Three-load Cyclic Controlled Single-Stage AC-AC Resonant Converter for Induction Cooking Applications

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2021 IEEE 2nd International Conference on Smart Technologies for Power, Energy and Control (STPEC) | 978-1-6654-4319-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/STPEC52385.2021.9718631

***Abstract*—This paper presents single-stage AC-AC resonant converter for three load induction cooking (IC) applications. The proposed work features power factor correction, boost operation and independent power control of loads. In this work cyclic control technique is used for independent power control. Three legs of the inverter are used to power three loads. Number of switching devices per load is two. ZVS operation is achieved for load variation of wider range and high converter is obtained. The developed approach has fewer components and uses one leg per load on average. It may also be expanded to accommodate more than three loads.**

***Index Terms*—Single-stage, Resonant converter, multiple load, Induction cooking.**

I. Introduction

Induction Heating (IH) is widely used in domestic cooking applications compared to other conventional heating methods due to compatibility, controllability, reliability and environmental friendly. In literature, various converter configurations are proposed [1]–[3], like multi-stage and single-stage converter topologies for single load and multiple load IC applications. Multi-stage multiple load resonant inverter configurations are popular [4], [5] due less component count, high efficiency and independent control. Power control of these configurations are achieved through pulse frequency modulation, asymmetric duty cycle control (ADC), asymmetric voltage cancellation, phase shift control (PS) and pulse density modulation (PDM) [6]–[10] and other different control techniques. These control techniques have there own advantages and limitations. In the past literature, most of the single-stage converter configurations available are suitable for single load IC applications. Few single-stage converter topologies are proposed for multiple-load IC applications. These multi load configurations are well suitable for domestic induction cooking due to unity power factor, boost operation and high efficiency [11]–[16]. These converter configurations have there own merits and demerits. In [17], a direct ac-ac matrix converter is used to supply multiple IH but this has a drawback of increased current harmonics. A multi-phase resonant inverter with vertically aligned coupled coil [18] improves power capability of the system with phase shift control.

In this paper, a three leg cyclic controlled single-stage resonant ac-ac converter configuration is proposed which is suitable for three IH loads. These loads are connected across the three legs in delta manner. Independent power control of respective load is achieved by 'cyclic control'. In this technique, On-Off of inverter legs are connected in cyclic way. The benefits that can be drawn from this converter are bridge less rectifier, unity power factor, boost operation and reduced number of legs per load. Independent control of three loads is also provided.

II. Proposed configuration

A. Circuit Description

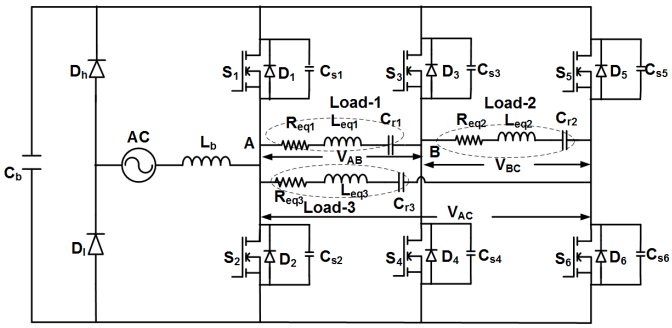

Fig. 1. Circuit diagram of single-stage three load converter

Single-stage resonant converter configuration has been proposed for three load domestic IC application. The circuit diagram of proposed converter is shown in Fig.1. The converter structure consists of a boost inductor L_b, and a small value of dc link capacitor C_b linked in such a manner that the utility frequency source voltage V_s is increased. v_b is the voltage across dc-link capacitor C_b. Diodes D_h and D_l form the rectifier branch and three legs of the resonant inverter supply power to three loads. Leg-1 switching devices S_1, S_2 and

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their anti parallel diodes D_1 and D_2 supply power to load-1. The parameters of load-1 are equivalent resistance R_{eq1} and equivalent inductance L_{eq1}. In order to resonate the load, external resonant capacitor C_{r1} is selected in such a way to make resonant load little inductive. Hence ZVS operation is achieved with snubber capacitor C_{s1} and C_{s2}. Leg-2 switches S_3, S_4 and their anti parallel diodes D_3 and D_4 supply power to load-2. The parameters of load-2 are equivalent resistance R_{eq2} and equivalent inductance L_{eq2}. In order to resonate the load, external resonant capacitor C_{r2} is selected in such a way to make resonant load little inductive. Hence ZVS operation is achieved with snubber capacitor C_{s3} and C_{s4}. Leg-3 switches S_5, S_6 and their anti parallel diodes D_5 and D_6 supply power to load-3. The parameters of load-3 are equivalent resistance R_{eq3} and equivalent inductance L_{eq3}. In order to resonate the load, external resonant capacitor C_{r3} is selected in such a way to make resonant load little inductive. Hence ZVS operation is achieved with snubber capacitor C_{s5} and C_{s6} IH loads are connected in delta manner with three legs of the resonant converter.

III. Modes of Operation

A. Cyclic control

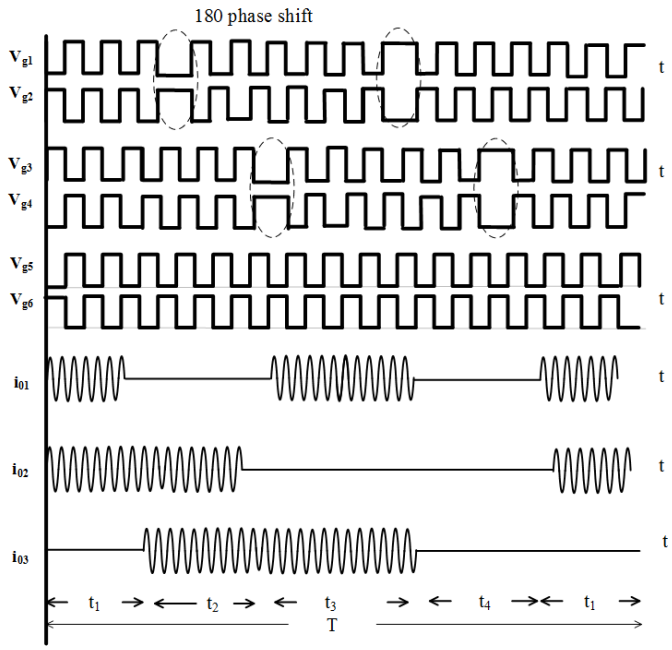

Fig. 2. Control pulses and load current waveforms

Operation of the proposed converter configuration is explained through eight modes based on the output voltage. Three loads are considered. T is the opeartion period. This period is divided into four intervals t_1, t_2, t_3 and t_4. Hence T= t_1+t_2+t_3+t_4.

Mode-1: Switching pulses to S_1, S_4 and S_5 are in phase and this operation is shown in Fig.3a. Time interval of this mode is t_1. During this interval voltage across load-1 and load-2 are V_b and voltage across load-3 is zero.

Mode-2: Switching pulses to S_2, S_4 and S_5 are in phase and this operation is shown in Fig.3b. Time interval of this mode is t_2. During this interval voltage across load-2 and load-3 are V_b and voltage across load-1 is zero.

Mode-3: Switching pulses to S_2, S_3 and S_5 are in phase and this operation is shown in Fig.3c. Time interval of this mode is t_3. During this interval voltage across load-1 and load-3 are V_b and voltage across load-2 is zero.

Mode-4: Switching pulses to S_1, S_3 and S_5 are in phase and this operation is shown in Fig.3d. Time interval of this mode is t_4. During this interval voltage across load-1, load-2 and load-3 is zero.

load-1 total powering time = t_1 +t_2
load-2 total powering time = t_2 +t_3
load-3 total powering time = t_1 +t_3

Depending on the power requirement of the different loads, there may be an interval 't_4' (mode-4) when none of the loads is powered. As a result, two loads are powered simultaneously while the third load receives no power. This procedure is performed in a cyclic pattern. Hence, this approach is known as 'cyclic control,' and it is depicted in Fig.2.

Average power supplied to the loads are expressed through equations (1)-(6) [16]

$$Average\ power\ of\ load-1\ , P_1 = \frac{t_1+t_2}{T}P_{max} \quad (1)$$

$$Average\ power\ of\ load-2\ , P_2 = \frac{t_2+t_3}{T}P_{max} \quad (2)$$

$$Average\ power\ of\ load-3\ , P_3 = \frac{t_1+t_3}{T}P_{max} \quad (3)$$

Load power during t_4, P_4 = zero

$$P_1{+}P_2{+}P_3{+}P_4 = \frac{t_1+t_2}{T}P_{max}{+}\frac{t_2+t_3}{T}P_{max}{+}\frac{t_1+t_3}{T}P_{max} \quad (4)$$

$$P_1+P_2+P_3+P_4 = \frac{t_1+t_2+t_2+t_3+t_1+t_3}{T}P_{max} \quad (5)$$

At specific instant, when t_1=t_2=t_3 then load powers are equal P_1 =P_2=P_3=P_l and t_1+t_2+t_3=T

$$P_l = \frac{2}{3}P_{max} \quad (6)$$

TABLE I
Simulation Circuit Parameters

Parameter	Value
AC input voltage (V_s)	50 V
Boost inductor	400 uH
dc-link capacitor	6.8 uF
IC load equivalent inductance (L_1,L_2,L_3)	62.03 uH
IC load equivalent resistance (R_1,R_2,R_3)	2.22 Ω
Load resonant capacitor (C_{r1},C_{r2},C_{r3})	1.205 uF
switching frequencys of legs (f_s)	50 kHz
IH load resonant frequency(f_{rl})	48.5 kHz
Snubber capacitors	2 nF

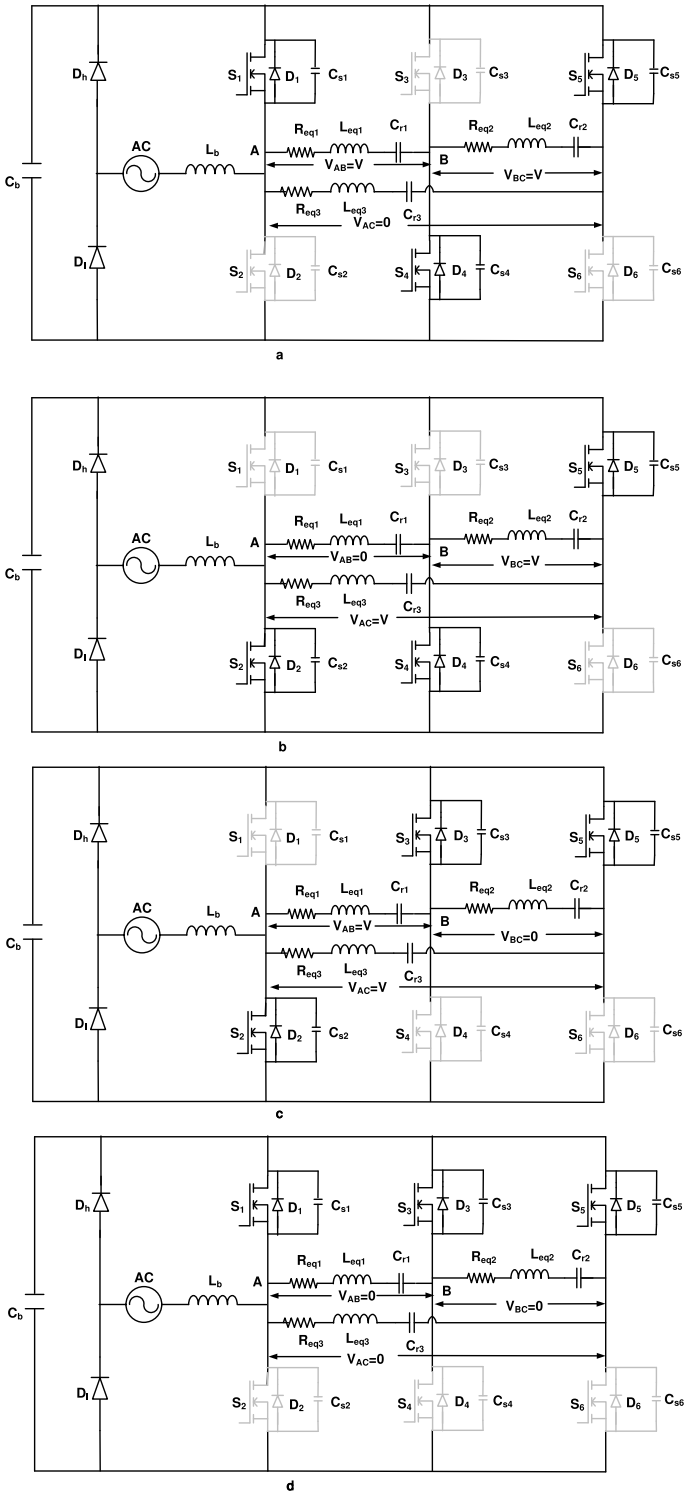

Fig. 3. Equivalent circuits For V_s>0 (Positive half cycle)
(a) Mode-1 v_{g1}, v_{g4} and v_{g5} are in phase
(b) Mode-2 v_{g2}, v_{g4} and v_{g5} are in phase
(c) Mode-3 v_{g2}, v_{g3} and v_{g5} are in phase
(d) Mode-4 v_{g1}, v_{g3} and v_{g5} are in phase

IV. SIMULATION WAVEFORMS

Simulation results of the proposed single-stage three leg converter configuration for three IC loads are shown in Fig.4 to Fig.17. Individual load duty cycles are calculated based on load power requirement. Fig.4 shows source voltage and soucre current wavefroms. From this figure it is observed that supply power factor is unity. Fig.5 to Fig.7 depict the simulation results with equal output powers of P_1 = 316 W, P_2 = 316 W, and P_3 = 316 W. From the time periods t_1, t_2, t_3, and t_4, the duty cycles of the loads are computed as d_1 =0.95, d_2 = 0.95, and d_3 = 0.95. Fig.8 shows the zoomed waveforms of all three load voltages and load currents. The

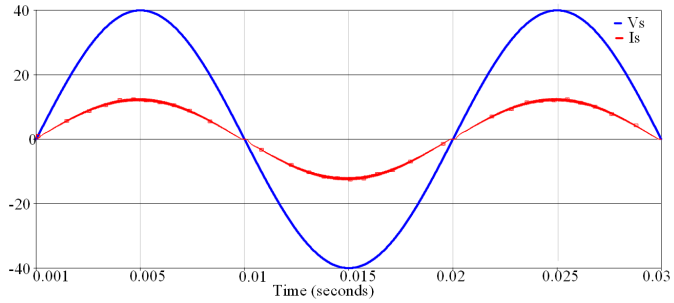

Fig. 4. Source Voltage(V_s) and Source Current (I_{02})

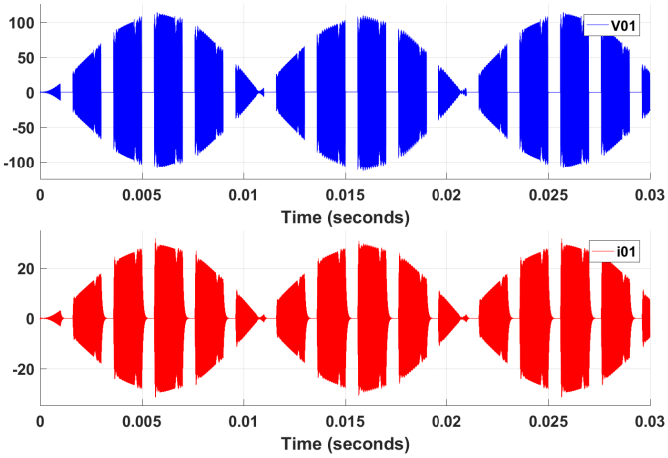

Fig. 5. Load-1 Voltage (V_{01}) and Current (I_{01}) at D_1= 0.95

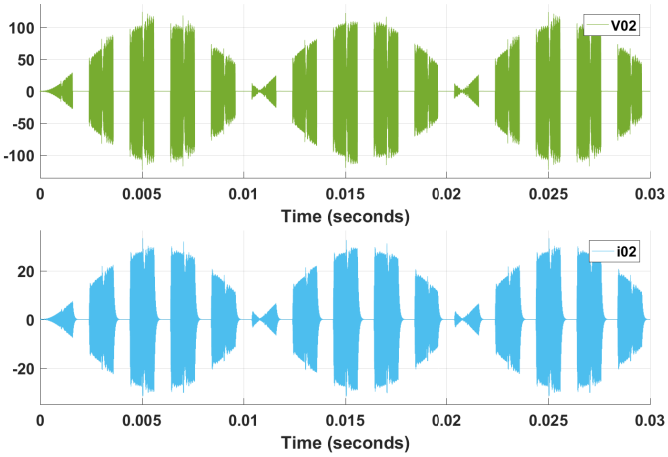

Fig. 6. Load-2 Voltage (V_{02}) and Current (I_{02}) at D_2= 0.95

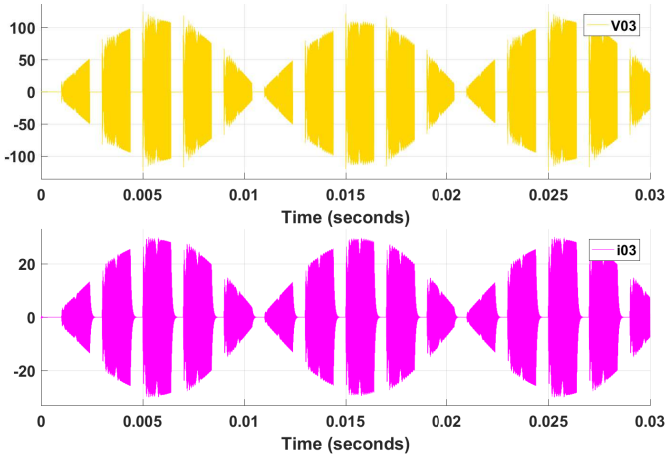

Fig. 7. Load-3 Voltage (V_{03}) and Current (I_{03}) at D_3= 0.95

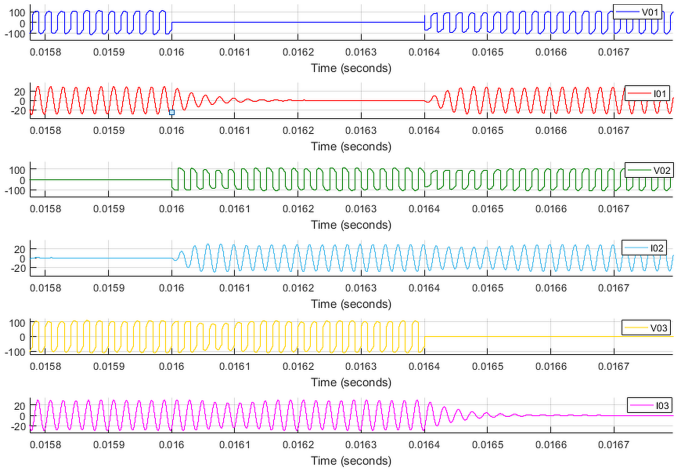

Fig. 8. Zoomed waveforms of load voltages and load currents

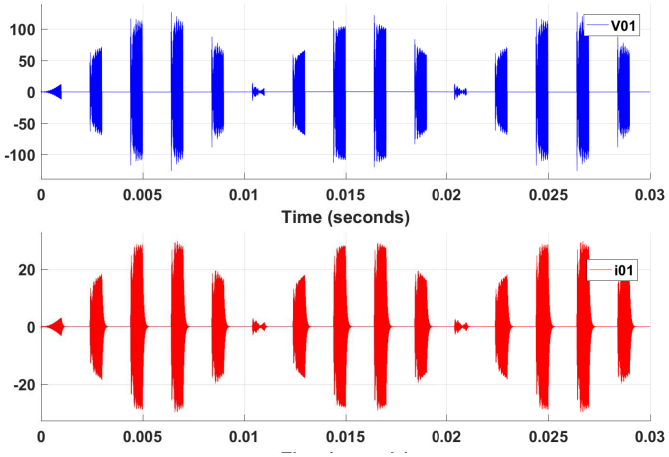

Fig. 9. Load-1 Voltage (V_{01}) and Current (I_{01}) at D_1= 0.3

simulation results with output powers of P_1 = 120 W, P_2 = 316 W, and P_3 = 316 W is shown in Fig.9 to Fig.11. The duty cycle of the loads is determined as d_1 =0.3, d_2 = 0.95, and d_3 = 0.95 from the time periods t_1, t_2, t_3, and t_4. The simulation

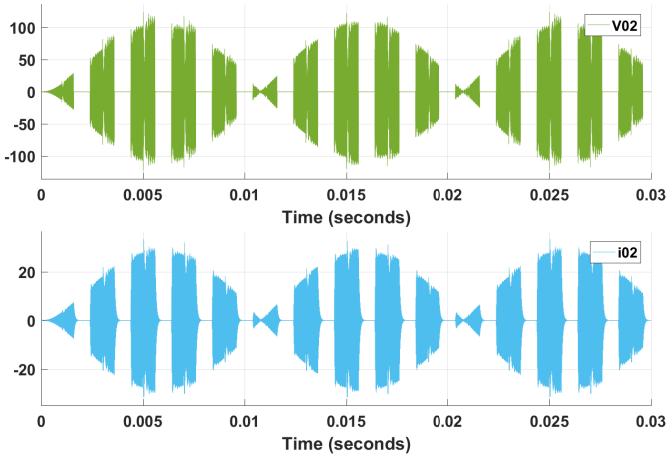

Fig. 10. Load-2 Voltage (V_{02}) and Current (I_{02}) at D_2= 0.95

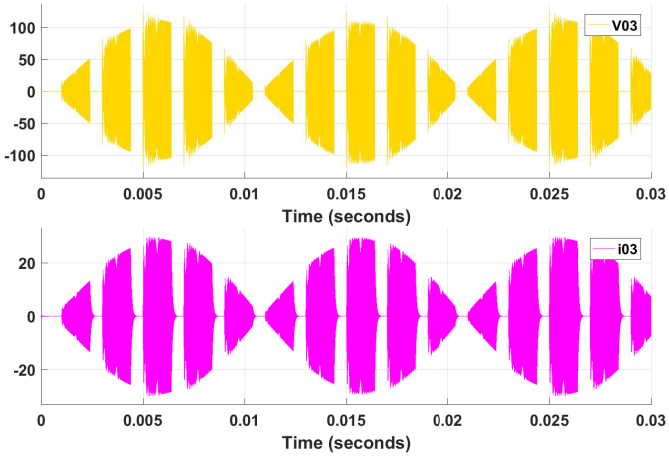

Fig. 11. Load-3 Voltage (V_{03}) and Current (I_{03}) at D_3= 0.95

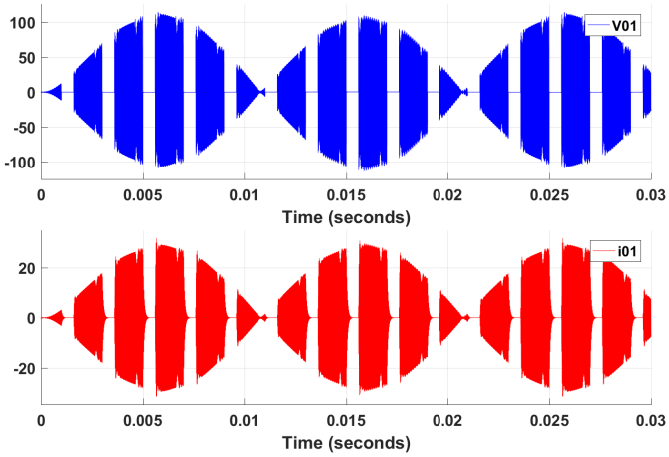

Fig. 12. Load-1 Voltage (V_{01}) and Current (I_{01}) at D_1= 0.95

results with output powers of P_1 = 316 W, P_2 = 120 W, and P_3 = 316 W is depicted in Fig.12 to Fig.14. The duty cycle of the loads is determined as d_1 =0.95, d_2 = 0.3, and d_3 = 0.95 based on the time periods t_1, t_2, t_3, and t_4. Fig.15 to Fig.17

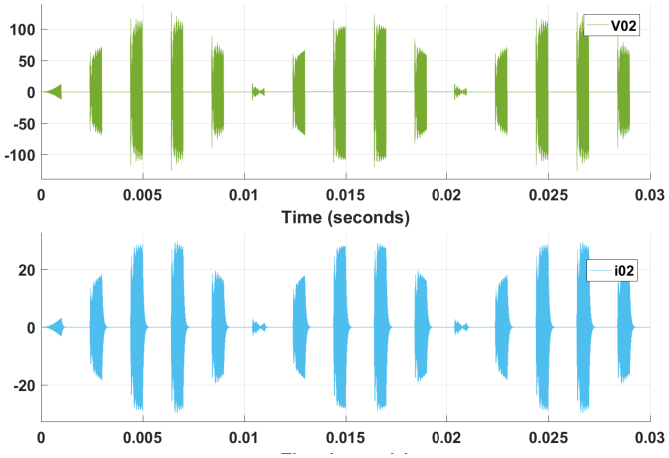

Fig. 13. Load-2 Voltage (V_{02}) and Current (I_{02}) at D_2= 0.3

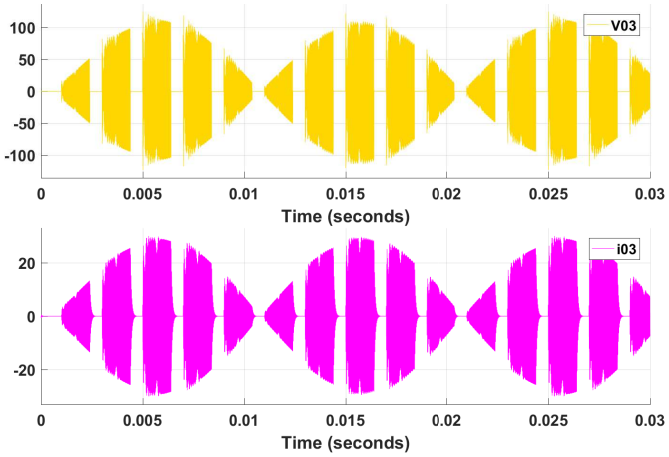

Fig. 14. Load-3 Voltage (V_{03}) and Current (I_{03}) at D_3= 0.95

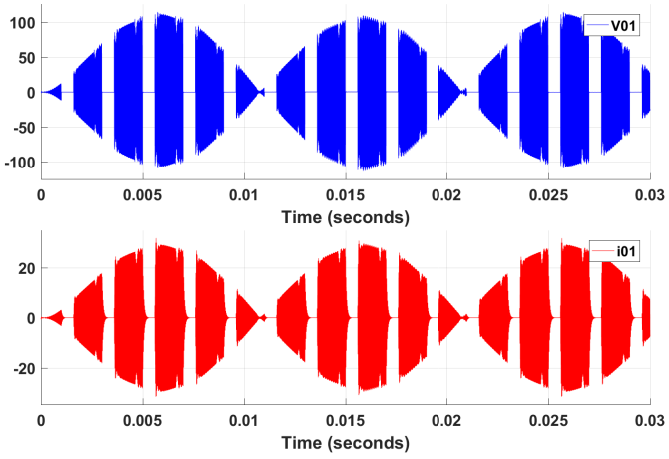

Fig. 15. Load-1 Voltage (V_{01}) and Current (I_{01}) at D_1= 0.95

show the simulation results with output powers of P_1 = 316 W, P_2 = 316 W, and P_3 = 120 W. The duty cycle of the loads is determined as d_1 =0.95, d_2 = 0.95, and d_3 = 0.3 from the time periods t_1, t_2, t_3, and t_4.

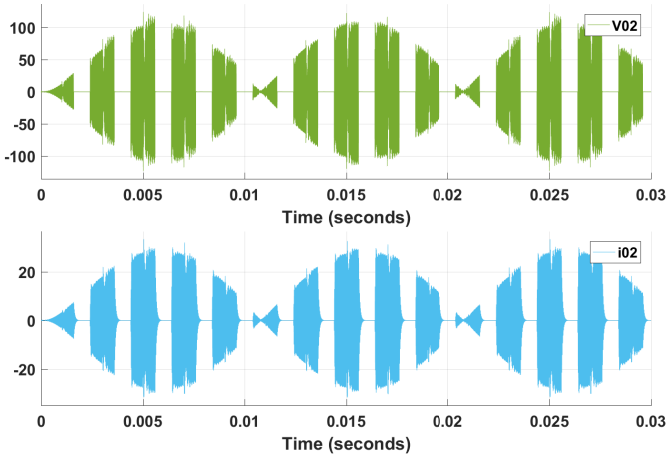

Fig. 16. Load-2 Voltage (V_{02}) and Current (I_{02}) at D_3= 0.95

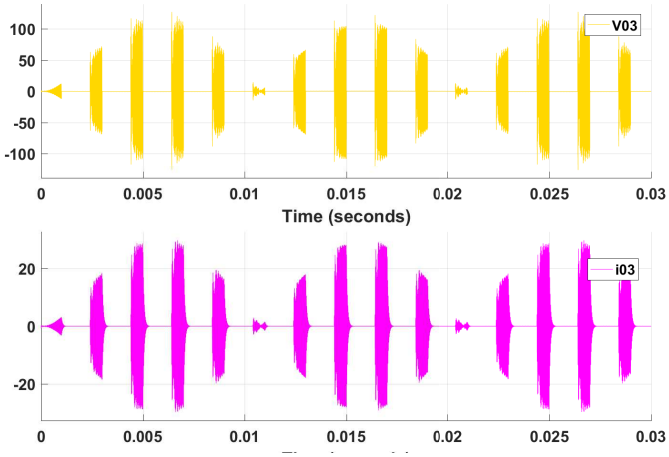

Fig. 17. Load-3 Voltage and Current at D_2= 0.3

Fig.18 presents independent load power regulation. According to Fig.18a, load-1 power varies with d_1 while load-2 and load-3 powers remain constant with fixed d_2 and d_3. According to Fig.18b, load-2 power varies d_2 while load-1 and load-3 powers remain constant with fixed d_1 and d_3. Similarly According to Fig.18c, load-3 power varies d_3 while load-1 and load-2 powers remain constantwith fixed d_1 and d_2 . At various power levels, the proposed resonant converter to obtain zero voltage or zero current during the switching period; if this desired feature is achieved, the switching power losses decreases to minimum, hence proposed converter achieves high efficiency ($\geq$95 %).

V. Conclusions

In this paper, a cyclic controlled single-stage three-leg resonant converter for three output domestic IH applications is proposed. The connverter offers bridge less rectifier operation, input power factor correction, boost operation, ZVS and operates at fixed switching frequencies. All three IH loads are regulated simultaneously and independently. The developed approach has fewer components and provides one leg per

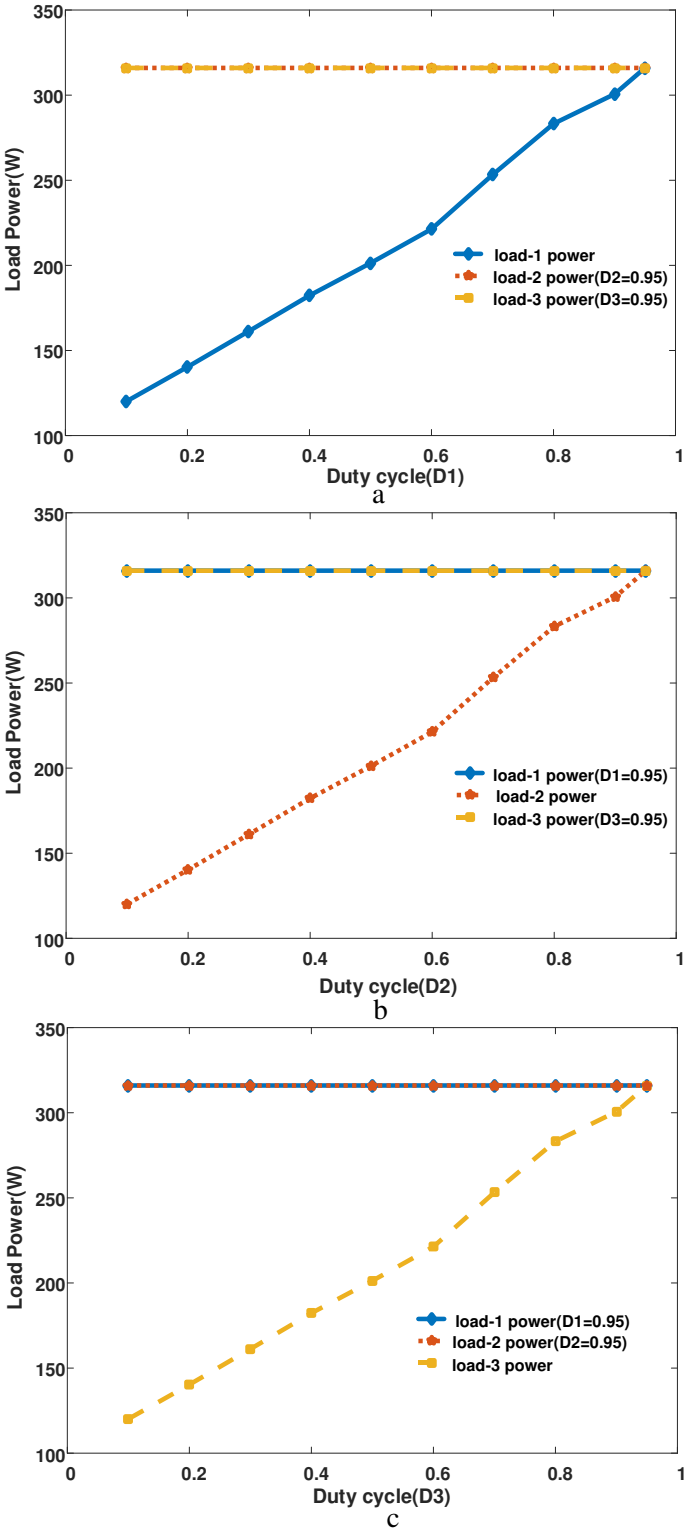

Fig. 18. independent Power control of loads (a) load-1 power control (b) load-2 power control (c) load-3 power control

load on average. It may also be expanded to accommodate more than three loads. The simulation results are presented. The proposed converter's design and control are simple, cost effective, and efficient.

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