A Full Bridge Resonant Inverter with Multiple Loads for Induction Cooking Application

[1]P. Sharath Kumar, *Student member IEEE,* [2]N. Vishwanathan, [3]Bhagwan K. Murthy
[1,2,3]Department of Electrical Engineering,
National Institute of Technology Warangal,
Warangal, A. P, India.
[1]namishpsk@ieee.org

***Abstract* – In this paper full bridge resonant inverter with independent output power control of two loads for induction cooking application is presented. The proposed configuration can be operating with efficient ZVS by constant switching frequency and constant duty ratio of full bridge resonant inverter. By varying the duty ratio of load switch, each load output power is controlled individually. And in this proposed configuration, synchronization of load switch switching pulse with inverter output voltage is done for output power control. The proposed configuration can be extended to multiple loads. It is more reliable for multiple load induction cooking application with output power control of each load independently. For theoretical predictions, the proposed configuration of two load full bridge resonant inverter for induction cooking application with independent control of each load is simulated in MATLAB/Simulink environment.**

***Index Terms* – Full bridge resonant inverter, Induction heating, Cooking application, ZVS operation, Multiple load.**

I. Introduction

NOW a days utilization of electrical energy is a basic necessity of human life for wide use of electrical appliances. Induction heating has several applications. Induction heating operates on high frequency AC supply. Induction cooking is one of the main applications of induction heating. Recent times have shown development of semiconductor devices and research in high frequency inverter circuits. There is progress in new control schemes and circuit modifications by the use of power semiconductor devices such as MOSFETs, IGBTs, MCTs and SITs having high efficiency and high reliability. The power semiconductor devices offer reduced switching losses by using soft switching techniques at high frequency operation. Induction heating method is a far better approach than other conventional methods because of generation of magnetic flux to inducing eddy currents in load based on Faraday's law of electromagnetic induction principle and there by producing heat by Joules heating principle [1]. In conventional methods the heat is transferred from heat source to load by conduction or radiation. But in induction heating method the heat is developed inside the load due to generation of eddy currents. The heat generated by eddy currents in the heating load is concentrated in a peripheral layer at skin depth (δ) [2], which is explained by

$$\delta = \sqrt{\frac{\rho}{\pi\mu f}} = \sqrt{\frac{1}{4\pi^2\times10^{-7}}} \times \sqrt{\frac{\rho}{\mu_r f}} \tag{1}$$

where, ρ is electrical resistivity, μ is magnetic permeability and μ_r is relative magnetic permeability of the load material and f is switching frequency of the inverter circuit.

Generally using topologies in induction cooking application are quasi resonant inverter, half bridge inverter and full bridge inverter. Full bridge inverter supplies a peak to peak voltage across the load which is twice the source voltage. So it leads to high power transfer to load from the source. Full bridge inverter has become very popular over other topologies and is widely used in high power applications [2].

Full bridge resonant inverter is generally used to energize the induction heating coil with high frequency current to generate high frequency magnetic flux between the induction heating coil and the cooking vessel. Consequently, high frequency eddy current is induced at a peripheral layer of skin depth level, inside the vessel and finally heat is developed in the bottom area of the vessel. The full bridge inverter takes the energy from the input source and converting into the dc voltage by diode rectifier. This dc supply is fed to inverter and converts into a high frequency ac voltage, supplying a high frequency current to the induction heating coil. The general series resonant inverter circuit for induction cooking application is shown in Fig. 1.

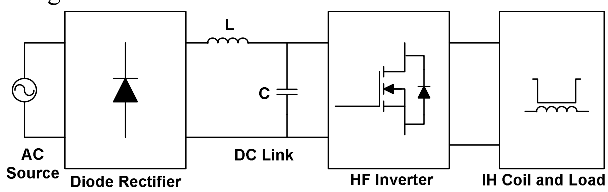


Fig. 1. Circuit of high frequency induction heating system

Induction cooking applications use Variable Frequency scheme, Pulse Frequency Modulation (PFM), Pulse Amplitude Modulation (PAM), and Phase Shift Modulation (PSM) to control the output power. In Variable Frequency scheme for constant load to control output power, varying the normalized switching frequency. In case of below resonance operation, filter components are large for the low-frequency range. In PAM control for constant load amplitude of the source voltage is varied to control the output power. In PFM control the resonant frequency is tracking, when load changes by using PLL circuit. PFM control has ZVS soft switching operating region is relatively narrow. PSM control gives high efficiency at higher duty ratio [3]-[4]. To overcome these problems, PWM technique is used.

This paper proposes full bridge resonant inverter configuration with two parallel loads for induction cooking application. The characteristics of full bridge series resonant inverter and proposed output power control scheme are explained in detail. In this configuration, synchronization of load switch switching pulse with inverter output voltage used for control the output power of each load independently. This configuration can be extended to multiple loads.

II. Full Bridge Series Resonant Inverter

A high frequency full bridge series resonant inverter is used to energize the IH coil. It generates high frequency magnetic flux and linking with the load. Consequently high frequency eddy current induces at skin depth level in the vessel bottom area. Finally heat is developed inside the vessel due to eddy currents.

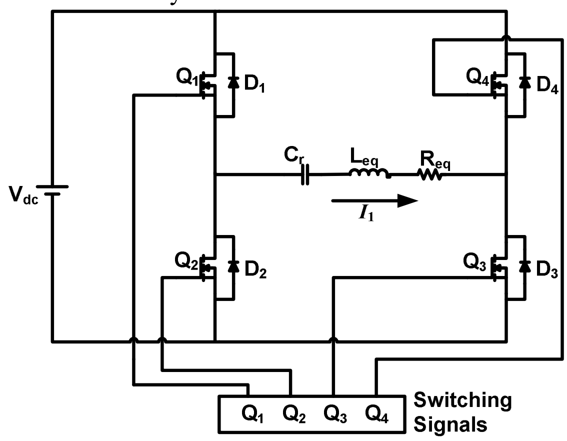


Fig. 2. Full bridge resonant inverter for IH cooking application

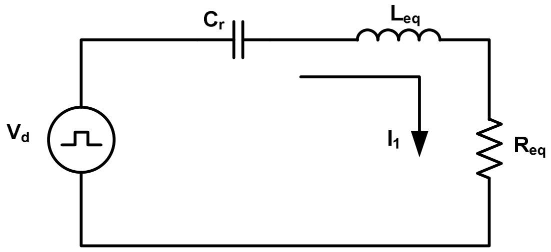


Fig. 3. Equivalent circuit of inverter

The full bridge series resonant inverter for induction cooking application is shown in Fig. 2. The full bridge inverter consists of four switches Q_1-Q_4 with anti parallel diodes D_1-D_4. The equivalent circuit of inverter is shown in Fig. 3. The resonant tank consists of resonant capacitor C_r and load. Load consists of a series combination of equivalent inductance L_{eq} and equivalent resistance R_{eq}. In particular, two switching devices in a leg are operated at square wave with suitable dead time between the two switching pulses. The class-E resonant inverter is operated above the resonant frequency which means the inverter switching devices are operates in ZVS region.

The steady state analysis of the class-E resonant inverter is based on the following assumptions:

i. The dc input voltage is constant.
ii. All components are ideal.
iii. The effects of the parasitic capacitances of the switching devices are neglected.

II.1. Theoretical Waveforms of Full Bridge Inverter

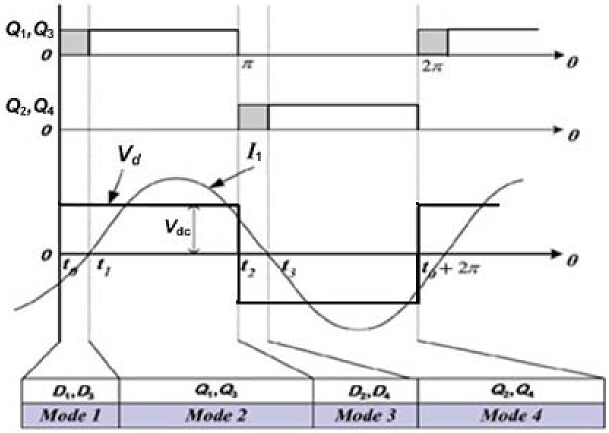


Fig. 4. Theoretical waveforms of full bridge inverter

Fig. 4 shows the theoretical waveforms including the switching gate pulses with dead time, inverter output voltage V_d and load current I_1. The switching frequency is chosen above the resonant frequency for the switching devices that are operated in ZVS region. The series resonant tank circuit represents an inductive load at above the resonant frequency and load current I_1 lags behind the inverter output voltage V_d. The load current I_1 flowing through two paths. They are $D_3 \rightarrow L_{eq} \rightarrow C_r \rightarrow D_1 \rightarrow Q_1 \rightarrow C_r \rightarrow L_{eq} \rightarrow Q_3$ and $D_2 \rightarrow C_r \rightarrow L_{eq} \rightarrow D_4 \rightarrow Q_4 \rightarrow L_{eq} \rightarrow C_r \rightarrow Q_2$.

II.2. Operation Modes of Full Bridge Resonant Inverter

Four operation modes exist in one switching cycle as shown in Fig. 4. Each mode of operation is explained below, and operation mode circuits are shown in Fig. 5.

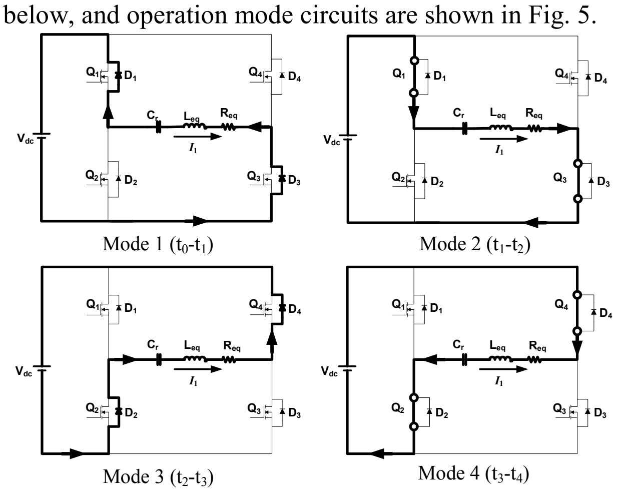


Fig. 5. Operation modes of full bridge series resonant inverter

1) Mode 1 (t_0-t_1): The switching devices Q_2 and Q_4 are turned off at $t = t_0$. Anti parallel diodes D_1 of Q_1 and D_3 of Q_3 are conducted by negative load current I_1. During this mode, negative load current I_1 flows through the load. The ZVS condition is obtained for Q_1 and Q_3.
2) Mode 2 (t_1-t_2): The anti parallel diodes D_1 of Q_1 and D_3 of Q_3 are turned off at $t = t_1$. The switching devices Q_1 and Q_3 are conducted and the ZVS condition is

achieved. During this mode, positive load current I_1 flows through the load.

3) Mode 3 (t_2-t_3): This mode is similar to mode 1, and the switching devices Q_1 and Q_3 are turned off at t = t_2. Anti parallel diodes D_2 of Q_2 and D_4 of Q_4 are conducted by positive load current I_1. During this mode, positive load current I_1 flows through the load. The ZVS condition is obtained for Q_2 and Q_4.

4) Mode 4 (t_3-t_4): This mode is similar to mode 2, and the anti parallel diodes D_2 of Q_2 and D_4 of Q_4 are turned off at t = t_3. The switching devices Q_2 and Q_4 are conducted and the ZVS condition is achieved. During this mode, negative load current I_1 flows through the load.

By completing four modes, one cycle of operation for full bridge inverter is finished. The operation of full bridge inverter continues by repeating the operation modes from 1 to 4.

II.3. Full Bridge Resonant Inverter Characteristics

The characteristics of resonant circuit of the full bridge inverter as shown in Fig. 2, can be described as follows

The resonant frequency is

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

The normalized switching frequency is

$$f_n = \frac{f_S}{f_r} \quad (3)$$

with f_S being the switching frequency

The characteristic impedance is

$$Z_0 = \sqrt{\frac{L_{eq}}{C_r}} = \frac{1}{2\pi f_r C_r} = 2\pi f_r L_{eq} \quad (4)$$

The resonant load quality factor is

$$Q = \frac{2\pi f_r L_{eq}}{R_{eq}} = \frac{1}{2\pi f_r C_r R_{eq}} = \frac{Z_0}{R_{eq}} \quad (5)$$

The impedance of the resonant tank circuit in Fig. 5 is given by

$$Z_{eq} = R_{eq} + j\left(2\pi f_r L_{eq} - \frac{1}{2\pi f_r C_r}\right) = R_{eq}\left(1 + jQ\left(f_n - \frac{1}{f_n}\right)\right) \quad (6)$$

$$\left|Z_{eq}\right| = R_{eq}\sqrt{1 + Q^2\left(f_n - \frac{1}{f_n}\right)^2} \quad (7)$$

The current phase angle is

$$\emptyset° = \tan^{-1}\left(Q\left(f_n - \frac{1}{f_n}\right)\right) \quad (8)$$

The voltage across the resonant tank circuit V_d is

$$V_d = \begin{cases} V_{dc}, & for\ 0 < \omega_s t \le \pi \\ -V_{dc}, & for\ \pi < \omega_s t \le 2\pi \end{cases} \quad (9)$$

The fundamental component of V_d can be found from Fourier analysis,

$$V_d(\omega) = V_m \sin \omega_s t, \text{ for } 0 < \omega_s t \le \pi \quad (10)$$

where

$$V_m = \frac{4}{\pi} V_{dc} \approx 1.273\, V_{dc} \quad (11)$$

The load current through the series resonant tank circuit is derived by

$$I_1 = I_m \sin(\omega_s t - \emptyset) \quad (12)$$

where

$$I_m = \frac{V_m}{|Z_{eq}|} = \frac{4V_{dc}}{\pi|Z_{eq}|} = \frac{4V_{dc}\cos\emptyset}{\pi R_{eq}} = \frac{4V_{dc}}{\pi R_{eq}\sqrt{1 + Q^2\left(f_n - \frac{1}{f_n}\right)^2}} \quad (13)$$

The output power can be derived as following by using eq. (13)

$$P_{out} = \frac{I_m^2}{2} R_{eq} = \frac{8V_{dc}^2 \cos\emptyset^2}{\pi^2 R_{eq}} = \frac{8V_{dc}^2}{\pi^2 R_{eq}\left(1 + Q^2\left(f_n - \frac{1}{f_n}\right)^2\right)} \quad (14)$$

From the eq. (14) the output power can be controlled by varying the load current by the duty ratio of the inverter. The output power also depends on load quality factor and normalized switching frequency. The inverter operates at switching frequency above its resonant frequency to ensure inverter switching devices are operating in ZVS region. From the eq. (14), to control the output power the switching frequency will be varied. For light loads low output power is desired. So, the switching frequency of inverter is needed high, comparing with its resonant frequency. For high output power, the switching frequency of inverter is close to its resonant frequency. Therefore, the ZVS region is relatively narrow under the PFM control technique. To solve these problems, new output power control scheme with a switching device at load is proposed with constant switching frequency of inverter.

III. Proposed Multiple Load Configuration

III.1. Two Load Full Bridge Series Resonant Inverter

The output power of multiple loads are individually controlled is the main aim in full bridge series resonant inverter [5]. We propose a new simple two load series resonant inverter with output power control scheme by varying the duty ratio of load switch.

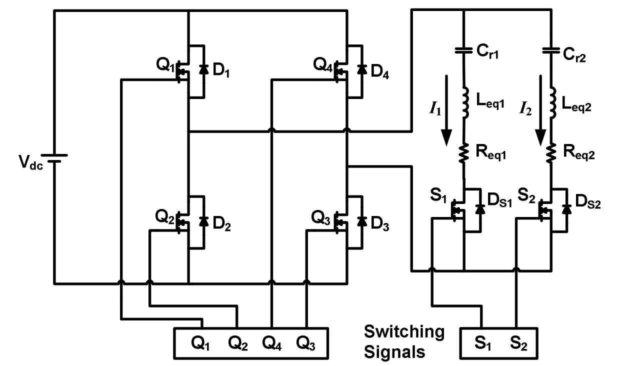


Fig. 6. Proposed two load full bridge series resonant inverter

The full bridge series resonant inverter operates at constant switching frequency and constant duty ratio. The inverter switching frequency is chosen above the resonant frequency for ZVS operation of inverter switching devices. The proposed two load configuration of full bridge series resonant inverter is shown in Fig. 6. The full bridge inverter has 4 switching devices Q_1 to Q_4 with anti parallel diodes D_1 to D_4. Each load consists of resonant capacitor C_r, L_{eq} is the equivalent inductance of IH coil with vessel and R_{eq} is the equivalent resistance of IH coil with vessel. A switching device (S) with anti parallel diode (D_S) is in series with each load. Controlling the output power of each load is done individually, with varying the duty ratio of S. This configuration can be extended to multiple loads.

III.2. Block Diagram of Power Control Scheme

In the proposed work the output power is regulated by S_{power}, and full bridge series resonant inverter is operated with constant switching frequency and constant duty ratio. Load output power is P_{out}. S_{power} is the duty ratio of load switch S. S_{power} can be obtained from the ratio of $P_{regulated}/P_{out}$. The $P_{regulated}$ load output power can be expressed as follows by using eq. (14),

$$P_{regulated} = P_{out} \cdot S_{power} = \left(\frac{I_m^2}{2} R_{eq}\right) S_{power} = \left(\frac{8V_{dc}^2 cos\emptyset^2}{\pi^2 R_{eq}}\right) S_{power} \quad (15)$$

The proposed output power control scheme consists of two functions. One is, controlling the load output power by varying the duty ratio of load switch (S_{power}) and the other is, constant low frequency switching pulse of load switch S, which is synchronized with inverter high frequency output voltage.

The block diagram of proposed output power control scheme is shown in Fig. 7. The load current I is compared with regulated output power $P_{regulated}$ to control S_{power}. S_{power} should be synchronized with the inverter high frequency output voltage.

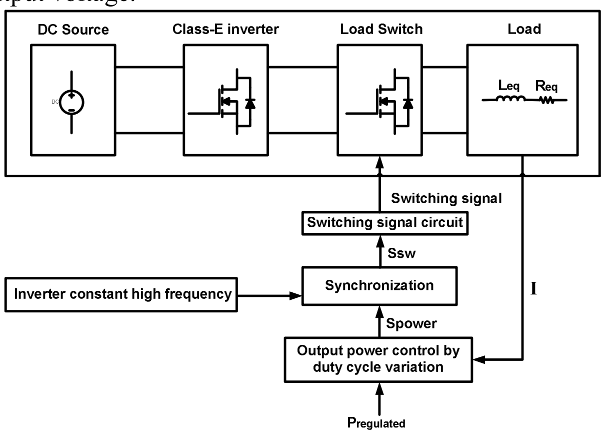


Fig. 7. Proposed block diagram of output power control scheme

When load switch S is on during T_{on} period, the load current I is flowing through the load. When load switch is off during T_{off} period, the load current is zero and it is disconnected from inverter output circuit. The load switch should be off, when the period of negative current is flowing through the load. In this duration the anti parallel diode D_S across the load switch S provides a path to complete the negative cycle of load current reaches to zero position. Then the load will be disconnected from the inverter output. The proposed inverter configuration provides the output power of each load can be controlled individually by varying the duty ratio of respective load switch S. The inverter switching devices are operated always in ZVS region with higher efficiency due to the inverter operates at constant switching frequency with constant duty ratio.

III.3. Process of Synchronization

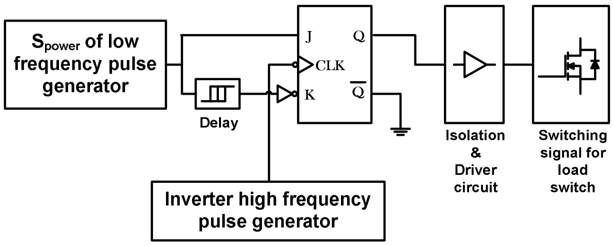


Fig. 8. Proposed control circuit of synchronization

Proposed synchronization control circuit of low frequency load switch switching pulse with inverter high frequency switching pulse is shown in Fig. 8. Low frequency and high frequency switching pulses are out of audible range. So low frequency load switch switching signal is below 20 Hz and high frequency inverter switching signal is just above resonant frequency, which is above 20 kHz. The JK flip flop is used for synchronization between the constant low frequency and high frequency switching pulses.

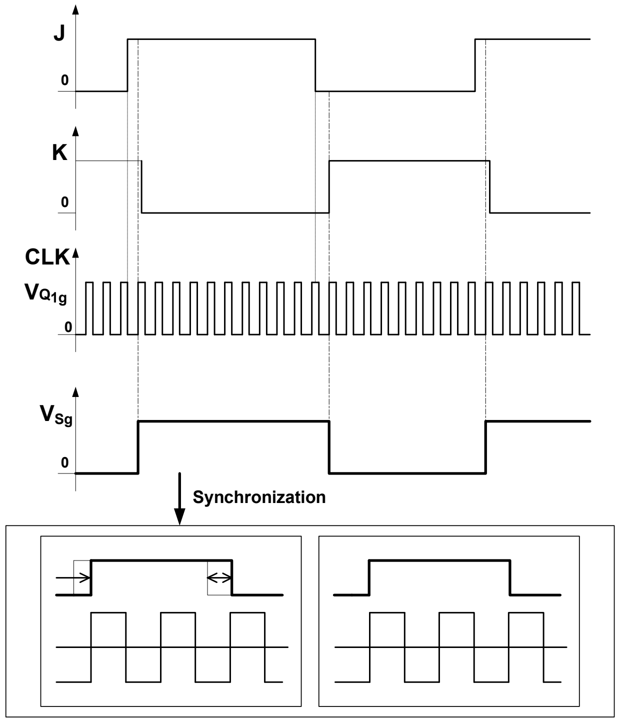


Fig. 9. Synchronized switching pulses for load switch

Wave forms of synchronized switching pulses for load switch S with inverter output voltage are shown in Fig. 9. Low frequency signal and its complimentary signal with a delay are fed to JK flip flop. The delay is taken between T/2 to T of inverter high frequency signal. Inverter switching device Q_1 switching signal is fed to CLK. With the synchronization process, the synchronized switching signal is fed to load switch through isolation & driver circuit. Due to synchronized load switch switching signal, the load switch will turn on at positive pulse rising edge of inverter output voltage and the load switch will turn off in negative pulse duration of inverter output voltage. At this position, anti parallel diode D_S of load switch S conduct up to load current reaches to zero position. Then the load is disconnected from inverter supply, up to load switch getting the switching signal from the control circuit. The output power of load is controlled by controlling the load current. This process is done also to second load. So this configuration can be extended to multiple loads.

IV. Simulation and Results

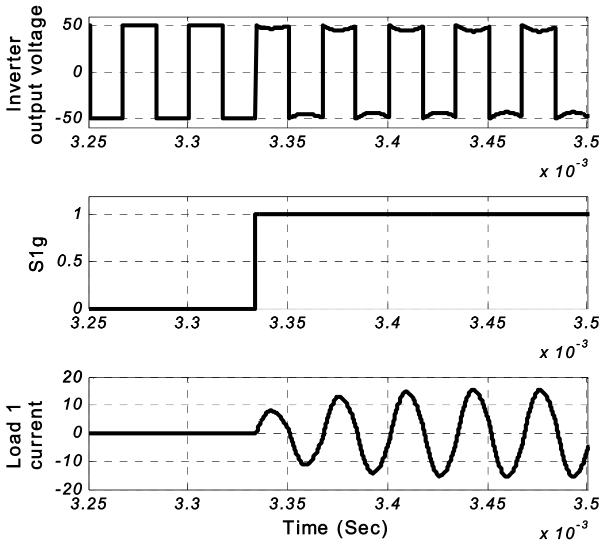
To verify theoretical predictions of proposed full bridge series resonant inverter system simulated in MATLAB/Simulink. ZVS operation for inverter switching devices is achieved by choosing the switching frequency more than its resonant frequency. The prototype system is simulated with the parameters as shown in Table I. The simulation results of full bridge series resonant inverter system are obtained using the proposed control scheme. The system output power can be varied by varying duty ratio from 0% to 100% of load switch S.

The full bridge series resonant inverter is operated at constant duty ratio, which is 100% duty ratio and constant switching frequency of 22 kHz to reduce EMI and turn on losses. The rated load output power P_{out} is 1.3 kW. To reduce acoustic noise, the load switching frequency S_{sw} is chosen as 11 Hz.

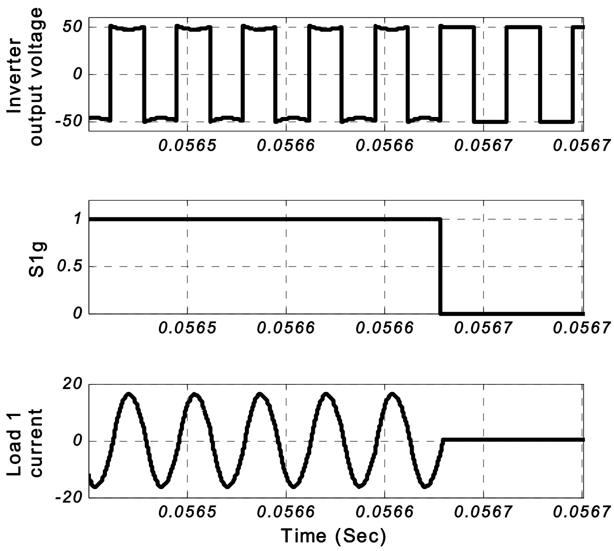
TABLE I
FULL BRIDGE INVERTER SPECIFICATIONS AND CIRCUIT PARAMETERS

Component	Symbol	Rating value
Source voltage	V_{dc}	50 V
Switching frequency	f_S	30 kHz
Rated output power	P_{out}	1.3 kW
Resonant capacitor	C_{r1}, C_{r2}	0.45 µF
Load inductance	L_{eq1}, L_{eq2}	67 µH
Load resistance	R_{eq1}, R_{eq2}	1.95 Ω
Resonant frequency	f_r	28.98 kHz
Load switch frequency	f_{SW}	15 Hz
Switching devices Q_1 to Q_4 and S_1, S_2	MOSFT IRFM250	200V, 27.4A
Duty ratio of S_1	D1	80%
Duty ratio of S_2	D2	40%
Dead time for inverter switches	T_d	0.3 µsec

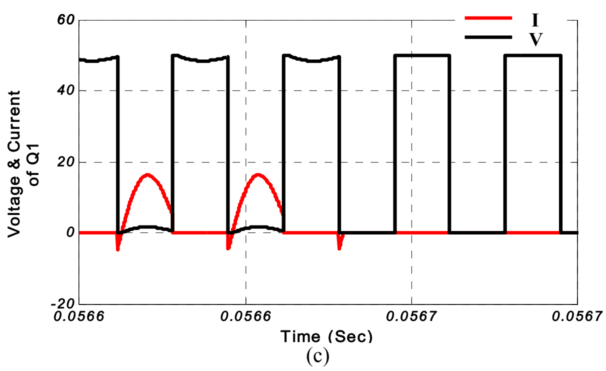
Load 1 current and inverter output voltage wave forms with synchronized switching gate pulse of load switch S_1 are shown in Fig. 10. Fig. 10(a) shows load1 current and inverter output voltage with synchronized switching gate pulse of load switch S_1 at turn on. Fig. 10(b) shows load1 current and inverter output voltage with synchronized switching gate pulse of load switch S_1 at turn off with a duty ratio of 80%. Fig. 10(c) shows the ZVS operation of inverter switch Q_1 at load switch S_1 turn off period. Load 2 current and inverter output voltage wave forms with synchronized switching gate pulse of load switch S_2 are shown in Fig. 11. Fig. 11(a) shows load1 current and inverter output voltage with synchronized switching gate pulse of load switch S_2 at turn on. Fig. 11(b) shows load1 current and inverter output voltage with synchronized switching gate pulse of load switch S_2 at turn off with a duty ratio of 40%. Fig. 11(c) shows the ZVS operation of inverter switch Q_1 at load switch S_2 turn off period.



(a)

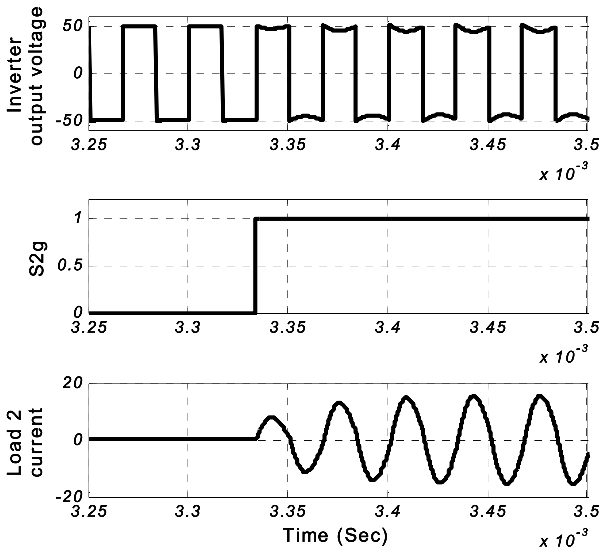


(b)

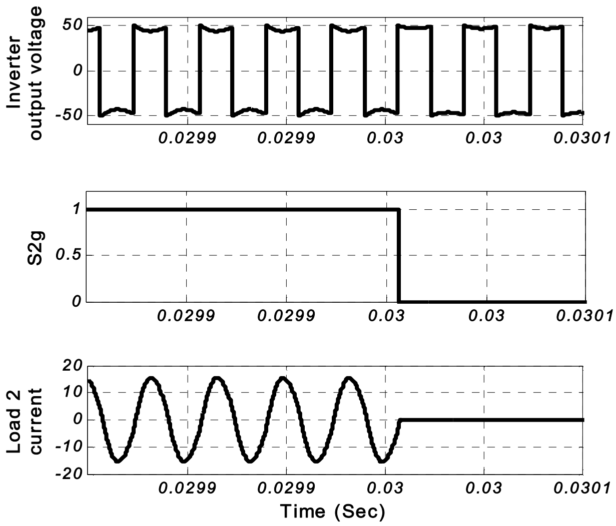


(c)

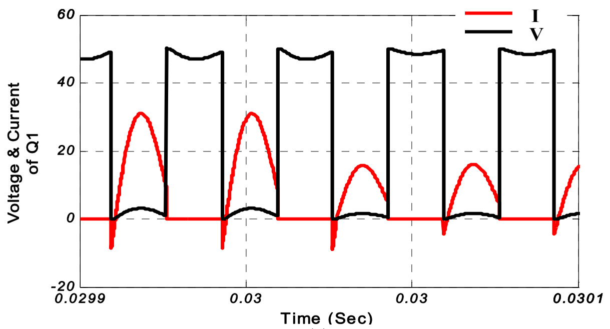
Fig. 10. Output voltage and load 1 current.
(a) Output voltage and load 1 current at S_1 turn on.
(b) Output voltage and load 1 current at S_1 turn off.
(c) Voltage and current of inverter switch Q_1.



(a)



(b)



(c)

Fig. 11. Output voltage and load 2 current.
(a) Output voltage and load 2 current at S_2 turn on.
(b) Output voltage and load 2 current at S_2 turn off.
(c) Voltage and current of inverter switch Q_1.

Load output power is controlled by variation of S_{power} duty ratio from 20% to 100% as shown in Fig. 12. The average output power is an increase in the duration of load switch is on. Similar output power control is done for load 2 also.

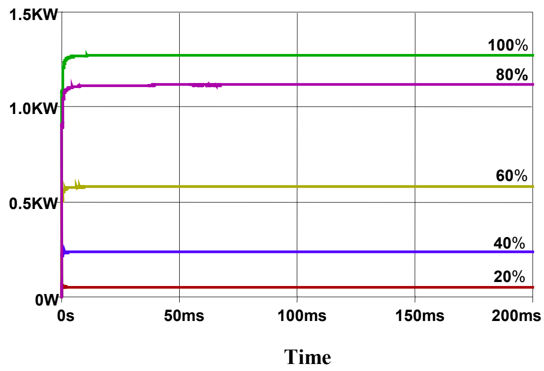


Fig. 12. Output power variation with S_{power} duty ratio

The proposed output power control scheme is simple and it can be extended to multiple loads. Each load output power can be controlled individually. The full bridge series resonant inverter operates at constant switching frequency with 100% duty ratio. So, full bridge series resonant inverter operates at maximum efficiency and reduces EMI, turn on losses with ZVS operation from light load to full load.

V. Conclusion

In this paper, a simple output power control scheme for multiple load full bridge series resonant inverter for induction cooking application has been proposed. Characteristics of full bridge series resonant inverter and proposed control scheme are explained in detail. The proposed control scheme is simulated with two loads, which are connected in parallel with inverter output. It can be extended to multiple loads. From the proposed multiple load full bridge series resonant inverter output power control scheme, we can obtain the output power controlled of each load individually, for wide power regulation range. Inverter switching devices are operating with ZVS from light load to full load. EMI and turn on losses of switching devices are reduced. Full bridge series resonant inverter is operating with maximum efficiency by 100% duty ratio and constant switching frequency.

References

[1] W. C. Moreland of The induction range: Its performance and its development problems, *IEEE Trans. Ind. Appl., vol. IA-9, no. 1*, Jan./Feb. 1973, pp. 81–85.

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

[3] 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.

[4] Burdio, J.M.; Barragan, L.A.; Monterde, F.; Navarro, D., Acero, J.; "Asymmetrical voltage-cancellation control for full-bridge series resonant inverters," *IEEE Transactions on Power Electronics*, Volume: 19, Issue: 2, Page(s): 461 - 469, 2004.

[5] Jose M. Burdio, Fernando Monterde, Jose R. Garcia, Luis A. Barragan, Abelardo Martinez of A Two-Output Series-Resonant Inverter for Induction-Heating Cooking Appliances, *IEEE Transactions on Power Electronics*, *Volume: 20, Issue: 4*, 2005, Page(s): 815 - 822.