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VOLTAGE CONTROLLED HYBRID RESONANT INVERTER– AN ESSENTIAL TOOL FOR INDUCTION HEATED EQUIPMENT

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Key words: High frequency, Hybrid resonant inverter, PSIM, Low pass (LP) filter, Induction heating, Controllability.

A new circuit topology of induction heating equipment consisting of voltage controlled hybrid resonant inverter is described in the present work and also it is simulated in PSIM. High frequency inverters are generally installed in modern induction heating equipments to produce the high frequency alternating magnetic field for better controllability, cost effectiveness and energy efficiency. In most of the cases of high frequency inverter, the inverter operates near the resonant frequency band to implement the soft switching technique which minimizes the switching loss. But earlier generally the switching frequency was varied to increase or decrease the heat in the work piece. This method has certain disadvantages. But in the proposed scheme shown here, there is a provision of changing the dc link voltage to change the intensity of heating. So in this method, the amount of heat produced in the work piece can be controlled, both by switching frequency control and supply voltage control resulting in the increase of controllability.

1. INTRODUCTION

Induction heating technique is comparatively cost effective, energy efficient and user friendly among other methods of electrical heating. So now a day, this technique is becoming very popular among the users. In induction heating, generally a high frequency alternating current is flown through the working coil to produce a rapidly alternating magnetic field. This high frequency alternating magnetic field links with the work piece when placed near the coil and eddy currents are induced in them [1]. These eddy currents when flow through the work piece produces heat due to Joule's effect. For the production of this rapidly alternating magnetic field, high frequency resonant inverters are employed in induction heating equipments [1–4]. The switching frequency of the inverter is chosen near the resonant frequency of the circuit to minimize the switching losses [4–8]. In the existing method, generally the switching frequency is varied to vary the intensity of heat in the work piece [8–10]. The depth of penetration of heat in the work piece changes with the change in switching frequency [11–13]. Depth of penetration is inversely proportional to the switching frequency. So uniform heating of the work piece cannot be achieved with the increase in switching frequency. Another difficulty which may arise in the course of operation is that if the frequency is varied widely, the resonant condition will no more exist in the circuit. So, soft switching technique cannot be implemented [14–18]. But in the proposed circuit there is a provision for changing the input dc link voltage of the inverter to change the intensity of heating in the work piece. In this induction heating equipment, three types of controlling technique can be used to change the intensity of heating in the work piece: voltage control, frequency control and both voltage and frequency control. Moreover, the relation between the developed heats with the change in frequency is nonlinear. But, the variation is almost linear with respect to the change in the dc link voltage. So, linear and smooth control can be achieved using the proposed scheme.

2. THE PROPOSED CIRCUIT AND ITS OPERATION

In this scheme, two full bridge rectifiers connected in parallel to convert the single phase ac supply to dc as shown in Fig. 1. In one of the rectifiers, four uncontrolled switches (diodes) are connected and in the other rectifier there are two uncontrolled switches and two controlled switches (MOSFETs). The dc link voltage can be varied by changing the switching frequency of the MOSFETs. This dc link voltage serves as the input of the high frequency hybrid resonant inverter. There are four controlled switches isolated gate bipolar transistors (IGBTs) in the inverter and the induction coil (working coil) along with the work piece behaves as the load of the inverter. Therefore by varying the switching frequency of MOSFETs connected in the half controlled rectifier, the intensity of heating in the work piece can be varied. The heating in the work piece can also be changed by changing the inverter switching frequency within a narrow band, such that resonant condition of the circuit remains unaffected. So in this scheme, three types of control can be implemented to vary the heat developed in the work piece: i) only voltage control, ii) only frequency control and iii) both voltage and frequency control. So controllability is improved appreciably as compared to the previous scheme. Due to high frequency switching in the inverter and the half controlled rectifier, high frequency harmonics are produced. When these high frequency harmonics are superimposed on the supply waveform, shape of the waveform will be distorted. So, to avoid this problem and to improve the input power quality, a low pass filter is connected in the input side of the equipment. This low pass filter will prevent the superposition of high frequency harmonics on the supply waveform.

3. ANALYSIS OF HYBRID RESONANT INVERTER

The developed scheme of hybrid resonant inverter fitted induction heating equipment is shown in Fig. 1. Here *G* represents the gate of the IGBTs of the high frequency inverter. Here the fluid passing through a non-metallic pipe is heated by induction heating. Metallic packages are fitted

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in this non-metallic pipe to heat the fluid flowing through it. Here an induction coil is wound on the non-metallic pipe. When high frequency alternating current flows through the pipe, eddy currents are induced in the metallic packages resulting in the heating of the fluid.

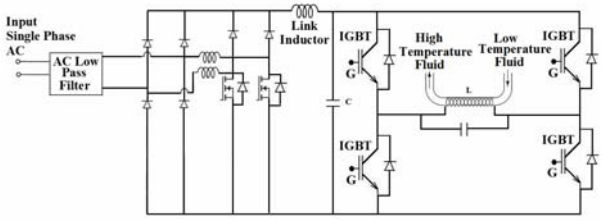

Fig. 1 – Present scheme of Hybrid resonant inverter fitted induction heating equipment.

The simplified equivalent circuit of the scheme is shown in Fig. 2. Here L_R, R_L and C_R represent the equivalent impedance of the induction coil and its secondary object reflected in primary. The equivalent impedance of the induction coil and the work piece is measured by connecting the non-metallic pipe with the metallic packages in it, across an LCR meter. The operating frequency of the meter is chosen equal to the inverter operating frequency. The various values of the inductance, capacitance and resistance are averaged and then the equivalent impedance model is developed. The circuit parameters are intentionally chosen to make the circuit an under damped one. In this circuit both series and parallel resonant circuits are combined. The switching operation is done at the zero crossing point of the current (ZCS) which results in the minimization of the switching loss. In this circuit at first a single phase ac supply is rectified to dc through two full bridge rectifiers connected in parallel. One of the rectifiers consists of four uncontrolled switches (diodes) and the other consists of two uncontrolled switches and two controlled switches (MOSFETs). By varying the switching frequency of the MOSFETs, the dc link voltage can be varied. This dc link voltage serves as the input of the high frequency inverter. In the circuit at first S_1 and S_4 is turned on. In this period a resonant current flows through the load and C_R is charged. At some zero current crossover point, S_1 and S_4 are switched off. Now the capacitor (C_R) starts discharging itself. In this discharging period, the current flows through L_R and R_L. So heat is produced according to Joule's effect. This is the required heat produced by eddy current heating in the work piece. S_2 and S_3 are switched on in the next half cycle and same process as mentioned previously is repeated. In this inverter the switching is done at very high frequency. So, a high frequency alternating current flows through the load. So, a rapidly alternating magnetic field is produced which cuts the secondary object (*i.e.* the metallic packages) and induces eddy currents in it. These eddy currents produce the required heat when flow through the secondary object.

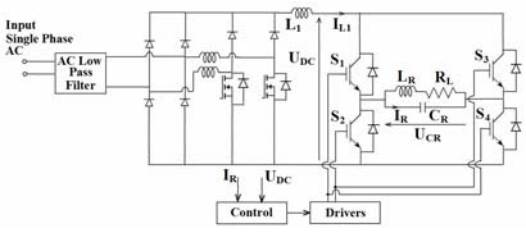

Fig. 2 – Equivalent circuit diagram for hybrid resonant inverter fitted induction heating equipment.

3.1. OUTPUT OF THE FIRST UNCONTROLLED RECTIFIER

Let, the input supply voltage is $V_m \sin \omega t$.

Then, the output voltage of the first rectifier will be $\frac{2V_m}{\pi}$.

Here the supply frequency $f_{Supp} = 50\,\text{Hz}$. So, time period is $T_1 = \frac{1}{f_{Supp}} = 0.02\,\text{s}$.

Switching frequency of MOSFETs is $f_{Sw} = 5000\,\text{Hz}$, then time period $T_{Sw} = \frac{1}{f_{Sw}}$.

3.2. OUTPUT OF THE SECOND HALF CONTROLLED RECTIFIER

Here, let the switching frequency of the MOSFETs be f_{Sw}. So, time period $T_{Sw} = \frac{1}{f_{Sw}}$.

In one half cycle of the output voltage of the second half controlled rectifier, there will be $\frac{T_1}{2T_{Sw}}$ number of switching cycles.

Duration of each partition in one half cycle is $\frac{T_{Sw}}{2}$.

The magnitude of i^{th} partition is $\frac{(b+a)}{2} + (-1)^i \cdot \frac{(b-a)}{2}$, where *a*, *b* are the magnitude of the two envelopes, both being functions of time. Here, $0 \le i \le \frac{1/2\, f_{Supp}}{1/f_{Sw}}$.

Otherwise, the least integer should be taken. Figure 3 depicts the simulated circuit diagram for the half controlled full bridge rectifier (frequency of MOSFET 11 kHz) on PSIM software and Fig. 4 depicts the waveform of output voltage for the half controlled full bridge rectifier (frequency of MOSFET 11 kHz) on PSIM software. So, putting the values of *b* and *a* from Fig. 4, it can be shown that the average output voltage of the half controlled rectifier is

$$V_{Oavg} = \int_0^{\pi} \left[\frac{(240\sin\omega t + 114.27\sin\omega t)}{2} + (-1)^i \frac{(240\sin\omega t - 114.27\sin\omega t)}{2}\right] \mathrm{d}(\omega t).$$

So, the dc link voltage can be mathematically expressed as $U_{DC} = \frac{2V_m}{\pi} - V_{Oavg}$.

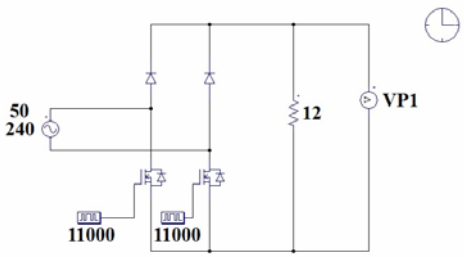

Fig. 3 – Simulated circuit diagram for the half controlled full bridge rectifier (frequency of MOSFET 11 kHz) on PSIM software.

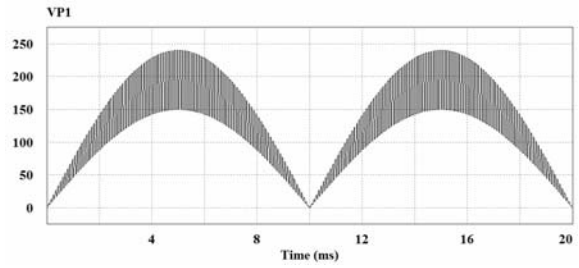

Fig. 4 – Waveform of output voltage for the half controlled full bridge rectifier (frequency of MOSFET 11 kHz) on PSIM software.

4. **SIMULATION DIAGRAM AND RESULTS**

The proposed topology of high frequency hybrid resonant inverter fitted induction heating equipment has been simulated in PSIM with the help of equivalent circuit parameters. The circuit diagrams and the obtained waveforms are depicted below when simulated in PSIM. Figure 5 shows the circuit diagram of the proposed scheme as simulated in PSIM. Here the switching frequency of the MOSFETs incorporated in the full bridge rectifier is chosen as 11 kHz. Fig. 6 depicts the waveform and RMS value of the output voltage (*VP*5) of the inverter when the switching frequency of the MOSFETs is 11 kHz. Here the RMS value of the output voltage (*VP*5) is 234.88 V. Figure 7 shows the waveform and RMS value of rectifier output voltage (*VP*7) and load current (*I*2) of the proposed scheme as simulated in PSIM when the frequency of the MOSFETs is 11 kHz. The waveform and RMS value of output voltage (*VP*5), which is 230.978, is shown in Fig. 8 when the switching frequency of the MOSFETs is 5 kHz. The waveform and RMS value of rectifier output voltage (*VP*7) and load current (*I*2) of the proposed scheme as simulated in PSIM when the frequency of the MOSFETs is 5 kHz is shown in Fig. 9. Figure 10 depicts the waveform of the output voltage and its rms value which is 231.93 V in this scheme when the frequency of the MOSFETs is 2 kHz. The waveform and rms value of rectifier output voltage (*VP*7) and load current (*I*2) of the proposed scheme as simulated in PSIM when the frequency of the MOSFETs is 2 kHz is shown in Fig. 11. The Table 1 depicts the comparison of different results of the proposed scheme of hybrid resonant inverter fitted induction heating equipment for different switching frequencies of MOSFETs of the controlled rectifier. So from the simulation results depicted above, it can be found that by changing the switching frequency of the MOSFETs incorporated in the rectifier, the output voltage can be varied smoothly. But in the earlier method, switching frequency of the inverter was changed to vary the output voltage. But in this method of output voltage control, the output voltage *i.e.* the heat in the work piece cannot be controlled smoothly. This can be shown by simulation in PSIM. Figure 12 shows the waveform and rms value of load voltage *i.e.* 244.68 V when the switching frequency of the inverter is 25 kHz and the frequency of MOSFETs of the half controlled rectifier is 11 kHz. It can be seen from Fig. 12 that when the switching frequency of the inverter is changed slightly from 22 kHz to 25 kHz, the rms value of the output voltage changes from 234.88 V to 244.68 V. So controllability of the proposed scheme is quite good in comparison with the previous one.

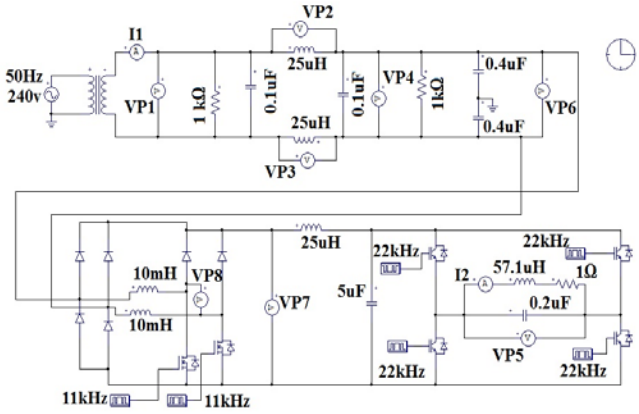

Fig. 5 – Simulated circuit diagram for the proposed scheme (frequency of MOSFET 11 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

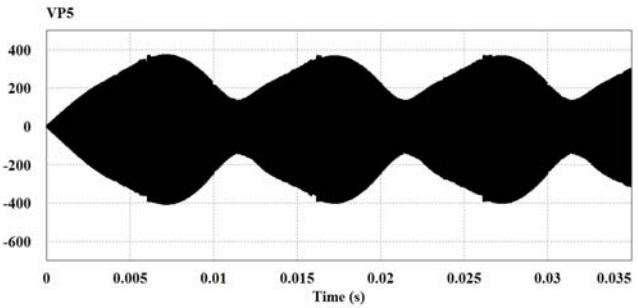

Fig. 6 – Waveform of load voltage (*VP*5) for the proposed scheme (frequency of MOSFET 11 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

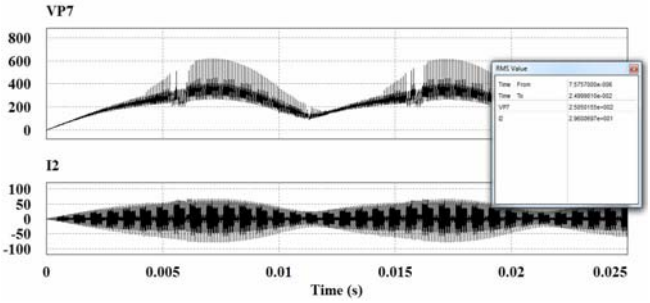

Fig. 7 – Waveform and RMS value of rectifier output voltage (*VP*7) and load current (*I*2) for the proposed scheme (frequency of MOSFET 11 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

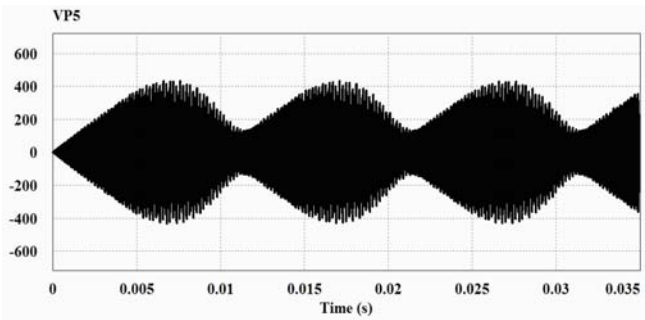

Fig. 8 – Waveform of load voltage (*VP*5) for the proposed scheme (frequency of MOSFET 5 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

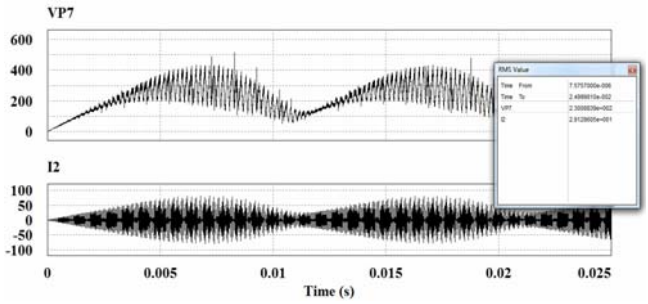

Fig. 9 – Waveform and RMS value of rectifier output voltage (*VP*7) and load current (*I*2) for the proposed scheme (frequency of MOSFET 5 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

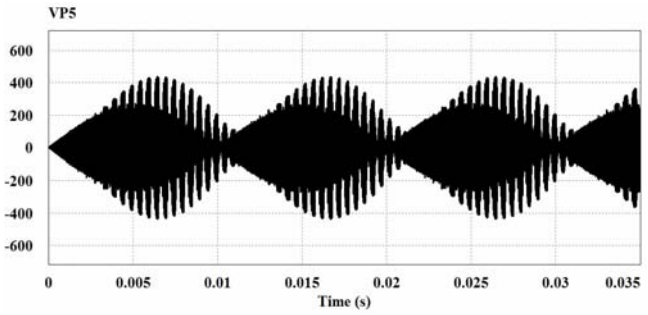

Fig. 10 – Waveform of load voltage (*VP*5) for the proposed scheme (frequency of MOSFET 2 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

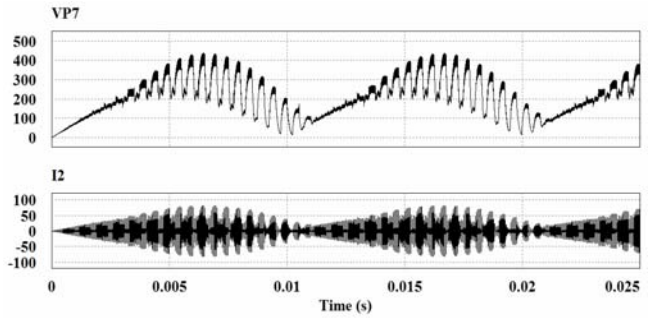

Fig. 11 – Waveform of rectifier output voltage (*VP*7) and load current (*I*2) for the proposed scheme (frequency of MOSFET 2 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software.

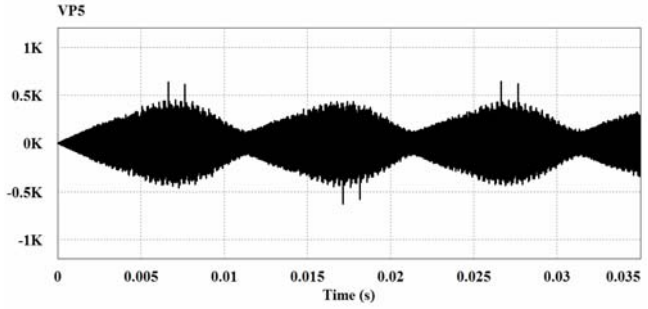

Fig. 12 – Waveform of load voltage (*VP*5) for the proposed scheme (frequency of MOSFET 11 kHz) of hybrid resonant inverter fitted induction heating equipment on PSIM software with inverter switching frequency of 25 kHz.

Table 1

Comparison of different results of the hybrid resonant inverter fitted induction heating equipment for different switching frequencies of MOSFETs of the controlled rectifier

	RMS value of load voltage (*VP*5)	RMS value of rectifier output voltage (*VP*7)	RMS value of load current (*I*2)
Switching frequency of the MOSFETs 11kHz	234.87 V	250.50 V	29.6 A
Switching frequency of the MOSFETs 5 kHz	230.98 V	230.08 V	29.13 A
Switching frequency of the MOSFETs 2 kHz	231.93 V	230.08 V	29.13 A

5. **CONCLUSION**

In this paper, a new scheme of hybrid resonant inverter fitted induction heating equipment is aimed to design and developed for industrial applications. To develop the high frequency alternating magnetic field required for the heating, high frequency resonant inverters are incorporated in the equipment. The simulation is done on the PSIM platform and output waveforms are shown in the figures. In this topology, there are two full bridge rectifiers connected in parallel, one uncontrolled and another half controlled. By changing the switching frequency of the controlled switches (MOSFETs), the dc link voltage can be changed. So by the control of the dc link voltage, the heat in the work piece can be changed. This serves as an additional benefit over the switching frequency control of the inverter to control the heat in the work piece. But there is one demerit of the proposed voltage control. The switching frequency of the controlled rectifier must be a multiple of the supply frequency. If this condition is not fulfilled, some switching problems will occur in the circuit. So, the output voltage of the rectifier stage cannot be controlled continuously, but only in steps. So overall, it may be concluded that this new topology of high frequency hybrid resonant inverter fitted induction heating equipment is cost effective, highly energy efficient and controllable if the if the switching frequency of the controlled rectifier is chosen as a multiple of the supply frequency.

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