Development of Series Resonant Inverters for Induction Heating Applications

Khairy Sayed, Farag Abo-Elyousr, Farid N. Abdelbar, and Heba El-Zohri

***Abstract*—This paper proposes a cost-effective series resonant inverter employed in applications of induction heating. The proposed inverter operates with high-frequency pulse-density modulation strategy for soft-switching. The high-frequency operation (20 kHz – 100 kHz) of this inverter results in a nearly sinusoidal output that is suitable for relatively fixed output applications such as induction heating. The series resonance circuit comprises an inductor and a capacitor that are in series with the load. The small size of resonating components is due to the high-frequency switching operation. The practical effectiveness of induction heating power supply is substantially proved by implementing a prototype series resonant inverter. To analyze the performance, comparison between the simulation and experimental results is done by using PSIM program.**

***Index Terms*—Resonant inverters; Induction heating; High frequency; Switching losses; soft switching.**

I. INTRODUCTION

Nowadays, resonant inverters are used intensively due to their merits such as reduced losses by soft-switching techniques and high-frequency operation, high efficiency, small size, and light weight. These resonant inverters nearly produce a sinusoidal output waveform at a high frequency (20 kHz – 100 kHz). This sinusoidal output is employed in nearly fixed output applications like induction heating [1]-[3]. Previous research works focused on the development of inverters so that producing high power to induction heating loads at high frequencies ranging from 10 to 200 kHz. These research works are devoted to get higher efficiency, lighter weight, and simplicity of the overall system [4]-[10].

An optimum capacitance is introduced in [11]. This capacitance maximizes the output power taking into account the capacitor loss simultaneously. This research work includes an equivalent series resistance in order to investigate the effect of capacitor heat-up. Cascade inverters are proposed as a cost-effective approach used in various renewable energy applications. This is due to its flexible modular design, transformer less connection, extended output voltage and output power, low maintenance, and high fault tolerance. Neutral-point-clamped inverter, flying capacitor inverter, and cascade H-bridge inverter are the most types of voltage source inverters that are usually used and available on the market [12],[13]. The variable-frequency operation of series resonant inverters is employed in order to control the power supplied to induction heating loads [14],[15].

This paper aims to develop a low-cost series resonant inverter that can be employed in induction heating applications. The performance is evaluated by simulating the circuit system with PSIM software package. The simulation results will be verified by comparing with the corresponding experimental results obtained with implementation of a prototype series resonant inverter.

II. CIRCUIT DESCRIPTION AND PRINCIPLE OF OPERATION

Power supplies of induction heating are resonant inverters that produce peak current at resonance. This peak current is sufficient to heat-up the work piece. The series resonant inverters got their name from placement of the resonating components and switches in series with the load in order to have an under-damped circuit. The switches are commutated naturally due to the natural characteristics of the circuit. Anti-parallel diodes are placed across the switches in the circuit scheme. These diodes are used in order to permit inductor's current conduction when the corresponding switches are turned-off. The use of resonant inverters reduces significantly the switching losses so that increasing the efficiency of energy conversion. Fig. 1 shows the circuit scheme of series resonant inverter employed in induction heating. Power MOSFETs are used as the switching devices due to their convenient capability for high-frequency operation.

In order to match between the supply impedance and the load impedance, a matching transformer is connected to the inverter output. This matching facilitates the transfer of maximum power from supply to load. The analysis of this circuit starts by expressing the frequency response as follows.

III. SWITCHING MODES OF OPERATION

The scheme of the circuit includes a full-bridge inverter comprises four MOSFETs as switching devices. The inverter has two legs with a pair of switches for each leg. The switches are operated with high-frequency switching so that at any instant of time only one switch at a leg is ON. The switching modes of operation are illustrated in Fig. 2 with two modes of operation. In mode (a), the two switches S_1 and S_4 are ON and positive voltage and current appears across the load. In mode (b), the two switches S_1 and S_4 are OFF whereas the other two switches S_2 and S_3 are ON and negative voltage appears across the load.

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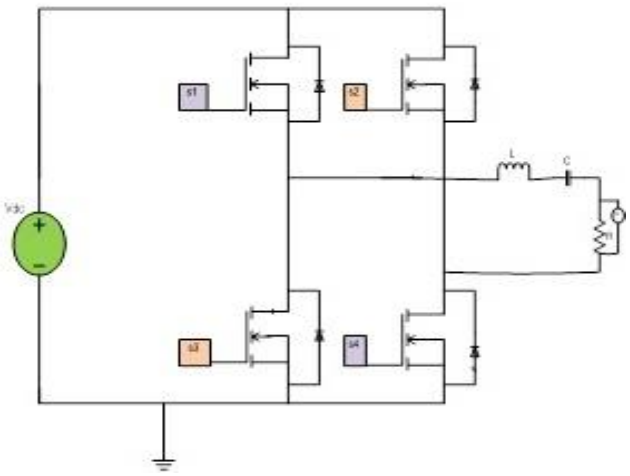

Fig. 1. Circuit diagram of series resonant inverter

$$\frac{z_0}{z} = \frac{1}{\sqrt{R^2+(\omega L-(1/\omega C))^2}} \frac{1}{\sqrt{1+((\omega L/R)-(1/\omega RC))^2}} \quad (1)$$

Resonance occurs at the frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

The angular resonant frequency ω_0 is given by:

$$\omega_0 = 2\pi f_0 = 1/\sqrt{\text{LC}} \quad (3)$$

and the characteristic impedance is calculated by:

$$z_0 = \sqrt{\frac{\text{L}}{\text{C}}} \quad (4)$$

IV. Switching Modes of Operation

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V. Simulation Results

In the simulation, the output switching frequency was 40 kHz. The two switches S_1 and S_4 were switched from angle 0 to 170 whereas the other two switches S_2 and S_3 were switched from angle 190 to 340. This switching delay is made in order to achieve a dead time zone between the two switches S_1 and S_4 in the first leg and the other two switches S_2 and S_3 in the other leg so that avoiding any short circuit (see Fig. 3). The simulated waveform of output load voltage is given in Fig. 4. Figure 5 shows the efficiency variation with the input power for the proposed series resonant inverter employing PWM control supplying an induction heating load. For the rated output, the efficiency reaches about 96%. On the other hand, for the minimum output the efficiency can be maintained to 84%.

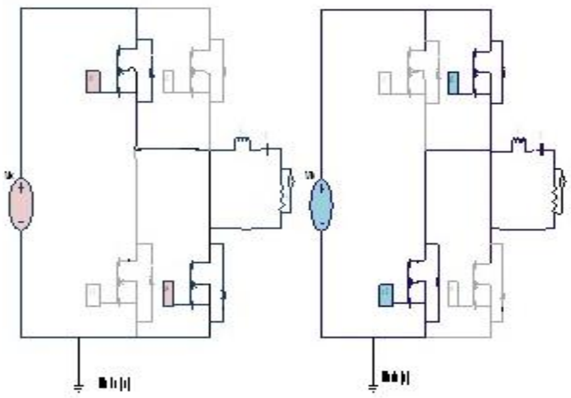


Fig. 2. Switching modes of series resonant inverter

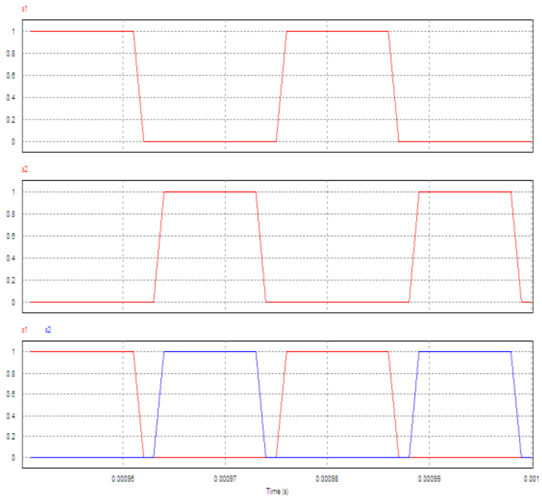


Fig. 3. Simulated switching gate pulses

VI. Experimental Setup and Results

An experimental prototype is implemented in order to verify the simulation results with adopting the same circuit parameters used for simulation. The circuit parameters are listed in Table I. The gate pulses are generated with a time delay so that avoiding short circuit for switches operation. In accordance with the circuit parameters, the required system has been implemented in the laboratory. The circuit was tested on test board as shown in Fig. 6a and the whole system is shown in Fig. 6b. After finishing the test, the circuit was implemented to the copper board as shown in Fig. 6c and connected with a control board by using (Arduino Mega2560) as shown in Fig. 6d. Fig. 7 shows a photograph of the implemented inverter.

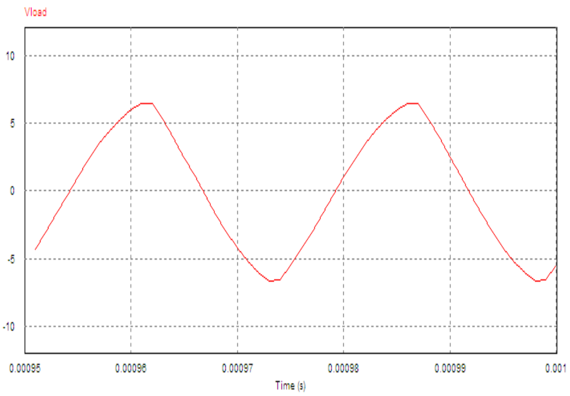


Fig. 4. Simulated waveform of output voltage

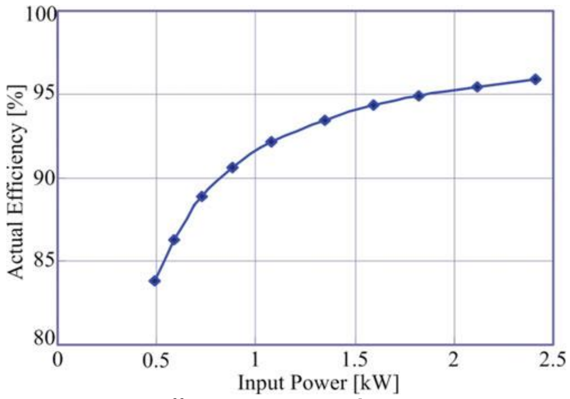


Fig. 5. Efficiency variation with input power

TABLE I: CIRCUIT PARAMETERS

ITEM	Description	Value
V_{DC}	Input voltage (power supply)	30 V
F_0	Resonant frequency	40 kHz
F_s	Switching frequency	40 kHz
S_1,S_4	Switch	0-170
S_2,S_3	Switch	190-340
IC	Optocoupler (TLB 250)	
IC	SG (3524)	
MOSFET	(SgHg40n60nv)	
L_1	Inductor coil	500 µH
C_1	Resonant capacitor	0.06 µF
R_l	Load resistor	10 Ω

The experimental switching pulses are shown in Fig. 8. The experimental results are in accordance with the simulated results. The switching frequency was f = 40.20 kHz and the duty cycle was 46.13%. Figure 9 shows the waveform of switching voltages where the value of the frequency was f = 38.61 kHz and the duty cycle was 46.24%. Figure 10 shows the waveform of output voltage after filtering by using an integrated circuit in Fig. 10a and by using a microcontroller in Fig. 10b.

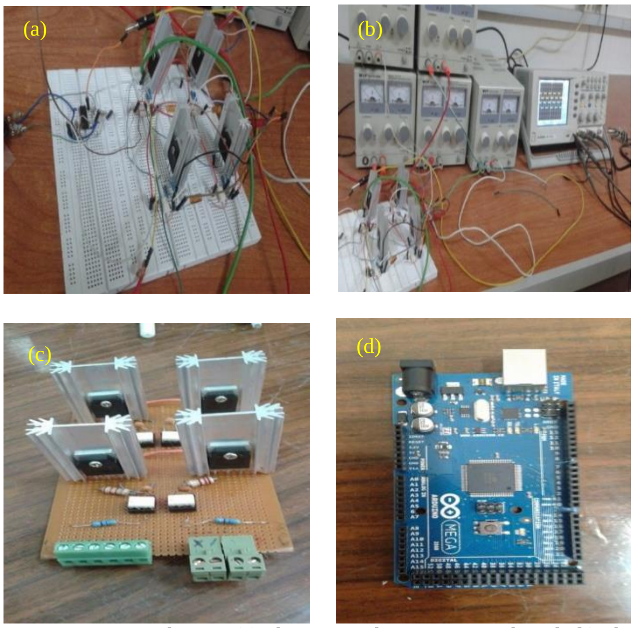


Fig. 6. Experimental setup: (a) The proposed system on test board, (b) The whole system, (c) Implementation of the circuit on copper board, and (d) control board by using Arduino Mega2560.

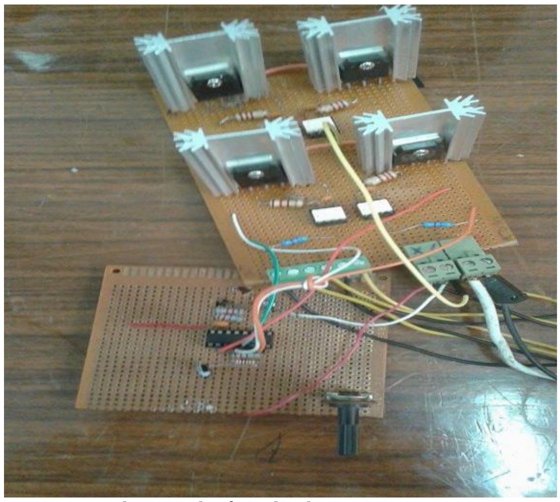


Fig. 7. A Photograph of single-phase series inverter circuit

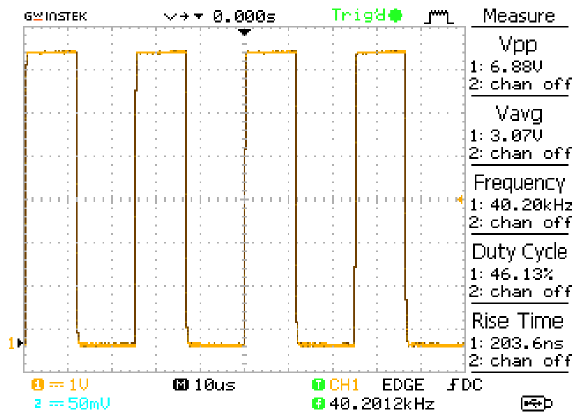


Fig. 8. Experimental switching pulses

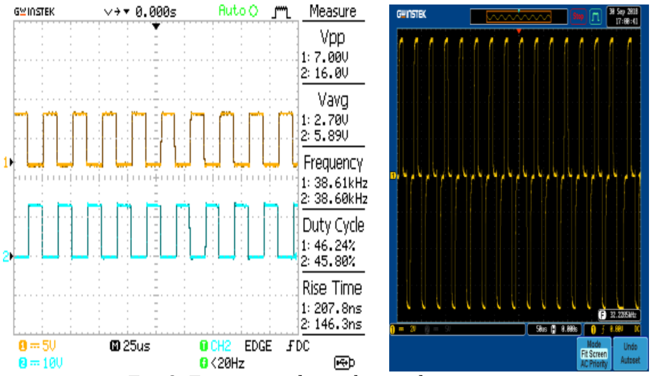
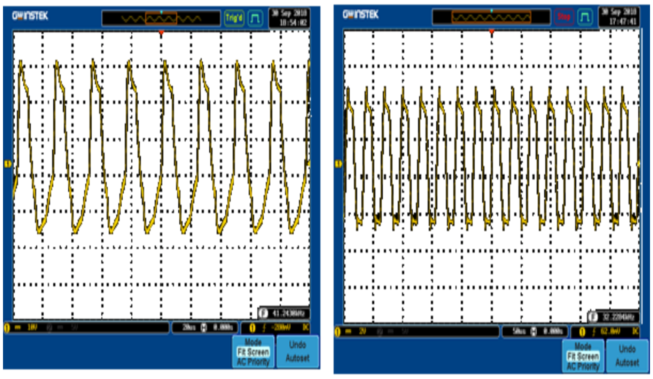


Fig. 9. Experimental switching voltages.



(a) (b)

Fig. 10. Output voltage after filtering: (a) By using IC (SG) and (b) by using Arduino Mega2560.

VII. Conclusion

In this research paper, a series resonant inverter was developed and analyzed for industrial induction heating application. The main advantage of the proposed series resonant converter is its simplicity and its high efficiency from full-load to light-load. The practical effectiveness of induction heating power supply was substantially proved by implementing prototype series resonant inverters. The operating principle and operating characteristics of the proposed high-frequency circuit treated here were illustrated and evaluated on the basis of simulation and experimental results. A Comparison between the simulation and experimental results was done to investigate the operating performance. There is a good agreement between simulation and experimental results.

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