

A novel circuit topology of modified switched boost hybrid resonant inverter fitted induction heating equipment

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Abstract: A novel circuit topology of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment is presented in this paper for efficient induction heating. Recently, induction heating technique is becoming very popular for both domestic and industrial purposes because of its high energy efficiency and controllability. Generally in induction heating, a high frequency alternating magnetic field is required to induce the eddy currents in the work piece. High frequency resonant inverters are incorporated in induction heating equipment which produce a high frequency alternating magnetic field surrounding the coil. Previously this high frequency alternating magnetic field was produced by voltage source inverters. But VSIs have several demerits. So, in this paper, a new scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment has been depicted which enhances the energy efficiency and controllability and the same is validated by PSIM.

Key words: modified switched boost, high frequency, hybrid resonant inverter, induction heating, controllability, VSI and PSIM

1. Introduction

Now a day, usage of induction heating technique has been significantly increased because of its energy efficiency, controllability and cost effectiveness. In induction heating, generally a high frequency alternating current is passed through a heating coil to produce a rapidly alternating magnetic field. When the work piece to be heated, is placed within that field, eddy currents are induced in the work piece by electromagnetic induction [1, 2]. These eddy currents when flow through the work piece, produce heat by Joule's effect due to inherent resistance of the work piece. High frequency resonant inverters are incorporated in the induction heating equipment to produce the high frequency alternating magnetic field [3]. In the earlier works, generally voltage source inverters were used for this purpose. But there are certain kinds of limitations in case of voltage source inverters [4-6].

- In voltage source inverters, output voltage is always less than dc input voltage. So, it is generally a buck inverter. VSIs do not have voltage boost up capability.
- VSIs do not allow shoot through in the inverter legs i.e. the upper and lower switches of the same leg of the inverter cannot be switched on simultaneously. Dead time circuit is required in voltage source inverters.
- The performance of VSIs is not reliable in case of EMI noise.

The proposed topology of modified switched boost high frequency hybrid resonant converter overcomes these limitations. Here an impedance network is used to couple the power circuit to the converter. In modified switched boost high frequency hybrid resonant converter, shoot through state can be utilized to boost up the output voltage of the inverter resulting in the increase in efficiency and controllability of the induction heating equipment.

2. The developed scheme and its operation

In the previous topology of induction heating equipment used in fluid heating purpose, at first there is an uncontrolled rectifier which converts the single phase ac to dc. Then there is a dc link high frequency inverter, which converts the input dc to high frequency ac. The previous scheme of high frequency voltage source hybrid resonant inverter fitted induction heating equipment is shown in Fig. 1. Here an induction coil wound non-metallic pipe with inbuilt metallic packages serves as load. Fig. 2 depicts the equivalent circuit of the previous scheme of high frequency voltage source hybrid resonant inverter fitted induction heating equipment. In the developed topology, at first the single phase ac supply is converted to dc by an uncontrolled full bridge rectifier. After that there is a switched boost network which is composed of one active switch, two diodes, one inductor and a capacitor. After that there is a high frequency hybrid resonant inverter comprising of four IGBT switches. The switching frequency of the high frequency inverter is near the resonant frequency of the tank circuit (load circuit) i.e. 47 kHz. The induction coil and the work piece to be heated act as the load of the hybrid resonant inverter. The equivalent circuit of the induction heating equipment is formed by the equivalent impedance of the induction coil and its secondary object as reflected in primary. The switched boost network provides an impedance source which couples the inverter to the dc source. Because of the high frequency switching of the hybrid resonant inverter, a high frequency alternating current flows through the coil resulting in induction heating of the work piece. In normal voltage source inverters, the shoot through condition cannot be utilized, because that will result in the direct short circuit of the voltage source. Whereas, in the present scheme of modified switched boost high frequency hybrid resonant inverter, the shoot-through condition can be used intentionally to step up the inverter output voltage [4, 7]. So, a wide variety of output voltage can be found for any input voltage. As the switching frequency of the inverter is very high, high frequency harmonics are produced in the load which tries to flow back towards the supply. This will result in the deterioration of the power quality. So, to improve the input power quality, a low pass filter is connected at the input which prevents the high frequency components to flow back towards supply side [8].

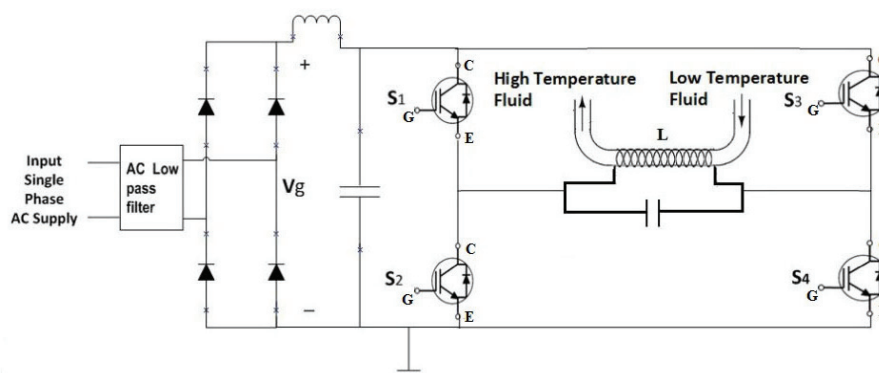


Fig. 1. Previous scheme of high frequency voltage source hybrid resonant inverter fitted induction heating equipment

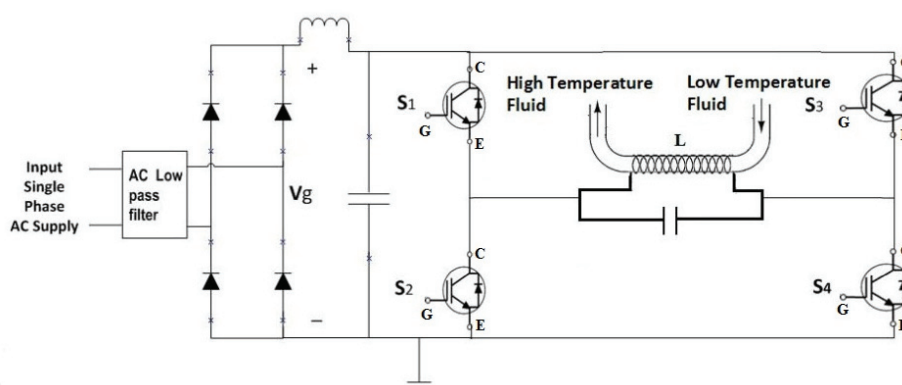


Fig. 2. Equivalent Circuit of the previous scheme of high frequency voltage source hybrid resonant inverter fitted induction heating equipment

3. Analysis of modified switched boost hybrid resonant inverter

The equivalent circuit of the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment is shown in Fig. 3. In this scheme, an induction coil wound non-metallic pipe serves as the load. The equipment is used for fluid heating purpose. Metallic packages are incorporated inside the non-metallic pipe to heat the fluid passing through it.

Here L_R , R_L and C_R represent the equivalent impedance of the induction coil and the work piece as referred to primary. The circuit parameters are intentionally chosen to make the circuit under damped. As the switching frequency of the high frequency inverter is very high, so appreciable amount of switching loss is associated with it. To minimize this switching loss, soft switching technique (ZCS) is implemented in the circuit [9-11]. Both series and parallel

resonance occurs in this circuit. Here at first there is an uncontrolled full bridge rectifier to rectify the single phase ac supply to dc. This dc voltage serves as the input of the modified switched boost high frequency hybrid resonant inverter. S_1 and S_4 are switched on first and resonant current flows through the load. In this period C_R is charged. In the period when S_1 and S_4 are on, for some instants S_2 and S_3 are also switched on at high frequency. The shoot through condition is intentionally created to boost up the output voltage. The load current becomes sinusoidal as the circuit is under damped. Then at some zero current crossover point, S_1 and S_4 are switched off. Now the capacitor (C_R) is discharged through L_R and R_L . So heat is produced due to Joule's effect.

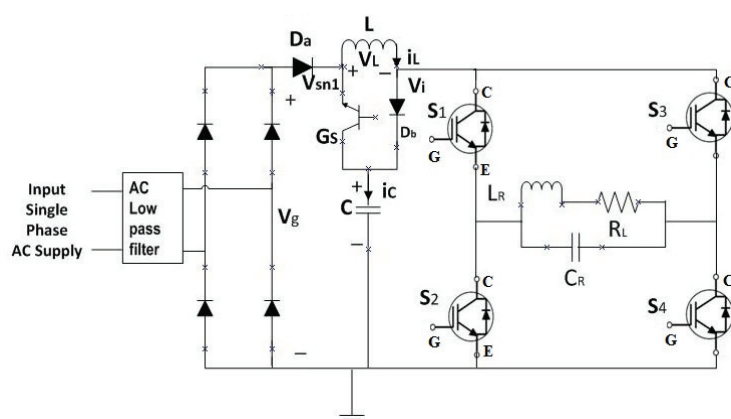


Fig. 3. Equivalent circuit of the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment

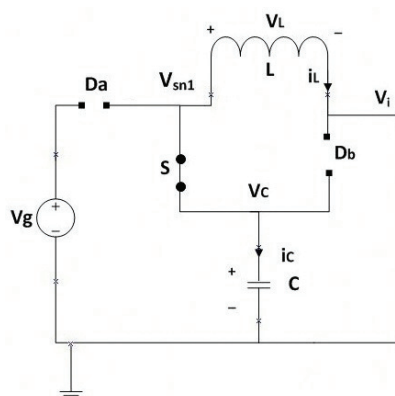


Fig. 4. Equivalent circuit of the modified switched boost high frequency hybrid resonant inverter when the inverter bridge is in the shoot-through state

At first to explain the steady state operation of a modified switched boost inverter, it is assumed that shoot through condition is intentionally created in the inverter for a duration of DT_S in a switching cycle of T_S [12-14]. During this shoot through state the switch S is turned

on. The equivalent circuit for this duration is shown in Fig 4. For the rest of the switching cycle i.e. for the duration of $(1-D)T_S$, the inverter is in the non-shoot-through state. In this duration, the switch S is turned off. The inverter bridge with load is represented by a current source as depicted in Fig. 5. Fig. 6 shows the various steady state waveforms of the modified switched boost high frequency hybrid resonant inverter [12].

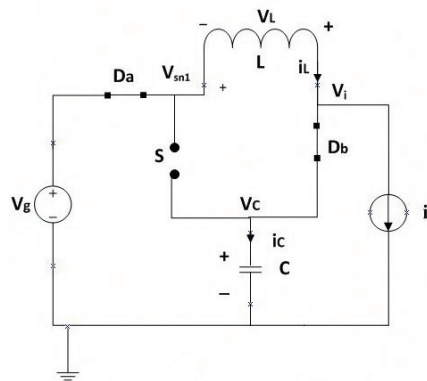


Fig. 5. Equivalent circuit of the modified switched boost high frequency hybrid resonant inverter when the inverter bridge is in non-shoot-through state

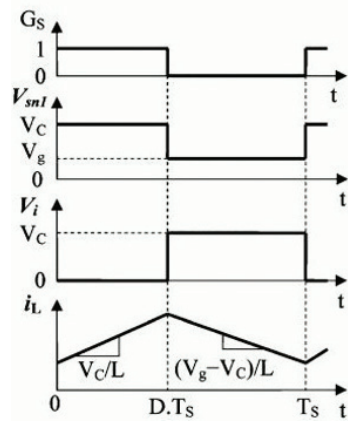


Fig. 6. Steady state waveforms of the modified switched boost high frequency hybrid resonant inverter

From Figs. 4 and 5, it can be concluded that

$$\begin{aligned}
 v_L(t) &= v_C(t) \quad \text{for } 0 < t < DT_S \\
 &= v_C(t) - V_g \quad \text{for } DT_S < t < T_S
 \end{aligned}
 \tag{1}$$

$$\begin{aligned}
 i_C(t) &= -i_L(t) \quad \text{for } 0 < t < DT_S \\
 &= i_L(t) - i_i(t) \quad \text{for } DT_S < t < T_S
 \end{aligned}
 \tag{2}$$

$$\begin{aligned} v_i(t) &= 0 \quad \text{for } 0 < t < DT_S \\ &= v_C(t) \quad \text{for } DT_S < t < T_S \end{aligned} \quad (3)$$

where $v_L(t)$, $v_C(t)$ and $i_L(t)$, $i_C(t)$ represent the instantaneous voltage across the inductor and capacitor and the instantaneous current through the inductor and capacitor of the modified switched boost network respectively. Also, $v_i(t)$ denotes the instantaneous voltage across the output of the modified switched boost network and $i_i(t)$ denotes the instantaneous current drawn by the inverter bridge in the duration of $(1-D)T_S$. V_g represents the output voltage of the uncontrolled full bridge rectifier.

Considering only the dc component, the equations can be rewritten as

$$\begin{aligned} v_L(t) &= V_C \quad \text{for } 0 < t < DT_S \\ &= V_g - V_C \quad \text{for } DT_S < t < T_S \end{aligned} \quad (4)$$

$$\begin{aligned} i_C(t) &= -I_L \quad \text{for } 0 < t < DT_S \\ &= I_L - I_i \quad \text{for } DT_S < t < T_S \end{aligned} \quad (5)$$

$$\begin{aligned} v_i(t) &= 0 \quad \text{for } 0 < t < DT_S \\ &= V_C \quad \text{for } DT_S < t < T_S \end{aligned} \quad (6)$$

Here V_C and I_L are average dc components of $v_C(t)$ and $i_L(t)$ and I_i is the dc current drawn by the inverter bridge in the duration of $(1-D)T_S$.

Under steady state, the average voltage across an inductor and the average current flowing through a capacitor in one complete switching cycle should be zero. Applying the volt-second balance, it can be found that

$$V_C \times D + (V_g - V_C) \times (1 - D) = 0, \quad \text{or} \quad \frac{V_C}{V_g} = \frac{(1 - D)}{(1 - 2D)} \quad (7)$$

Again, using the charge-second balance, it can be found that

$$-I_L \times D + (I_L - I_i) \times (1 - D) = 0, \quad \text{or} \quad \frac{I_L}{I_i} = \frac{(1 - D)}{(1 - 2D)} \quad (8)$$

So, the average dc link voltage V_i will be

$$V_i = 0 \times D + V_C \times (1 - D) = V_C \times (1 - D) \quad (9)$$

For successful operation of the high frequency inverter as shown in Fig. 3, the switching frequency must be chosen properly near the resonant frequency of the load tank. So, the resonant frequency of the load tank should be determined correctly. Fig. 7 depicts the load circuit of the equipment. Here L_R , R_L and C_R represent the equivalent impedance of the induction coil and its secondary object as referred to primary.

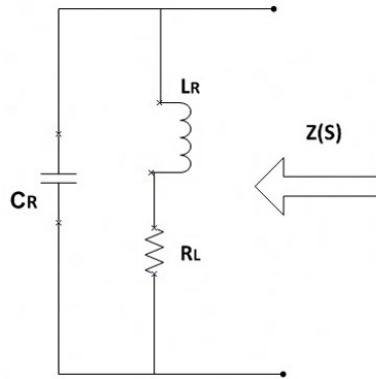


Fig. 7. Resonant load circuit of the modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment

Here:

$$Z(S) = \frac{(R_L + sL_R) \times \frac{1}{sC_R}}{(R_L + sL_R + \frac{1}{sC_R})} = \frac{(R_L + sL_R)}{(s^2 L_R C_R + sR_L C_R + 1)}$$

Now:

$$\begin{aligned} Z(j\omega) &= \frac{(R_L + j\omega L_R)}{[(j\omega)^2 L_R C_R + j\omega R_L C_R + 1]} \\ &= \frac{(R_L + j\omega L_R)[(1 - \omega^2 L_R C_R) - j\omega R_L C_R]}{[(1 - \omega^2 L_R C_R) + j\omega R_L C_R][(1 - \omega^2 L_R C_R) - j\omega R_L C_R]} \\ &= \frac{R_L + j\omega L_R - j\omega^3 L_R^2 C_R - j\omega R_L^2 C_R}{(1 - \omega^2 L_R C_R)^2 + \omega^2 R_L^2 C_R^2} \\ &= \frac{R_L + j(\omega L_R - \omega^3 L_R^2 C_R - \omega R_L^2 C_R)}{(1 - \omega^2 L_R C_R)^2 + \omega^2 R_L^2 C_R^2} \end{aligned}$$

At resonance, the imaginary part of $Z(j\omega)$ should be equal to zero.

$$(\omega L_R - \omega^3 L_R^2 C_R - \omega R_L^2 C_R) = 0, \text{ or } \omega(L_R - \omega^2 L_R^2 C_R - R_L^2 C_R) = 0, \text{ or } \omega = \sqrt{\frac{L_R - R_L^2 C_R}{L_R^2 C_R}} \quad (10)$$

Putting the values of $L_R = 57.1 \mu\text{H}$, $R_L = 1 \Omega$ and $C_R = 0.2 \mu\text{F}$, it can be found that

$$\begin{aligned} \omega^2 &= 0.087 \times 10^{12}, \text{ or } \omega = 0.295 \times 10^6, \text{ or } 2\pi f = 0.295 \times 10^6, \\ \text{or } f &= 46.97 \times 10^3, \text{ or } f \approx 47 \text{ kHz}. \end{aligned}$$

Now, the resonant frequency of the load tank circuit is approximately 47 kHz. So, the modified switched boost high frequency hybrid resonant inverter is operated at this switching frequency to minimize the associated switching loss and to maximize the output voltage.

4. Simulation diagram and results

The simplified equivalent circuit of the proposed topology of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment has been developed and then simulated in PSIM. The simulated circuit diagrams and the obtained waveforms are shown in the following figures. Fig. 8 depicts the simulated circuit diagram for the previous scheme of high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software. The waveform and RMS value of load voltage (VP5) and load current (I2) for the previous scheme is shown in Fig. 9. It can be seen from Fig. 9 that the RMS value of output voltage (VP5) and output current (I2) is 168.41 V and 9.151 A respectively. Fig. 10 depicts the waveform of inverter input voltage (VP7) for the previous scheme of high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software. The RMS value and average value of this dc link voltage (VP7) is 169.71 V and 152.79 V respectively as seen in Fig. 10. The circuit diagram of the developed scheme in PSIM is shown in Fig. 11. Here the switching frequency of the inverter is selected as 47 kHz. The obtained waveform of the output voltage (VP5) and output current (I2) after simulation and their RMS values are shown in Fig. 12. The RMS value of the output voltage (VP5) is 251.41 V and output current is 16.7 A as depicted in Fig. 12. So, from Fig. 9 and Fig. 12, it can be seen that in the new developed scheme, the RMS values of output voltage and output current are far better than in the previous existing scheme. So, efficient heating can be achieved in the proposed topology of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment. Fig. 13 depicts the waveform, RMS value and average value of inverter input voltage (VP7) for the developed scheme. From Fig. 13 it can be found that the RMS value and average value of inverter input voltage is 309.71 V and 245.09 V respectively. The gate voltage waveforms for the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment are shown in Fig. 14. It can be seen from the figure that there are some instances when intentionally the shoot through condition is created in the inverter i.e. both the IGBTs of the same leg are switched on. This shoot through condition is prohibited in normal voltage source inverter, but in modified switched boost high frequency hybrid resonant inverter, this switching state can be implemented to boost up the output voltage.

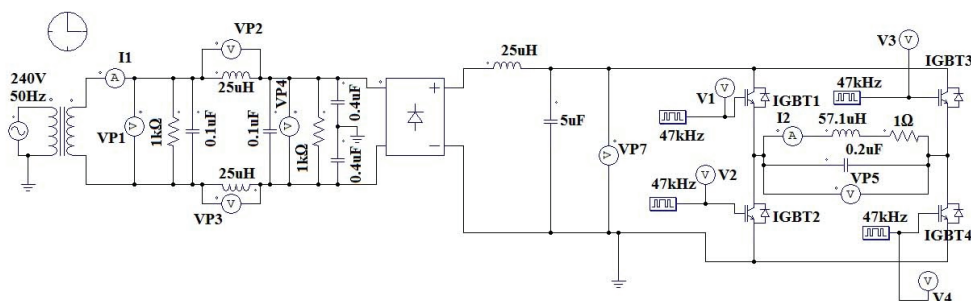


Fig. 8. Simulated circuit diagram for the previous scheme of high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

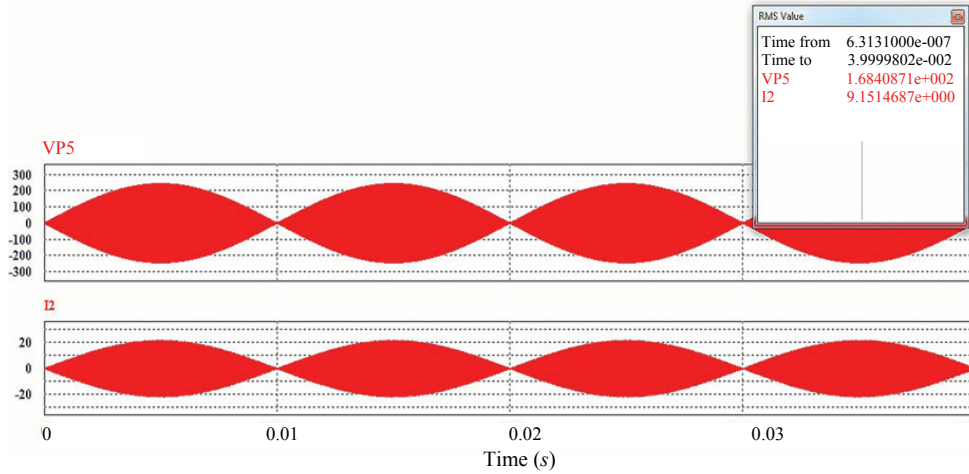


Fig. 9. Waveform and RMS value of load voltage (VP5) and load current (I2) for the previous scheme of high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

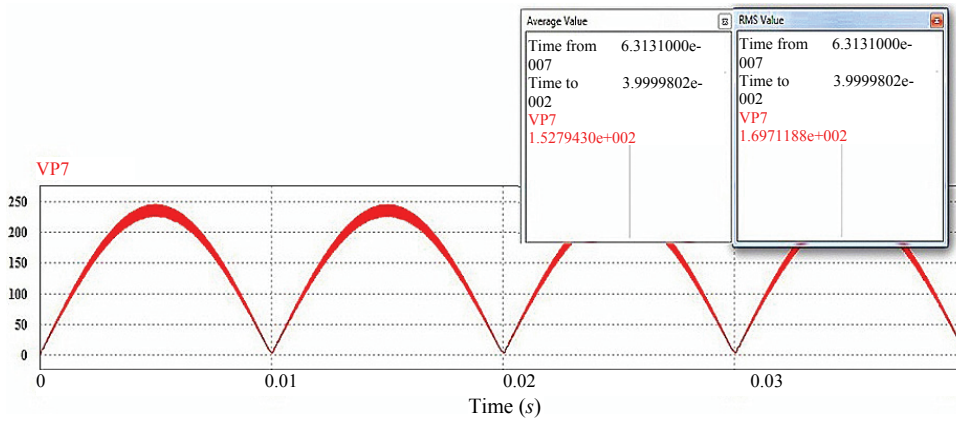


Fig. 10. Waveform, RMS value and average value of inverter input voltage (VP7) for the previous scheme of high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

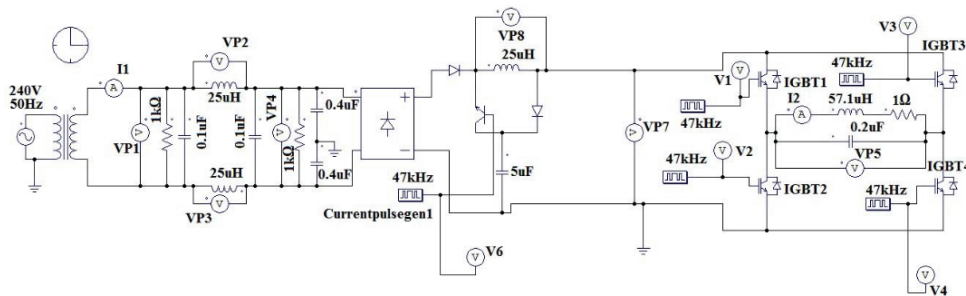


Fig. 11. Simulated circuit diagram for the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

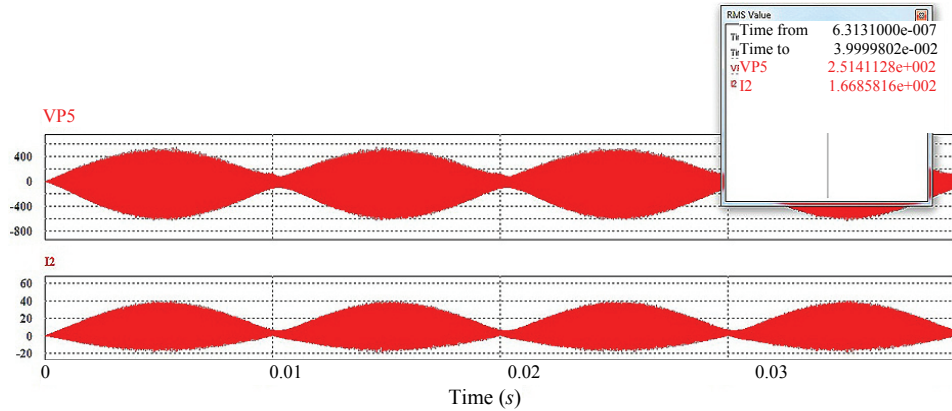


Fig. 12. Waveform and RMS value of load voltage (VP5) and load current (I2) for the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

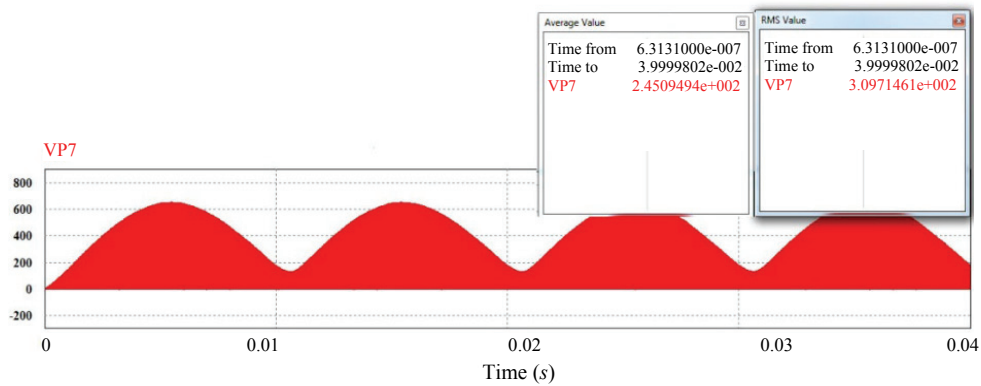


Fig. 13. Waveform, RMS value and average value of inverter input voltage (VP7) for the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

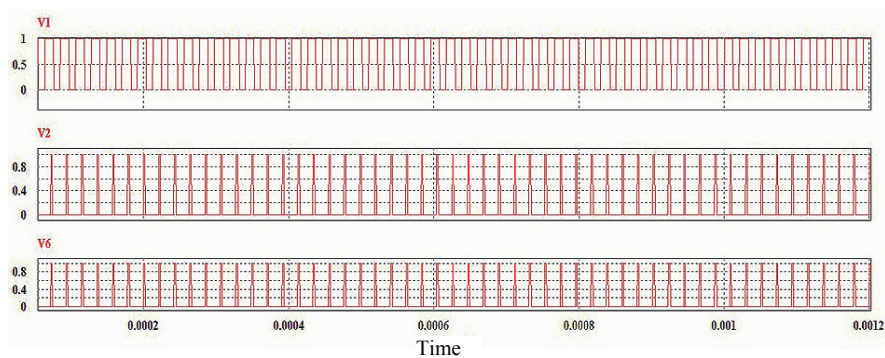


Fig. 14. Gate voltage waveforms for the developed scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment on PSIM software

Table. 1. Comparison of different results of previous scheme and present scheme obtained from simulation

	Previous Scheme	Present Scheme
RMS value of output voltage	168.41 V	251.41 V
RMS value of output current	9.151 A	16.7 A
RMS value of DC link voltage	169.71 V	309.71 V
Average value of DC link voltage	152.79 V	245.09 V

6. Conclusion

In this paper, a novel topology of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment is built which is useful both for domestic and industrial applications. The modified switched boost high frequency hybrid resonant inverter is operating near the resonant frequency of the load tank i.e. at 47 kHz. The equivalent circuit diagram is simulated on PSIM platform and the obtained waveforms are shown in figures. Here an impedance network couples the power circuit to the high frequency inverter circuit. So, the limitations of conventional voltage source inverters can be overcome by using this inverter. In this modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment, the shoot through condition can be intentionally implemented to boost up the load voltage. From the comparison table, it can be found that in the present scheme, the RMS value of output voltage and current is significantly higher than that of the previous scheme. So, a wide range of output voltage can be generated using this scheme resulting in a wide range of heating. This facility makes it applicable for high power induction heating applications. So, it can be concluded that this novel scheme of modified switched boost high frequency hybrid resonant inverter fitted induction heating equipment is highly energy efficient, controllable and suitable especially for high power applications.

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