Cascaded Load Inverter Configuration for Induction Cooking Application

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***Abstract* - In this paper a single full bridge resonant inverter with independent output power control of two cascaded loads for induction cooking application is presented. In proposed configuration, the full bridge inverter can be operated with constant switching frequency and constant duty ratio for efficient zero voltage switching. Independent output power control of each load is done by varying the duty ratio of respective switching device at load. The proposed configuration can be extended to multiple loads. It is more reliable for multiple load induction cooking application. For theoretical predictions, the proposed configuration of cascaded load inverter configuration for induction cooking application with independent control of each load is simulated in ORCAD (P-Spice) environment.**

Keywords – Full bridge resonant inverter, Induction heating, Cooking application, ZVS operation, Multiple load.

I. INTRODUCTION

Now a days utilization of electrical energy in various aspects is a basic necessity for human life with widely used of electrical appliances. Induction heating operates on high frequency AC supply in the range of 20 kHz to 600 kHz according to its application. Induction heating has several applications. 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 topologies and control circuits. There is a tremendous progress in new control schemes and circuit modifications by the use of power semiconductor devices such as MOSFETs, IGBTs, MCTs and SITs for high efficiency and high reliability. The power semiconductor devices at high frequency operation offer reduced switching losses by using soft switching techniques. Induction heating method is a far better approach than other conventional methods. In induction heating, eddy currents are induced in load due to generation of magnetic flux based on Faraday's law of electromagnetic induction principle and there by producing heat by Joules heating principle [1]. In conventional methods, from source to load the heat is transferred by conduction or radiation. But in induction heating, due to generation of eddy currents the heat is developed inside the load. The induced eddy currents are concentrated in load at skin depth (δ) [2] level, which is explained by

$$\delta = \sqrt{\frac{\rho}{\pi\mu f_s}} = \sqrt{\frac{1}{4\pi^2\times10^{-7}}} \times \sqrt{\frac{\rho}{\mu_r f_s}} \quad (1)$$

where, ρ is electrical resistivity, μ is magnetic permeability and μ_r is relative magnetic permeability of load material and f_s 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 from source to load. Full bridge inverter has become very popular over other topologies and is widely used in high power applications [3].

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 currents are 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 ac 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, and supplying a high frequency ac current to the induction heating coil. The typical circuit of series resonant inverter for induction cooking application is shown in Fig. 1.

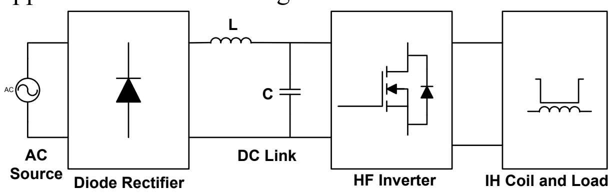


Fig. 1. Typical circuit of high frequency induction heating system

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 to control the output power for a constant load by 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 [4]. In

978-1-4799-2751-7/13/$31.00 ©2013 IEEE

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 [5]-[6]. PSM control gives high efficiency at higher duty ratio [7]-[8].

This paper proposes cascaded load inverter configuration for induction cooking application. The characteristics of full bridge series resonant inverter and proposed configuration with independent output power control of each load are explained in detail. In this configuration by varying the load switching device duty ratio, output power control of each load is done independently. This configuration can be extended to multiple loads.

II. Full Bridge Series Resonant Inverter

For high power applications, a high frequency full bridge series resonant inverter is used to energize the induction heating coil. Because of, full bridge inverter output voltage is $+V_{dc}$ to $-V_{dc}$. High frequency eddy currents are induced at skin depth level in the vessel bottom area. The vessel thickness will be chosen twice of skin depth level. Heat is developed inside the vessel due to these eddy currents.

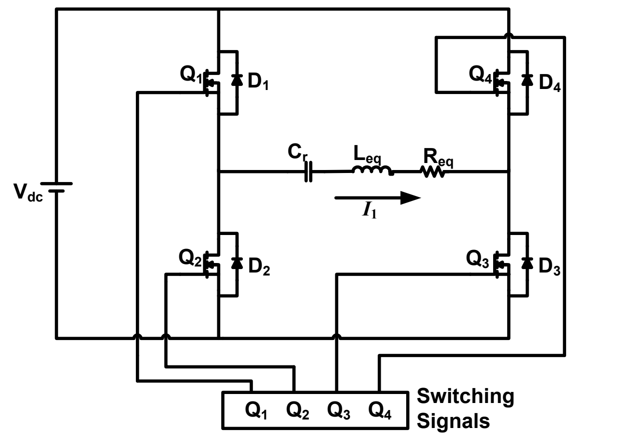


Fig. 2. Full bridge resonant inverter for induction cooking application

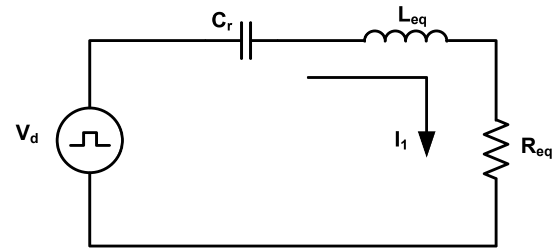


Fig. 3. Equivalent circuit of series resonant inverter

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

The steady state analysis of the full bridge series 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.

A. Theoretical Waveforms of Full Bridge Inverter

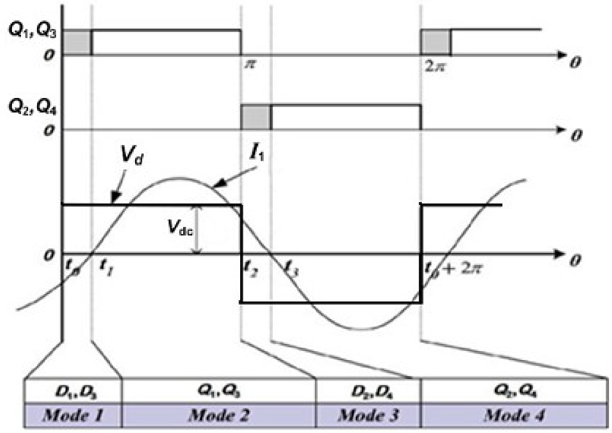


Fig. 4. Theoretical waveforms of full bridge inverter

Fig. 4 shows the theoretical waveforms at 100% duty ratio of a inverter switching device, 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 that the switching devices 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 $D_2 \rightarrow C_r \rightarrow L_{eq} \rightarrow D_4 \rightarrow Q_4 \rightarrow L_{eq} \rightarrow C_r \rightarrow Q_2$.

B. Operation Modes of Full Bridge Series 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.

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.

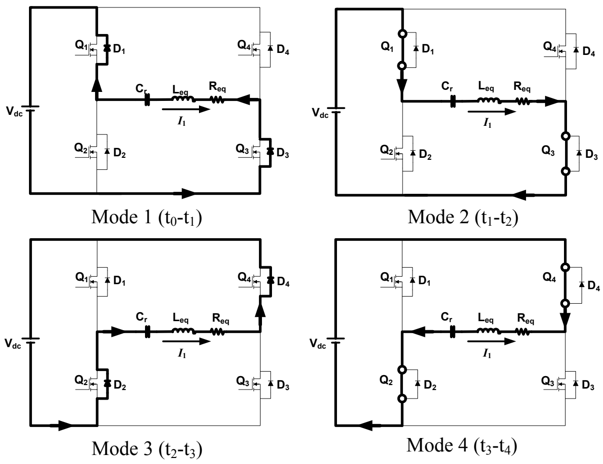


Fig. 5. Operation modes of full bridge series resonant inverter

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 of modes from 1 to 4.

C. 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

$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C_r}} \tag{2}$$

The normalized switching frequency is

$$f_n = \frac{f_s}{f_r} \tag{3}$$

with f_S being the switching frequency

The characteristic impedance is

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

The resonant load quality factor is

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

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

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

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

The current phase angle is

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

The voltage across the resonant tank circuit V_d is

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

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

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

where

$$V_m = \frac{4}{\pi} V_{dc} \approx 1.273\, V_{dc} \tag{11}$$

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

$$I_1 = I_m \sin(\omega_s t - \emptyset) \tag{12}$$

where

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

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

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

From the eq. (14) the output power can be controlled by varying the load current by the duty ratio of the inverter. At low duty ratios, the efficiency of the inverter is also low comparing with high duty ratios. 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, a cascaded load inverter configuration is proposed with constant switching frequency and constant duty ratio of inverter with a switching device at load. Independent output power control of each load is done by varying the duty ratio of load switching device.

III. Proposed Cascaded Load Inverter Configuration

A. Cascaded Load Inverter Configuration

Single inverter with two load configuration is proposed and analyzed and it uses variable switching frequency control scheme [9]. The output power of two loads are individually controlled is the main aim in 3-leg full bridge series resonant inverter [10]-[11]. We propose a two cascaded load series resonant inverter configuration with independent output power control of each load by varying the duty ratio of load switching device. The inverter switching frequency is chosen above its resonant frequency for ZVS operation of inverter switching devices. The full bridge inverter operates with constant switching frequency at constant duty ratio for efficient ZVS operation with high efficiency.

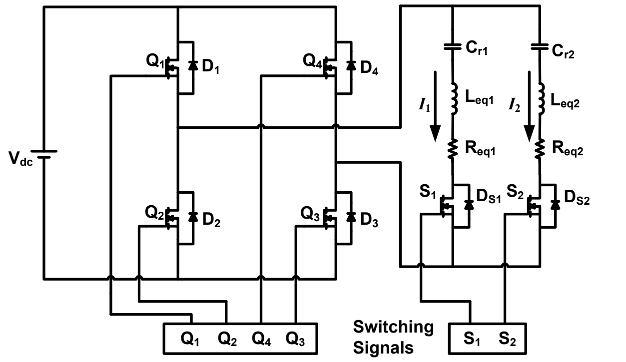


Fig. 6. Proposed two load full bridge series resonant inverter

The proposed two cascaded load inverter configuration for induction cooking application 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 induction coil with vessel and R_{eq} is the equivalent resistance of induction coil with vessel. A switching device ($S_{1,2}$) with anti parallel diode ($D_{S1,S2}$) is in series with each load. Controlling the output power of each load is done independently, by varying the duty ratio of $S_{1,2}$. This configuration can be extended to multiple loads.

B. Block Diagram of Output Power Control

In proposed configuration, the output power is controlled by S_{power}, and full bridge inverter is operated with constant switching frequency at constant duty ratio. Load output power is P_{out}. S_{power} is defined as the duty ratio of load switching device $S_{1,2}$. 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),

$$P_{regulated} = P_{out}.\ S_{power}.$$

$$= \left(\frac{I_m^2}{2} R_{eq}\right) S_{power}$$

$$= \left(\frac{8V_{dc}^2 \cos\emptyset^2}{\pi^2 R_{eq}}\right) S_{power} \qquad (15)$$

The proposed output power control has a function of controlling the load output power by varying the duty ratio of load switching device (S_{power}).

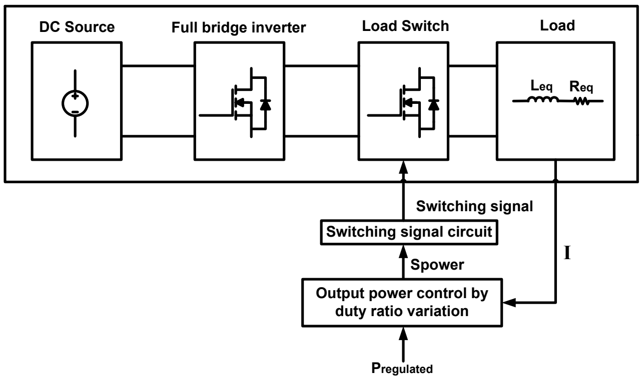


Fig. 7. Proposed block diagram of output power control

The block diagram of output power control for the proposed inverter configuration is shown in Fig. 7. Generally, load switching device $S_{1,2}$ is turned-on during T_{on} period, the load current I is flowing through the load. When load switching device is turned-off during T_{off} period, the load current is zero. The load switching device $S_{1,2}$ should be turned-off, with the positive cycle of inverter output voltage starts. In this duration the anti parallel diode $D_{S1,S2}$ across the load switching device $S_{1,2}$ provides a path to complete the negative cycle of load current reaches to zero position. Once the load current reaches to zero position, there is no path for positive cycle of load current and the load current will be in zero position till the load switching device turned-on, due to its high quality factor. When switching pulse is given to the load switching device $S_{1,2}$, the positive cycle of load current starts to flowing through the load. The switching frequency of load switching device is equal to the inverter switching frequency. The proposed inverter configuration provides the output power of each load can be controlled independently by varying the duty ratio of respective load switching device $S_{1,2}$. 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. Output power of each load is controlled by controlling the respective load current. So this configuration can be extended to multiple loads.

IV. Simulation and Results

To verify theoretical predictions, the proposed cascaded load inverter configuration for induction cooking application is simulated in ORCAD (P-Spice). ZVS operation for inverter switching devices is achieved by choosing the switching frequency more than its load resonant frequency. The inverter is also operated with constant switching frequency of 30 kHz at constant duty ratio of 100%. The load switching device $S_{1,2}$ switching frequency is 30 kHz and its duty ratio is varied from 60% to 100% for controlling the output power of each load independently. At source voltage (V_{dc}) of 35V, the output power of each load is 370 watts. The output power of each load is varied from 10W to 370W. The proposed cascaded load inverter configuration is simulated with the parameters as shown in Table I.

TABLE I
FULL BRIDGE INVERTER SPECIFICATIONS AND CIRCUIT PARAMETERS

Component	Symbol	Rating value
Source voltage	V_{dc}	35 V
Switching frequency	f_S	30 kHz
Rated output power	P_{out}	375 W
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 switching frequency	f_{SW}	30 kHz
Switching devices Q_1 to Q_4 and S_1, S_2	MOSFET IRFM 250	200V, 27.4A
Duty ratio of S_1	D_1	80%
Duty ratio of S_2	D_2	60%
Dead time for inverter switches	T_d	0.3 µsec

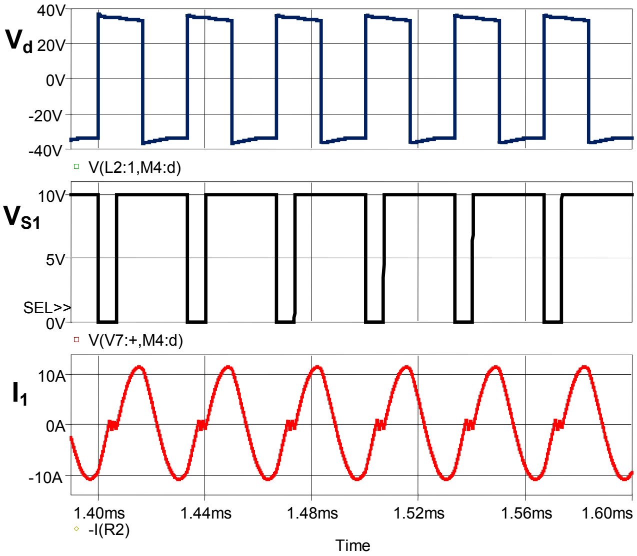


Fig. 8. Inverter output voltage and load-1 current at 80% duty ratio of its load switching device

Fig. 8 shows inverter output voltage V_d, switching gate pulse V_{S1} for load switching device S_1 with the same switching frequency of inverter and also it should be turned-off with the positive cycle of inverter output voltage V_d starts. The load-1 current waveform shows that, when the load switching device S_1 is turned-off and also D_{S1} provides a path for the negative load current comes to zero position. Here, the duty ratio of load switching device S_1 is 80%. i.e., after S_1 is switched on, the load-1 current is flows through the load.

Similarly, Fig. 9 shows inverter output voltage V_d, switching gate pulse V_{S2} for load switching device S_2 with the same switching frequency of inverter and also it should be turned-off with the positive cycle of inverter output voltage V_d starts. The load-2 current waveform shows that the load switching device S_2 is turn-off also D_{S2} provides a path for the negative load current comes to zero position. Here, the duty ratio of load switching device S_2 is 60%. i.e., after S_2 is switched on, the load-2 current is flows through the load.

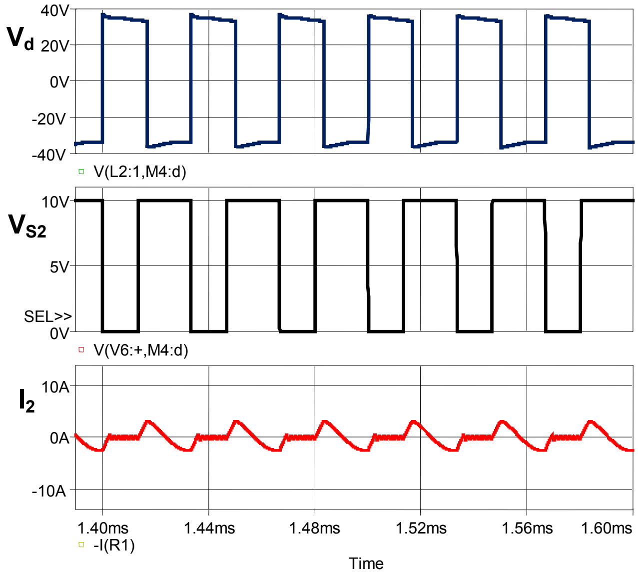
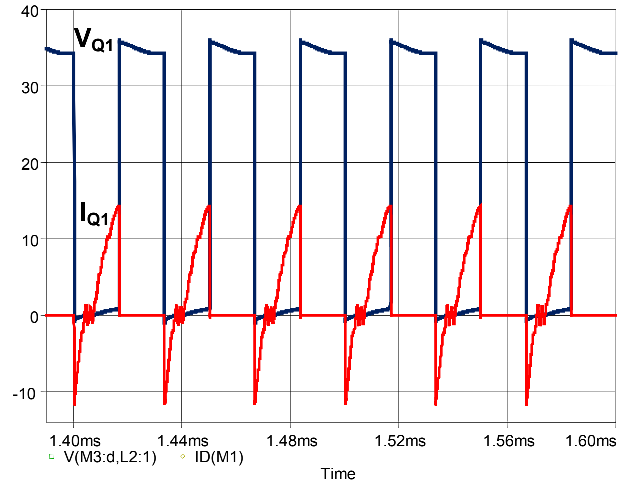
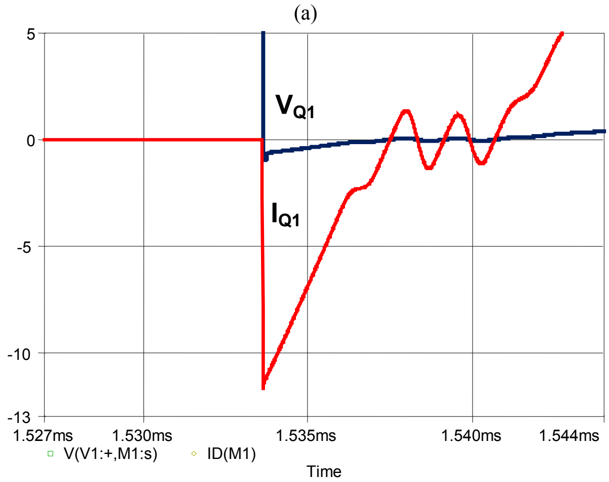


Fig. 9. Inverter output voltage and load-2 current at 60% duty ratio of its load switching device



(a)



(b)

Fig. 10. Voltage and current waveforms of inverter switch Q_1. (a) ZVS operation of inverter switch Q_1 (b) ZVS at turned-on position

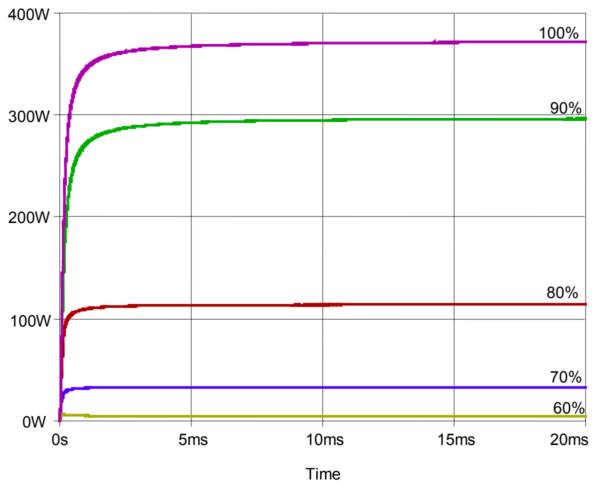


Fig. 11. Output power control with varying of S_1 duty ratio

Fig. 10 shows the voltage and current waveforms of inverter switch Q_1. Fig. 10(a) shows the ZVS is obtained at inverter switching device Q_1. Fig. 10(b) shows the ZVS at turned-on position of inverter switching device Q_1. The inverter switches are operated with ZVS by constant switching frequency at 100% duty ratio. So, the inverter is operated at higher efficiency. Load-1 output power is controlled by variation of load switching device S_1 duty ratio from 60% to 100% as shown in Fig. 12. Similarly, the load-2 output power is also controlled by variation of load switching device S_2. The load output power is more at higher duty ratios. Each load output power can be controlled independently. The full bridge inverter operates at constant switching frequency with 100% duty ratio. So, the full bridge inverter operates at maximum efficiency and reduces switching losses with ZVS operation from light load to full load. The proposed configuration can be extended to multiple loads also.

V. CONCLUSION

In this paper, a cascaded load inverter configuration for induction cooking application with independent output power control has been proposed. Characteristics of full bridge series resonant inverter at 100% duty ratio and proposed inverter configuration are explained in detail. The proposed configuration is simulated with two loads, which are connected to inverter output terminals, with a series load switching device. From the proposed inverter configuration, we can obtain the output power controlled of each load independently, for wide power regulation range. Inverter switching devices are operating with efficient ZVS with constant switching frequency of 30 kHz and constant duty ratio of 100%. Each load output power can be varied from 10W to 370W, by varying the duty ratio of load switching device from 60% to 100%. This proposed configuration can be extended to multiple loads.

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