proposed configuration, load power of each half bridge is controlled and also dc link voltage is maintained constant. The switching pulses and corresponding output powers of high and low frequency legs are shown in Fig. 3(a) and (b) respectively.

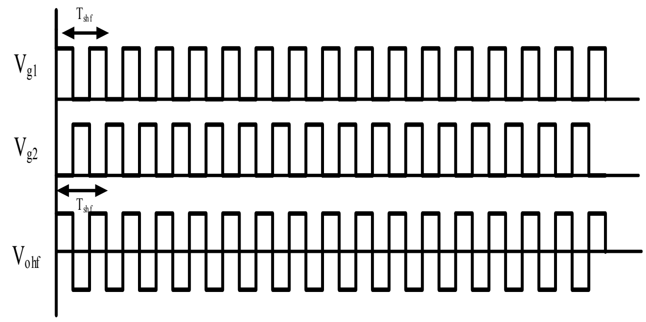

Fig. 3(a). High frequency switching pulses and output voltage

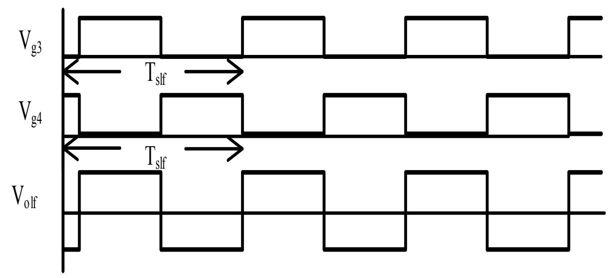

Fig. 3(b). Low frequency switching pulses and output voltage

Here f_{shf} is high switching frequency at leg-1 and T_{shf} is the corresponding time period. Also f_{slf} is low switching frequency at leg-2 and T_{slf} is corresponding time period,

In this PFC, switching frequency is always controlled above the resonant frequency. The low frequency load resonates at f_{rlf} and high frequency load resonates at f_{rhf} and thereby, the switching frequencies of inverter legs are selected above their corresponding resonant frequencies based on admittance curve shown in Fig. 4.

Here $$f_{rhf} = \frac{1}{2\pi\sqrt{Lr1Cr1}} \quad (4)$$

and $$f_{rhf} = \frac{1}{2\pi\sqrt{Lr2Cr2}} \quad (5)$$

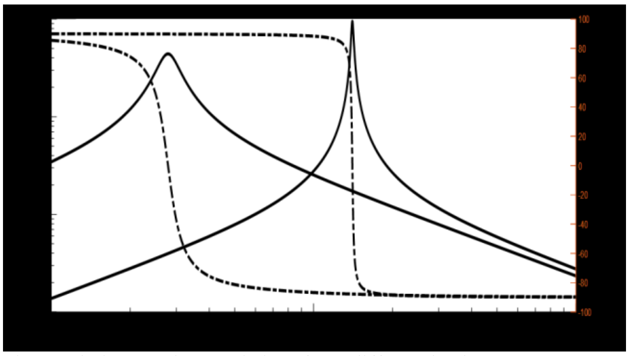

Fig. 4 Admittance characteristics of two different loads

IV. RESULT ANALYSIS

TABLE 1. LOAD PARAMETERS

Parameter	Value
DC Voltage (V_{DC})	115 V
High frequency inductance (L_{r1})	68.1 µH
High frequency vessel equivalent resistance (R_{eqr1})	1.05 Ω
High frequency vessel resonant capacitor (C_{r1})	0.021 uF
Low frequency vessel inductance (L_{r2})	58.8 µH
Low frequency vessel equivalent resistance (R_{req2})	2.27 Ω
Low frequency vessel resonant capacitor (C_{r2})	0.48 uF
High switching frequency (f_{hf})	150 kHz
Low switching frequency (f_{lf})	35 kHz

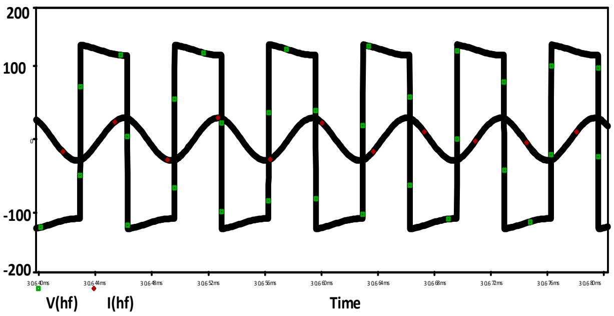

Fig. 5(a). Simulation waveforms of high frequency voltage and current (35 kHz and 150 kHz)

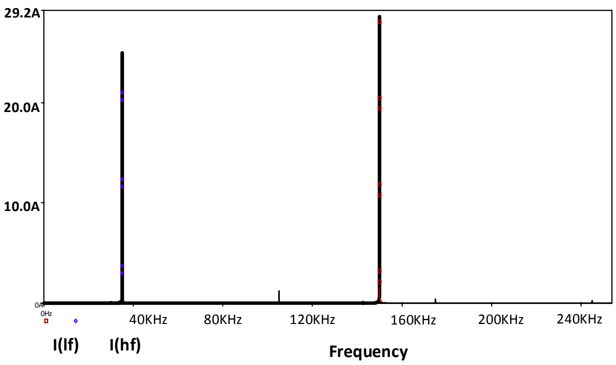

Fig. 5(b). FFT of output currents (35 kHz and 150 kHz)

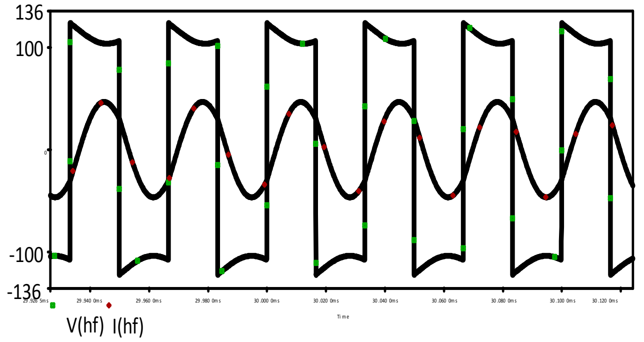

Fig. 6(a). Simulation waveforms of high frequency voltage and current (35 kHz and 155 kHz)

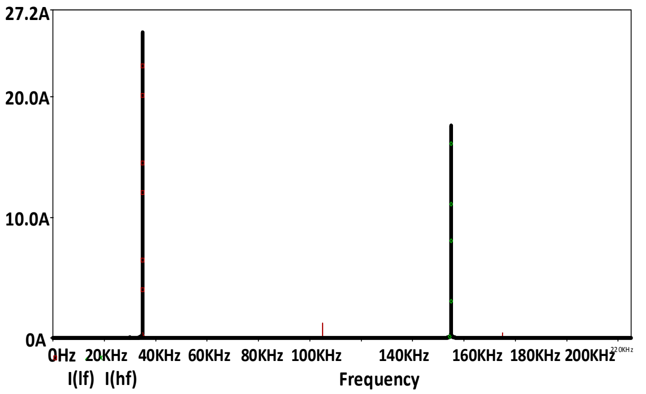

Fig. 6(b). FFT of output currents (35 kHz and 155 kHz)

Proposed resonant inverter with PFC control technique is simulated using OrCAD PSpice. The design parameters are shown in Table 1. This series resonant half bridge configuration is simulated for two different metal vessel induction heating loads. It is operated for a total output power of 2.2 kW with a source voltage of 115 V. The simulations are done for different combinations of high switching frequency f_{hf} and low switching frequency f_{lf}. Corresponding inverter output voltages are V_{ohf} and V_{olf} respectively. High frequency output voltage and current waveforms and FFT of load currents are shown in Figs. 5(a) and (b), when the inverter legs are operated at switching frequencies of 150 kHz and 35 kHz respectively. Figs. 6(a) and (b) show the high frequency output voltage and current waveforms and FFT of load currents, with leg-1 frequency is increased to 155 kHz and leg-2 frequency remains same at 35 kHz. From the FFTs it is observed that the low frequency current remains constant in both cases whereas high frequency current is reduced. Simulation waveforms of low frequency output voltage and current waveforms and FFT of load currents at switching frequencies of 39 kHz, 150 kHz and 40 kHz and 150 kHz are shown in Figs. 7(a), 7(b), 8(a) and 8(b) respectively. FFTs prove that low frequency load current reduces and high frequency load current remains same. This proves independent control of low and high frequency currents.

Total output power (PT) $=P_{ohf}+P_{0lf}$ (6)

where

$$P_{ohf}=I_{r1}^{2}\,R_{eqr1}$$

$$P_{olf}=I_{r2}^{2}\,R_{eqr2}$$

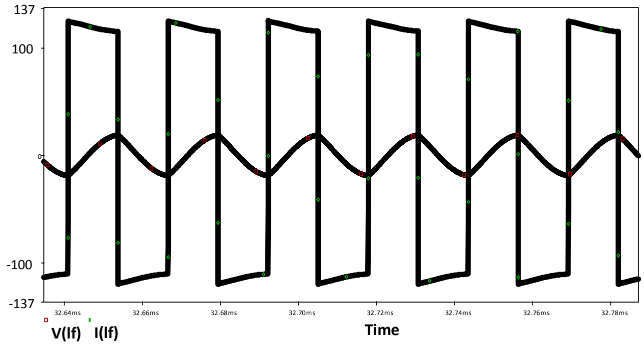

Fig. 7(a).Simulation waveforms of low frequency voltage and current (39 kHz and 150 kHz)

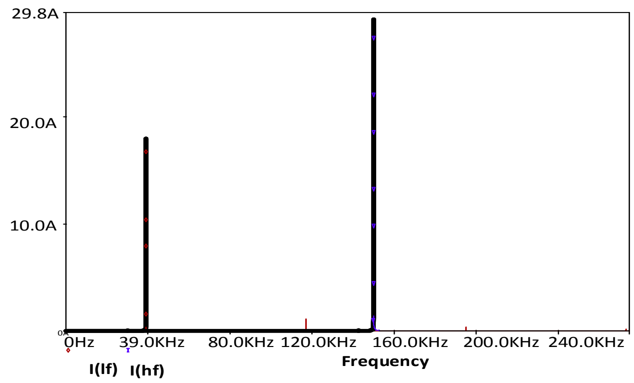

Fig. 7(b).FFT of output currents (39 kHz and 150 kHz)

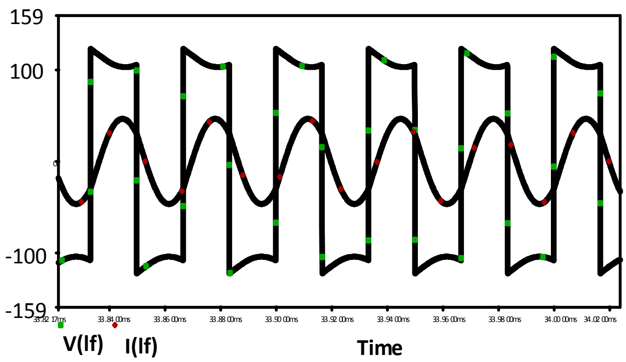

Fig. 8(a). Simulation waveforms of low frequency voltage and current (40 kHz and 150 kHz)

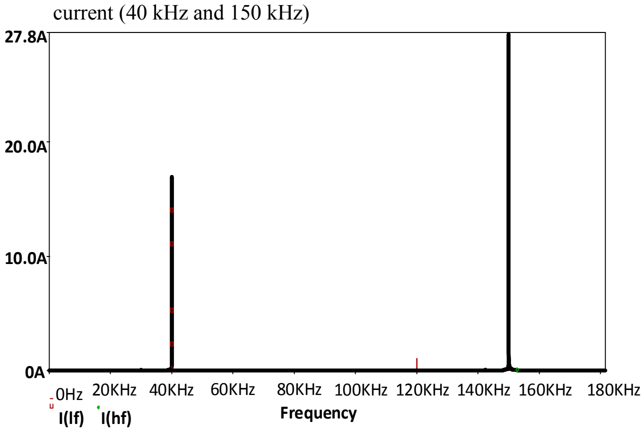

Fig. 8(b). FFT of output currents (40 kHz and 150 kHz)

$$I_{r1}=\frac{Vohf}{Zeq1}$$

$$I_{r2}=\frac{Volf}{Zeq2}$$

$$\text{Inverter efficiency} =\frac{PT}{Pin}$$

Where P_T is total output power and P_{in} is input power.

V. INDEPENDENT OUTPUT POWER CONTROL

Two different material induction cooking loads are controlled using PFC technique. Each load power depends on the corresponding load currents. The load currents are controlled by varying the corresponding switching frequency. In Table 2, different frequency combinations and corresponding load currents and output powers are presented. This load current variation with PFC technique is shown in Figs. 9 and 10. Fig. 9 shows the variation of load currents with low switching frequency when high switching frequency is kept constant at 150 kHz. It is observed that it results in variation of low frequency load current and thereby low frequency vessel load power. Now the high frequency output remains unaffected.

TABLE.2. OUTPUT POWER CONTROL

f_{lf} (kHz)	f_{hf} (kHz)	I_{lf} (A)	I_{hf} (A)	P_{olf} (W)	P_{ohf} (W)
35	**150**	24	27.7	1307.5	**805.6**
35	155	24	15.4	1307.5	249
39	150	16.7	27.7	633.0	805.6
40	**150**	15.2	27.7	**524.4**	**805.6**
40	155	15.2	15.4	**524.4**	249

Fig. 10 shows the variation of load currents with high switching frequency when low switching frequency is kept constant at 35 kHz. It is observed that it results in variation of high frequency load current and thereby high frequency vessel load power. Now the low frequency output remains unaffected. Similarly with both legs frequency variations, simultaneous and independent control of the load currents is also possible.

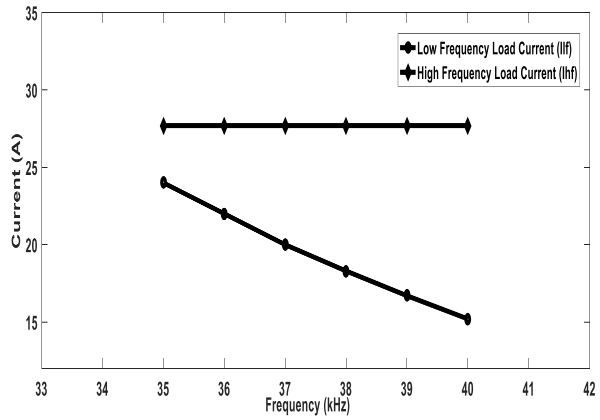

Fig. 9. Load current vs low frequency f_{lf} (f_{hf} = 150 kHz)

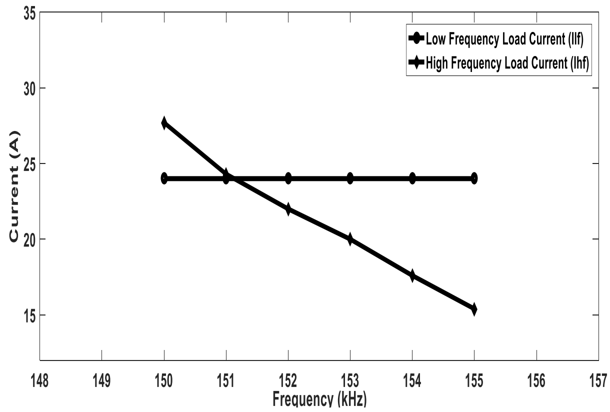

Fig. 10. Load current vs high frequency f_{hf} (f_{lf} = 35 kHz)

VI. Conclusions

In this paper, pulse frequency controlled multi frequency resonant inverter configuration has been proposed for two different material vessels induction cooking application. In this work output power of half-bridge inverter is increased to that of a full-bridge inverter with the help of buck-boost converter. Two different frequency legs are used for the different vessels with switching frequencies of 35 kHz and 150 kHz. Number of switching devices is two per load. Using pulse frequency control technique independent power control of loads is achieved. Overall efficiency of greater than 92% is achieved at full load. This topology provides the advantages of reduced component count, compatibility with different material vessels, independent control and high efficiency.

References

[1] M. K. Kazimierczuk and D. Czarkowski, *Resonant Power Converters*. New York: Wiley, 1995

[2] H. W. Koertzen, J. D. van Wyk, and J. A. Ferreira, "Design of the half bridge series resonant converter for induction cooking," in *Proc. IEEE Power Electronics Specialists Conf. (PESC)*, 1995, pp. 729–735.

[3]] M. Kamli, S. Yamamoto, and M. Abe, "A 50 150 kHz half-bridge inverter for induction heating applications," *IEEE Trans. Ind. Electron.*, vol. 43, no. 1, pp. 163–172, Feb. 1996

[4] S.M.W. Ahmed, M.M. Eissa, M. Edress, T.S. Abdel-Hameed, "Experimental investigation of full-bridge Series Resonant Inverters for Induction-Heating Cooking Appliances", *4th IEEE Conference on Industrial Electronics and Applications*, ICIEA 2009, pp.3327-3332.

[5] J. M. Burdio, L. A. Barragan, F. Monterde, D.Navarro, J. Acero, "Asymmetrical voltage cancellation control for full-bridge series resonant inverters," *IEEE Trans. Power Electronics*, vol. 19, no. 2, 2004, pp. 461-469

[6]Young-Sup Kwon, Sang-Bong Yoo, Dong-Seok Hyun, "Half-Bridge Series Resonant Inverter for Induction Heating Applications with Load-Adaptive PFM Control Strategy", *14th Applied Power Electronics Conference and Exposition*, APEC' 99, vol. 1, 1999, pp. 575-581

[7] Satoshi Nagai, Hirokazu Nagura, Mutsuo Nakaoka, Atsushi Okuno, "High-Frequency Inverter with Phase- Shifted PWM and Load-Adaptive PFM Control Strategy for Industrial Induction-Heating", *Industry Applications Society Annual Meeting*, vol. 3, 1993, pp. 2165-2172.

[8] Sharath Kumar. P, Vishwanathan. N and Bhagwan K. Murthy, "Dual frequency inverter configuration for multiple-load induction cooking application," IET Power Electronics. 2014; ISSN 1755-4535

[9] Sharath Kumar. P, Vishwanathan. N and Bhagwan K. Murthy, "Buck-Boost Interleaved Inverter Configuration for Multiple-Load Induction Cooking Application," J Electr Eng Technol. 2015, 10(1), pp. 271-279.

[10] Atsushi Okuno, Hitoshi Kawano, Junming Sun,Manabu Kurokawa, Akira Kojina, Mutsuo Nakaoka, "Feasible Development of Soft-Switched SIT Inverter with Load-Adaptive Frequency Tracking Control Scheme for Induction Heating," *IEEE Trans. Industry Applications*, vol. 34, no. 4, 1998, pp. 713-718

[11] D Mounika, S Porpandiselvi, V K Satyakar Veeramallu, "Dual Frequency Full-Bridge Inverter for All Metal Induction Heating Cooking Applications," IEEE International Conference on Inventive Computing and Informatics, 2017, pp. 292-296