A Direct AC-AC Multiple Load Inverter for Vessels of Different Materials

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***Abstract*—Induction heating (IH) systems are emerging as an alluring solution to the domestic heating appliances market. Heating multiple loads and loads of different materials is often required. It is challenging to heat ferromagnetic as well non-ferromagnetic materials simultaneously due to their different heating requirements. Classical IH solutions consist of two power conversion stages which reduces the overall efficiency of the system. In order to overcome this, a direct ac-ac multiple load inverter for different materials is proposed in this paper. Dual frequency approach is used to meet different heating requirements of the ferromagnetic and non-ferromagnetic material loads. Asymmetric duty cycle control (ADC) is used to obtain independent control of each load. The performance of the proposed direct ac-ac multiple load inverter is verified by simulations in MATLAB/Simulink environment.**

***Index Terms*—induction heating, soft switching, multiple loads, dual frequency approach, asymmetrical duty cycle**

I. Introduction

Induction heating (IH) systems are gaining popularity in the market primarily due to their advantages over other conventional heating systems [1]. IH systems are highly efficient as the heat will be produced directly into the vessel. IH offer a clean and fast heating solution which is very much desirable in heating applications.

A converter with wide bandwidth and high output power levels is required to implement such IH system [2], [3]. Traditional IH converter consists of two stages namely rectification and inversion [4]–[8]. A full-bridge rectifier with four diodes along with dc link capacitor is used to convert input ac voltage into pure dc voltage. Then a high frequency resonant inverter is used to feed IH loads. Due to more stages of power conversion, such solutions suffer more power loss. This problem can be overcome with direct ac-ac converters which will help in reduced component count and dc link filter requirement. In the literature, ac-ac converter based IH systems are proposed in [9]–[14]. Most of these existing topologies are suitable for single IH load and only for ferromagnetic loads.

In this paper, a direct ac-ac converter for multiple loads is proposed for different material IH loads. The proposed converter offers high efficiency due to reduction in conversion stage and reduced component count per load. In the proposed topology, MOSFETs are used for control in positive and negative half cycles whereas, diodes are used in the existing topologies. Existing ac-ac inverter topologies use two diodes to obtain control over positive and negative cycles of ac supply voltage. Due to higher current requirements of IH systems, the losses in the diodes are high which leads to reduced efficiency. To overcome this problem, in this paper MOSFETs are used which reduces the losses significantly and increases the overall efficiency of the system.

Ferromagnetic and non-ferromagnetic loads have different heating requirements. The resistances offered by these loads are varying with frequency. Non-ferromagnetic materials offer very low resistance at lower frequency range while ferromagnetic material offers high resistance in that range. So, ferromagnetic material can be heated at low range of frequencies typically of 20 kHz-30 kHz but non-ferromagnetic materials require higher frequency operation typically in the range of 100 kHz-200 kHz. In order to heat these two different material, dual frequency approach is used in this paper. The concept of variable impedance of inductor and capacitor is used to heat loads at different frequencies. Asymmetric duty cycle (ADC) control is used to obtain independent control of different loads.

II. Proposed ac-ac inverter configuration

Fig. 1 shows circuit of the proposed ac-ac multi-load inverter. It uses two full-bridges which are powered respectively during positive and negative half cycles of the supply voltage. Switches S_1, S_2, S_3 and S_4 constitute one full-bridge which is powered in positive half cycle while S_5, S_6, S_7 and S_8 constitute another bridge which is powered during negative half cycle. Switch S_p will conduct during positive half cycle

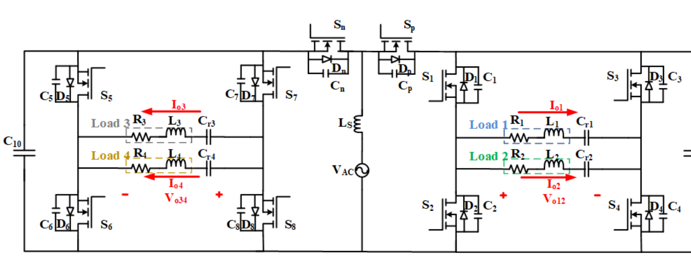

Fig. 1. Proposed ac-ac multi-load inverter

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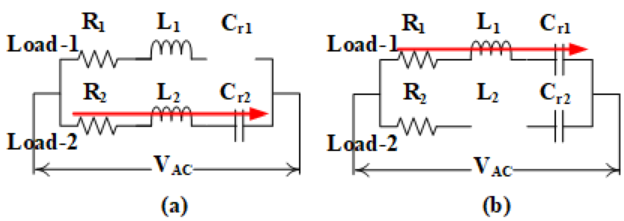

Fig. 2. Principle of operation

to power the first bridge and switch S_n will conduct during negative half cycle to power the second bridge. Induction heating load which is the combination of IH coil and the vessel, can be modelled as series combination of R and L. Where R and L are equivalent resistance and inductance of IH load as seen from the IH coil. R_1, R_2, R_3 and R_4 are equivalent resistances of the four IH loads respectively. L_1, L_2, L_3 and L_4 are equivalent inductances of the four IH loads respectively. Resonant capacitors C_{r1}, C_{r2}, C_{r3} and C_{r4} are selected to resonate the four IH loads at respective frequencies. The indicated conventions of voltages and currents in Fig. 1 are taken as reference for further analysis.

A. Principle of operation

Impedances offered by inductors and capacitors are variable with operating frequencies. At higher frequencies, inductors offer high impedance and may behave as open circuit. Capacitors offer high impedance at low frequencies and may act as open circuit. This principle is used to obtain control over current flowing through magnetic and non-magnetic loads. Load-1 and Load-3 are non-magnetic IH loads. Load-2 and Load-4 are ferromagnetic IH loads. C_{r1} and C_{r3} are equal and are selected to resonate Load-1 and Load-3 at higher frequency. C_{r1} and C_{r4} are equal and are selected to resonate Load-2 and Load-4 at lower frequency. C_{r1} and C_{r2} are selected such that $C_{r1} << C_{r2}$. At lower ranges of frequencies, resonant capacitor C_{r1} will offer very high impedance and do not allow current flow through Load-1. Now, load-2 offers low impedance and allows low frequency currents as shown in Fig. 2(a). At higher frequencies, L_2 will offer very high impedance which restrains current from flowing through the Load-2 branch and it passes through Load-1 as shown in Fig. 2(b).

Ferromagnetic load is resonated at lower frequency. Non-ferromagnetic load is resonated at higher frequency as it offers high resistance at higher frequencies which facilitates in developing more heat in the vessel. Dual frequency voltage components across each bridge are obtained by operating each leg of full-bridge at different frequencies. As per the principle explained above, high frequency currents will pass through the non-ferromagnetic load and low frequency currents will flow through the ferromagnetic load and produce heat in the respective vessels.

B. Modes of operation and control

In order to obtain dual-frequency voltage component across full-bridge, the legs are operated at different frequencies. The inverter leg comprising of S_1 and S_2 is operated at lower frequency while that of S_3 and S_4 is operated at higher frequency. The switching frequencies are selected slightly higher than that of the corresponding resonant frequencies to ensure ZVS operation. The switching pulses and output voltage waveforms are shown in Fig. 3. When S_1-S_3 or S_2-S_4 are ON, voltage across the bridge, V_{o12} will be zero. With S_1 and S_4 ON, positive voltage will appear across the bridge. Negative voltage across the bridge is obtained with S_2 and S_3 are ON.

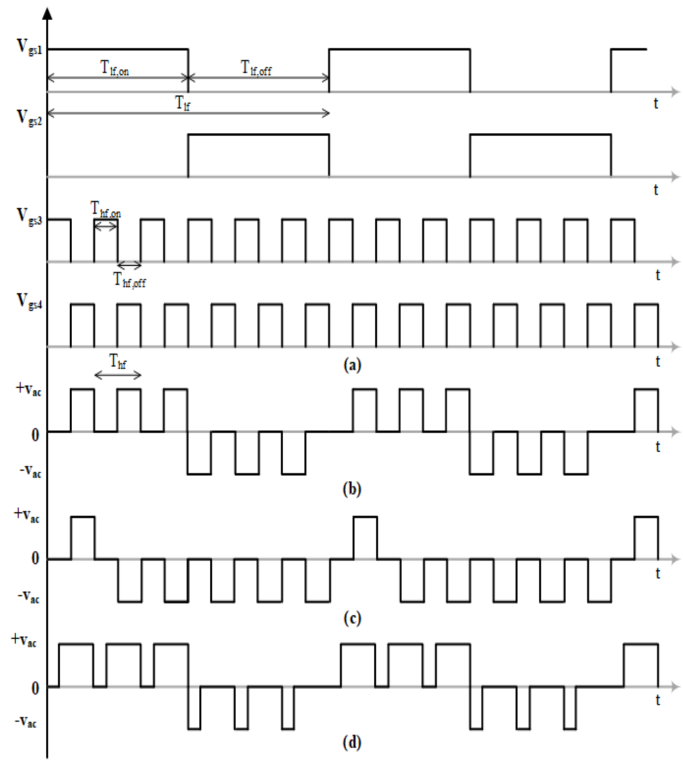

Fig. 3. Key Waveforms of the proposed ac-ac multiple load inverter, (a) low frequency and high frequency gate pulses, (b) voltage across loads when both the loads are operated at full duty cycles, (c) Load voltage at $D_{lf} = 0.5$ and $D_{hf} = 1$, (d) Load voltage at $D_{lf} = 1$ and $D_{hf} = 0.5$

ADC control is used to control powers in the individual loads. Duty cycle for controlling power of low frequency load,

$$D_{lf} = \frac{T_{lf,on}}{T_{lf}/2} \qquad (1)$$

Similarly, duty cycle for controlling power of high frequency operated load,

$$D_{hf} = \frac{T_{hf,on}}{T_{hf}/2} \qquad (2)$$

Where, T_{lf} and $T_{lf,on}$ are respectively the time period and ON duration of low frequency gate pulse. T_{hf} and $T_{hf,on}$ are respectively the time period and ON duration of high frequency gate pulse. The variation range for $T_{lf,on}$ and $T_{hf,on}$ are $0 \leq T_{lf,on} \leq T_{lf}/2$ and $0 \leq T_{hf,on} \leq T_{hf}/2$ respectively. The Output voltage waveform at full power operation of both the loads is shown in Fig. 3(b). Fig. 3(c) and Fig. 3(d) show output

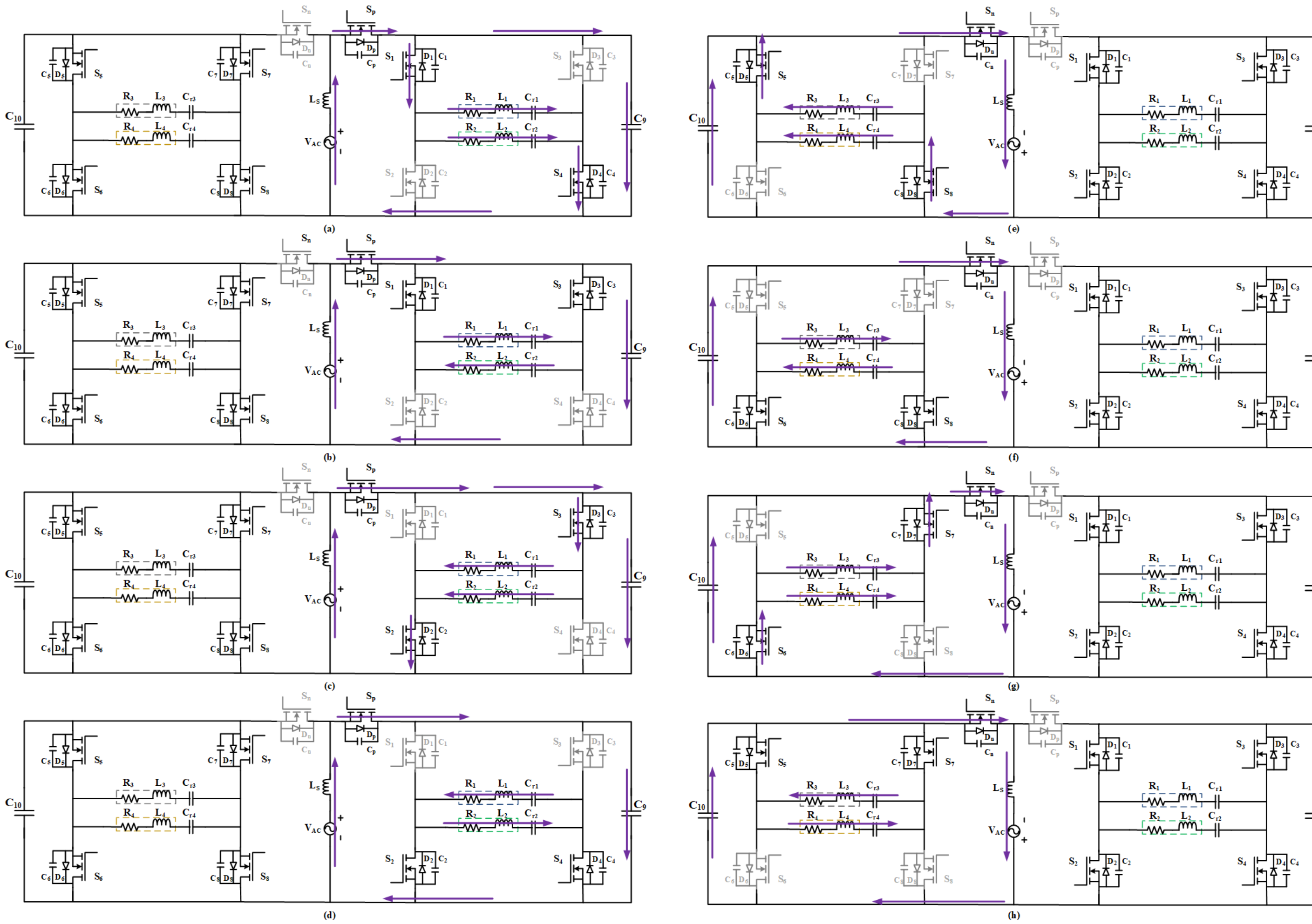

Fig. 4. Modes of operation, (a) to (d) operation during positive half cycle of ac mains, (e) to (h) operation during negative half cycle of ac mains

voltage waveform across the bridge for D_{lf} = 0.5, D_{hf} = 1 and D_{hf} = 0.5, D_{lf} = 1 respectively.

The complete operation of the proposed inverter is depicted in Fig. 4. Fig. 4(a) to Fig. 4(d) show operation of the proposed circuit during positive half cycle of the ac input, V_{AC} with switch S_p is ON. As shown in Fig. 4(a), both the loads are powered when switches S_1, S_4 are ON while S_2, S_3 being OFF. With only S_1 and S_3 are ON, load currents will freewheel in a loop as shown in Fig. 4(b). The voltage polarity across the loads will be reversed when only S_2 and S_3 are ON. Both the loads will be powered in the opposite direction as shown in the Fig. 4(c). With only S_2 and S_4 are ON, the load currents will freewheel in a loop as shown in Fig. 4(d).

Fig. 4(e) to Fig. 4(h) show the operation of the proposed circuit during negative half cycle of the ac input, V_{AC} with switch S_n is ON. As shown in Fig. 4(e), both the loads are powered when switches S_5, S_8 are ON while S_6, S_7 being OFF. With only S_6 and S_8 ON, loads will freewheel in a loop as shown in Fig. 4(f). The voltage polarity across the loads will be reversed when only S_6 and S_7 are ON. Both the loads will be powered in the opposite direction as shown in the Fig. 4(g). With only S_5 and S_7 ON, the loads will freewheel in a loop as shown in Fig. 4(h). The pair of Load-1 and Load-2 are powered only during positive half cycle of the AC input while Load-3 and Load-4 are powered only during negative half cycle of the AC input.

C. Output Power Expression

The output power expression for the proposed ac-ac inverter can be expressed as

$$P_o = \sum_{n=0}^{\infty} I_{o,n}^2 R_{eq} = \sum_{n=0}^{\infty} \frac{V_{o,n}^2}{Z_{o,n}^2} R_{eq} \quad (3)$$

where, n is the harmonic order, $I_{o,n}$ is the load current, $V_{o,n}$ is the output voltage of the inverter, $Z_{o,n}$ is the impedance of the $R_{eq} - L_{eq} - C_r$ load. At resonance, considering only fundamental component, the output power expression can be written as

$$P_o = I_{o,rms}^2 R_{eq} \quad (4)$$

Where, $I_{o,rms}$ is the rms value of the load current. The ouput power expression for HB-SRI is derived in [15]. The output

TABLE I
PARAMETERS OF THE PROPOSED AC-AC INVERTER

Component	***Value***
Supply volage	230V
IH Load-1 and Load-3 equivalent series resistance, R_1 & R_3	2.09 Ω
IH Load-1 and Load-3 equivalent series inductance, L_1 & L_3	4.4 μH
IH Load-1 and Load-3 equivalent series resonant capacitors, C_{r1} & C_{r3}	0.1 μF
IH Load-2 and Load-4 equivalent series resistance, R_2 & R_4	2.05 Ω
IH Load-2 and Load-4 equivalent series inductance, L_2 & L_4	10.9 μH
IH Load-2 and Load-4 equivalent series resonant capacitors, C_{r2} & C_{r4}	3 μF
Switching frequencies for two different legs of each full-bridge	150 kHz, 30 kHz

power of the full-bridge inverter operated in dual frequency mode is the combination of the output powers of individual half bridge inverters [16]. So, the total output power delivered to the loads can be given as

$$P_o = \frac{(1-\cos 2\pi D_{hf})}{2\pi^2}\frac{R_1 V_{ac}^2}{[R_1^2+(2\pi f_{hf}L_1-\frac{1}{2\pi f_{hf}C_{r1}})^2]} + \frac{(1-\cos 2\pi D_{lf})}{2\pi^2}\frac{R_2 V_{ac}^2}{[R_2^2+(2\pi f_{lf}L_2-\frac{1}{2\pi f_{lf}C_{r2}})^2]} \quad (5)$$

Where, V_{ac} is the rms value of the input supply, f_{hf} is the high frequency and f_{lf} is the low frequency.

III. SIMULATION RESULTS

The proposed ac-ac inverter for multiple loads is simulated for parameters mentioned in Table I. The proposed inverter is used to power four loads, each full-bridge powering two different material loads. Load-1 and Load-3 are two similar aluminium vessels and Load-2 and Load-4 are two similar steel vessels. Aluminium and steel vessel loads are resonated at 27.27 kHz and 227.27 kHz respectively with suitable values of resonant capacitors. The quality factor for the series R-L-C load is given as $Q = \omega_0 L/R$. The Q factor for aluminium vessel load is $Q_{al} = 3$ and steel vessel load is $Q_{steel} = 1$. Switching frequencies are chosen slightly higher than resonant frequencies to ensure zero voltage switching in the devices. One leg of each full-bridge is operated at 30 kHz and another leg is operated at 250 kHz.

TABLE II
PERFORMANCE OF THE PROPOSED INVERTER

P1	P2	P3	P4	THD(%)
133.76 W	1028.61 V	690 W	480.51 W	1.4
924.69 W	484.28 V	677.91 W	1113.88 W	5.12
385.43 W	1047.06 V	384.86 W	820 W	3.9
1003.3 W	1108.15 V	1003.3 W	1108.15 W	0.29

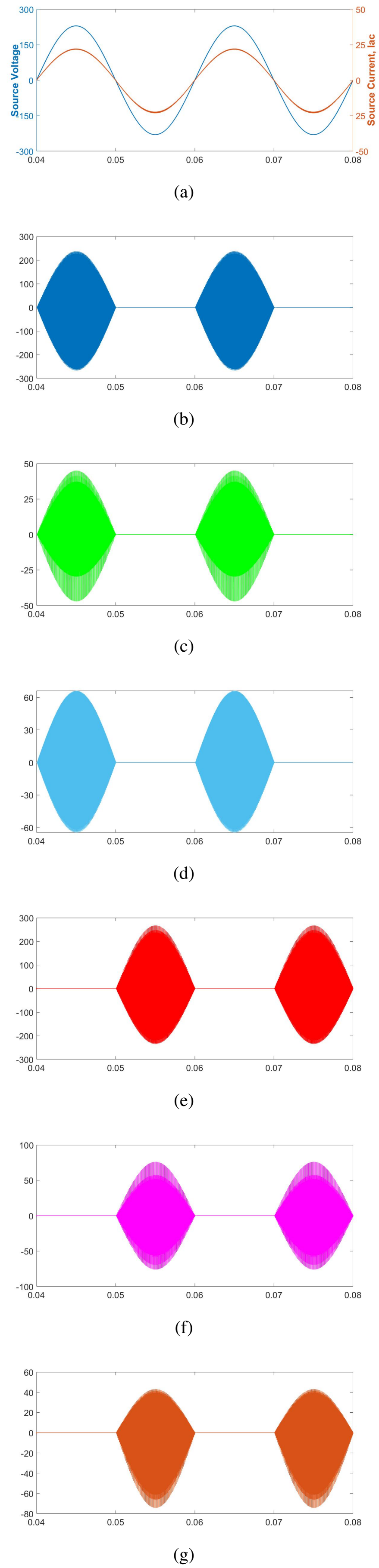

Fig. 5. Simulation results for variable load operation, (a) source voltage and source current, (b) V_{o12},voltage across Load-1 and Load-2, (c) I_{o1}, current through Load-1, (d) I_{o2}, current through Load-2, (e) V_{o34}, voltage across Load-3 and Load-4, (f) I_{o3}, current through Load-3, (g) I_{o4} current through Load-4

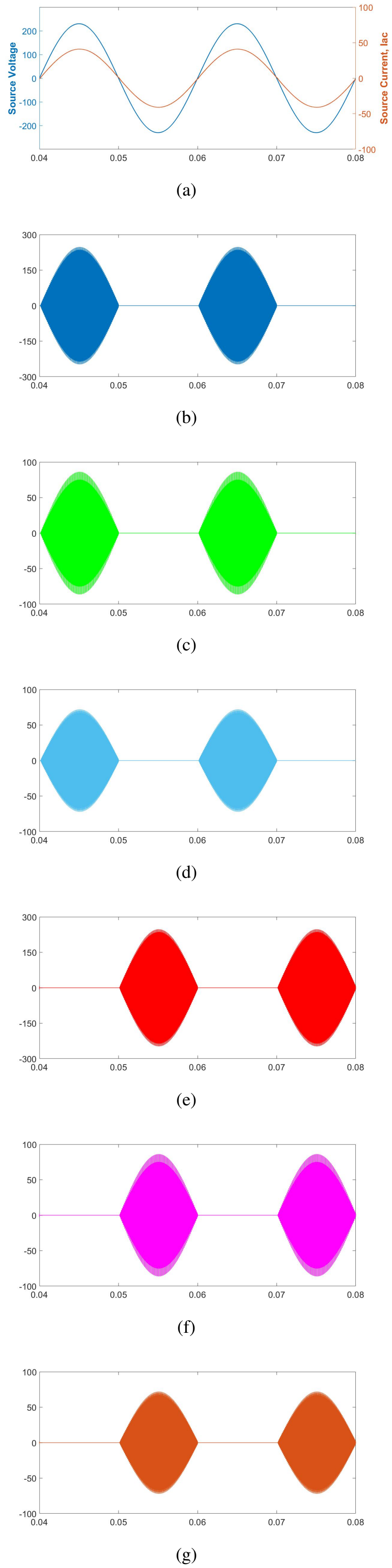

Fig. 6. Simulation results for full load operation, (a) source voltage and source current, (b) V_{o12},voltage across Load-1 and Load-2, (c) I_{o1}, current through Load-1, (d) I_{o2}, current through Load-2, (e) V_{o34},voltage across Load-3 and Load-4, (f) I_{o3}, current through Load-3, (g) I_{o4} current through Load-4

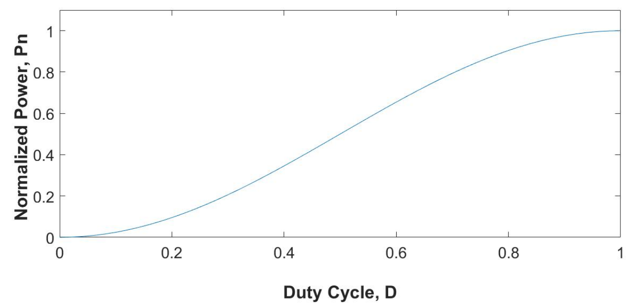

Fig. 7. Variation of the output power with the duty cycle

The operation of the proposed inverter at variable duty cycle is shown in Fig. 5. Load-1 is powered at 133.76 W with 20% duty cycle, Load-2 is powered at 1028.87 W with 80% duty cycle, Load-3 is powered at 690 W with 60% duty cycle and Load-4 is powered at 480.5 W with 40% duty cycle. Fig. 5(a) shows the source voltage and the source current waveforms. Total harmonic distortion in the source current is 1.4% for the considered variable load condition. Fig. 5(b) shows voltage across Load-1 and Load-2. Currents of 8 A and 22.4 A flows through Load-1 and Load-2 respectively as shown in Fig. 5(c) and Fig. 5(d). Fig. 5(e) shows voltage across Load-3 and Load-4. Currents of 18.17 A and 15.31 A flows through Load-3 and Load-4 respectively as shown in Fig. 5(f) and Fig. 5(g).

Fig. 6 limns the full load operation for all the four loads. Load-1, Load-3 are powered at 1003.3 W and Load-2, Load-4 are powered at 1108.15 W at full duty cycle operation. Fig. 6(a) shows the source voltage and the source current waveforms. Total harmonic distortion in the source current is 0.29% for the considered full load condition. Fig. 6(b) shows voltage across Load-1 and Load-2. Currents of 21.91 A flows through Load-1 and Load-3 as shown in Fig. 6(c) and Fig. 6(f). Fig. 6(e) shows voltage across Load-3 and Load-4. Currents of rms value 23.25 A flows through Load-2 and Load-4 as shown in Fig. 6(d) and Fig. 6(g). The performance of the proposed inverter for different load condition is shown in Table II. The normalized output power with the duty cycle variation is shown in Fig. 7. The normalized output power has been defined as $P_n = P_o R_{eq}/V_{ac}^2$. The output power is maximum for duty cycle D=1.

Conclusions

In this paper, a direct ac-ac multiple load inverter for vessels of different material is proposed. Different heating requirements of ferromagnetic and non-ferromagnetic loads is met by using dual frequency approach. Four loads can be simultaneously powered as well as independently controlled using this proposed inverter. ADC control is used to gain independent control over four loads. The proposed inverter is tested for powering four different loads at 1 kW each simultaneously. The operation of the proposed ac-ac multiple loads for different loads is tested and verified by performing simulations in MATLAB/Simulink enviornment. Use of two

MOSFETs to power two bridges during positive and negative cycles independently reduces the losses in the inverter significantly when compared to that of two diodes approach typically used in ac-ac topologies. The proposed inverter maintains a good input current profile during the entire range of power control of IH loads.

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References

[1] O. Lucía, P. Maussion, E. J. Dede, and J. M. Burdío, "Induction heating technology and its applications: past developments, current technology, and future challenges," *IEEE Transactions on industrial electronics*, vol. 61, no. 5, pp. 2509–2520, 2013.

[2] J. Acero, J. Burdio, L. Barragan, D. Navarro, R. Alonso, J. Ramon, F. Monterde, P. Hernandez, S. Llorente, and I. Garde, "Domestic induction appliances," *IEEE Industry Applications Magazine*, vol. 16, no. 2, pp. 39–47, 2010.

[3] H. Sarnago, O. Lucia, A. Mediano, and J. M. Burdio, "Modulation scheme for improved operation of an rb-igbt-based resonant inverter applied to domestic induction heating," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 2066–2073, 2012.

[4] H. N. Pham, H. Fujita, K. Ozaki, and N. Uchida, "Dynamic analysis and control for resonant currents in a zone-control induction heating system," *IEEE Transactions on Power Electronics*, vol. 28, no. 3, pp. 1297–1307, 2012.

[5] I. Yilmaz, M. Ermis, and I. Cadirci, "Medium-frequency induction melting furnace as a load on the power system," *IEEE Transactions on Industry Applications*, vol. 48, no. 4, pp. 1203–1214, 2012.

[6] J. Egalon, S. Caux, P. Maussion, M. Souley, and O. Pateau, "Multiphase system for metal disc induction heating: Modeling and rms current control," *IEEE Transactions on industry applications*, vol. 48, no. 5, pp. 1692–1699, 2012.

[7] D. Vijaya Bhaskar, N. Vishwanathan, T. Maity, and S. Porpandiselvi, "Hybrid controlled dual frequency inverter for two load induction cooking application," *EPE Journal*, vol. 27, no. 2, pp. 60–73, 2017.

[8] S. Khatroth and P. Shunmugam, "Cascaded full-bridge resonant inverter configuration for different material vessel induction cooking," *IET Power Electronics*, vol. 13, no. 19, pp. 4428–4438, 2020.

[9] A. Trentin, P. Zanchetta, J. Clare, and P. Wheeler, "Automated optimal design of input filters for direct ac/ac matrix converters," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 7, pp. 2811–2823, 2011.

[10] H. L. Li, A. P. Hu, and G. A. Covic, "A direct ac–ac converter for inductive power-transfer systems," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 661–668, 2011.

[11] X. Lie, J. C. Clare, P. W. Wheeler, L. Empringham, and L. Yongdong, "Capacitor clamped multilevel matrix converter space vector modulation," *IEEE Transactions on industrial electronics*, vol. 59, no. 1, pp. 105–115, 2011.

[12] T. Wijekoon, C. Klumpner, P. Zanchetta, and P. W. Wheeler, "Implementation of a hybrid ac–ac direct power converter with unity voltage transfer," *IEEE Transactions on power electronics*, vol. 23, no. 4, pp. 1918–1926, 2008.

[13] H. Sarnago, O. Lucia, A. Mediano, and J. M. Burdio, "Direct ac–ac resonant boost converter for efficient domestic induction heating applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1128–1139, 2013.

[14] H. Sarnago, Ó. Lucía, M. Pérez-Tarragona, and J. M. Burdío, "Dual-output boost resonant full-bridge topology and its modulation strategies for high-performance induction heating applications," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 6, pp. 3554–3561, 2016.

[15] H. Sarnago, O. Lucia, A. Mediano, and J. M. Burdio, "Direct ac–ac resonant boost converter for efficient domestic induction heating applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1128–1139, 2013.

[16] S. K. Papani, V. Neti, and B. K. Murthy, "Dual frequency inverter configuration for multiple-load induction cooking application," *IET Power Electronics*, vol. 8, no. 4, pp. 591–601, 2015.