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SIMULATION OF SERIES RESONANT INVERTER USING PULSE-DENSITY MODULATION

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ABSTRACT

This paper explains the simulation of a high frequency (20kHz) single phase full-bridge voltage-fed Series Resonant Inverter for the Induction heater and the Pulse Density Modulation has been employed in-order to control the output power.. The open loop system and the closed loop system with PI and FLC are simulated and their results are presented. The results of FLC based system are compared with those of PI based system.This inverter system has advantages like high power density, reduced steady-state error and improved response.

Keywords: induction heating, series resonant inverter, proportional integral controller, fuzzy controller.

1. INTRODUCTION

Induction heating is used to produce very high temperature for applications like steel-melting, brazing and surface-hardening. The metals to be welded, melted or hardened are heated using Series Resonant Inverter [1, 2] and are widely used for the high power applications in industrial field and as well as in electric home applications. The principle of Induction heating is that when an alternating current is induced in the coil then magnetic field is produced. This produces eddy current in the coil and it results into heating effect. Induction heating loads can be modelled by using resistor R and inductor L of the circuit. The frequency is selected depending on the work piece, geometry and its skin depth .The main topologies of these applications are full bridge and half bridge inverter [3]. These resonant inverters comprising of an induction coil and a charging capacitor which forms a resonant tank in an "Induction Heating System". The basic requirements of the induction heating system are:

1. High switching frequency
2. Power factor maintained as unity
3. Efficiency of the system has to be high [3]
4. Cost of the system is low and
5. Reliability of the system [9]

Conventionally the SRI'S are fed from bridge-rectifier which is designed to supply a variable -dc voltage. As this method involves few drawbacks in size, cost, the power control by frequency or phase-shift has been used. Even these possess increase switching losses and electromagnetic noise due to the incapability of the switching devices to be turned on and tuned off at zero current. In order to resolve this problem the system frequency must be adjusted close to the resonant frequency allowing zero current switching operation. The output power control of such a system is employed by using pulse-density modulation [5, 6].This type of power modulation technique is called as Pulse Density Modulation technique. This work proposes FLC for the control of Induction Heating system.

This paper is organized into VII sections which are explained as below. Section II explains circuit description of the simulated circuit and section III presents modes of operation of the inverter and section IV presents Design parameter and section V presents Simulation results and section VI describes comparison of PI and fuzzy controllers and section VII presents the conclusions of the paper.

2. CIRCUIT DESCRIPTION

The circuit of the inverter is as shown in fig:1 It consists of a single phase voltage-source inverter using four IGBT'S. The inverter is connected to series resonant circuit with matching transformer, maximum rms output voltage and output power is obtained. The operating characteristics have the complexity due to fixed switching frequency which limits the performance of the output power. And also the advantage of the power control is the simple configuration, wide power regulation range. And also the output power of the SRI can be controlled by adjusting the pulse-density of the square-wave voltage. The resonant inductor and the capacitor are in series with the load. The series resonant circuit formed by the L,C and load must be under damped. And the condition satisfying for the under-damped condition is given by the condition as:

$$R * R < \left(\frac{4L}{C}\right) \tag{1}$$

And the resonating frequency is given by the formula

$$fo = 1/2\pi\sqrt{LC} \tag{2}$$

And the switching frequency is given as the reciprocal of total time period.

$$fs = 1/T \tag{3}$$

where,

fs = switching frequency
fo = resonant frequency
L = Inductor coil of the load
C = Capacitor connected in series with load
F = system frequency
R = ripple factor
R = resistance of the load.

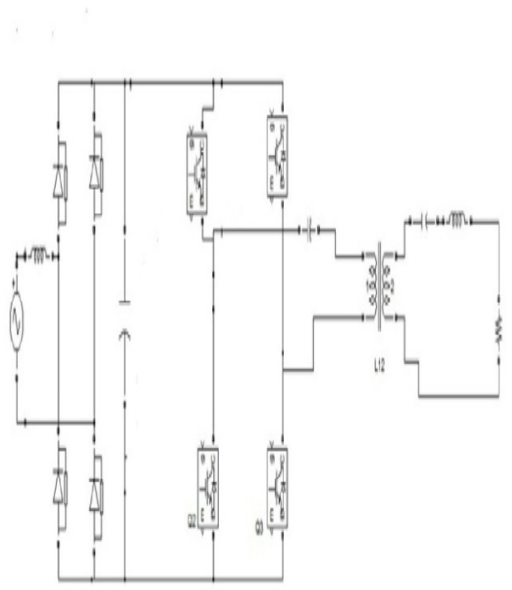

Figure-1. System configuration.

3. MODES OF OPERATION

A single phase full bridge resonant inverter is as shown in the Figure-1. The series resonant inverter takes energy from the input source, the DC voltage is converted into high frequency AC voltage system by using series resonant inverter. It consists of a four full switches Q1, Q2, Q3, Q4 and a resonant capacitor CS and a transformer. The transformer works as impedance and also it provides voltage transformation or the isolation between the DC source and the load. The resonant inverters comprising of an induction coil and a charging capacitor which forms a resonant tank in an "Induction Heating and are designed to supply a variable dc voltage. As this method involves a few drawbacks of size and cost an inverter with power control by frequency has been employed. Even this system posses increase switching losses due to the incapability of switching devices at urn on and turn off at zero current. Inorder to overcome the above mentioned problem the system frequency must be adjusted close to the resonant frequency allowing Zero Current Switching operation. This type of power modulation technique is called as Pulse Density Modulation technique. The modes of operation of the series resonant inverter are based on the pulse-density modulation. During the generation of the positive half-current of the inverter, Q1, Q4 has been turned on and Q2, Q3 has been turned off. And during the generation of the negative half-current Q2,Q3 has been turned on and Q1,Q4 has been turned off. And the advantage of the PDM is to achieve high power density of the inverter.

4. DESIGN PARAMETERS

VDc is the input ac supply which is given as 48 volts to the uncontrolled rectifier. The switching frequency of the inverter is given as the reciprocal of total time period given to the pulses and is given as 20kHz.The resonant frequency has been determined as frequency during which the maximum output voltage and current has been produced under resonating conditions and is given as 13.2kHz.The transformer used for the proposed work is the step-up transformer and the turns ratio is given as

$$N = n1/n2 = 48/96 \quad (4)$$

The switches used for the proposed inverter are the IGBT switches which are relatively low in cost and also suitable for high power applications. The switches selected for the inverter circuit are IRF840.The dc blocking capacitor is used as a filter which is used to reduce the harmonics distortions and the value is given as 2mF. The ripple factor for the circuit is given as the ratio of ac current to the dc current and it is given as 4%.

$$\text{Ripple factor} = Iac/Idc \quad (5)$$

The load for the induction heating is designed with an equivalent resistor with the work piece and an inductor coil with a capacitor in series with the load. And the capacitor value can be designed by the equation

$$r = 1/4\sqrt{3}*F*C*R \quad (6)$$

Where,
r is the ripple factor, F is the system frequency and R is the resistance with the work piece.

5. SIMULATION RESULTS

The open-loop circuit with Pulse-density modulation is as shown in Figure-2. By using PDM the system frequency can be adjusted close to the resonant frequency. The maximum output power produced is 550 watts. The AC input voltage waveform is shown in the Figure-2(a), input voltage waveform of the inverter is shown in Figure-2 (b), the switching pulse for the switches Q1,Q3 are shown in Figure-2 (c),output voltage of the inverter is as shown in Figure-2 (d), output current of the inverter is as shown in the Figure-2 (e) ,output power of the inverter is as shown in Figure-2 (f) and transformer primary voltage an secondary voltage waveforms are shown in Figure-2 (g) and 2(h) respectively. The input voltage of the rectifier is a single phase AC voltage source which is given as 48 volts The Input voltage of the inverter is fed from the output of the rectifier and it is given as 40 volts. The output voltage of the inverter is obtained as102 volts for the open loop system. The output current of the inverter is obtained as 25 amps for the open loop system. The output voltage of the inverter is obtained as102 volts for the open loop system. The output current of the inverter is obtained as 25 amps for the open loop system. The IGBT switches are fixed according to the pulse pattern generated using pulse density modulation for the switches s1,s3 as shown The output power of the inverter is obtained as 550 watts for the open loop system. The transformer primary voltage is obtained as 48 volts. The transformer used is step-up transformer. The output voltage of the inverter is obtained as102 volts for the open loop system. The output current of the inverter is obtained as 25 amps for the open loop system.

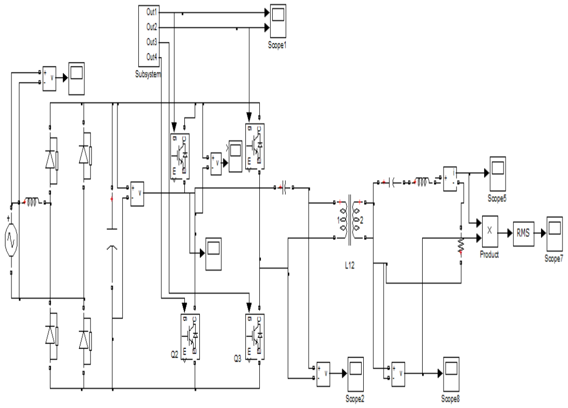

Figure-2. Open loop system with pulse density modulation.

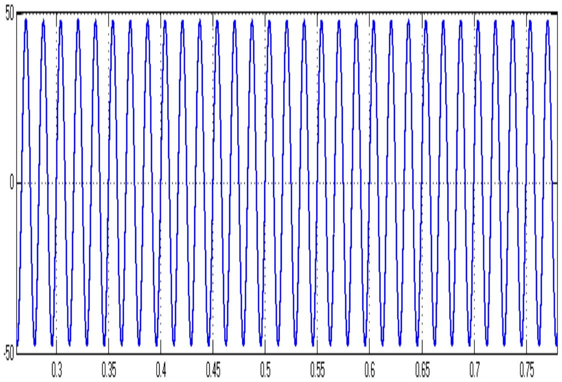

Figure-2(a). Input AC voltage waveform of the rectifier.

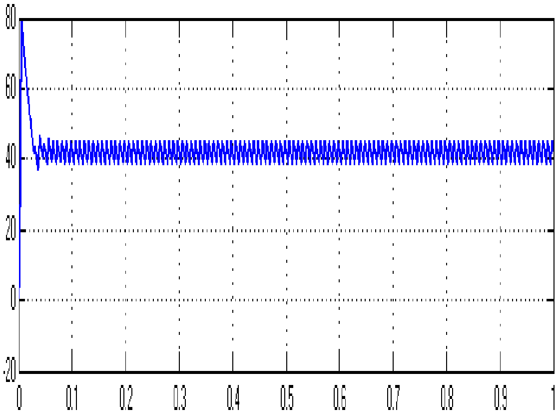

Figure-2(b). Input DC voltage waveform.

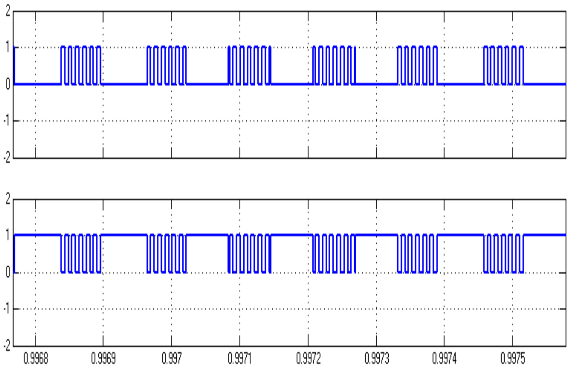

Figure-2(c). Switching pulse of the inverter using pulse density modulation technique for the switches s1 and s3.

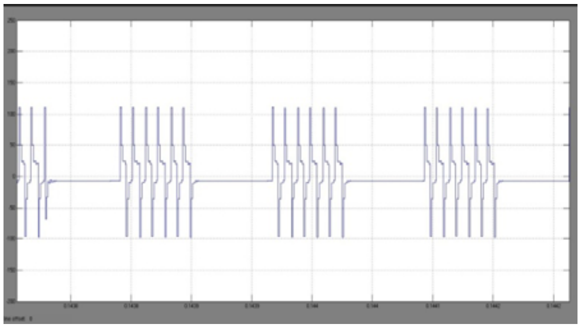

Figure-2(d). Output voltage of the inverter.

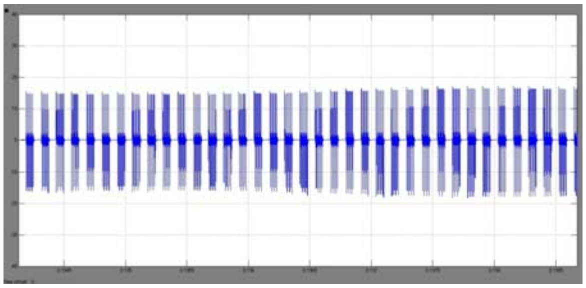

Figure-2(e). output current of the inverter.

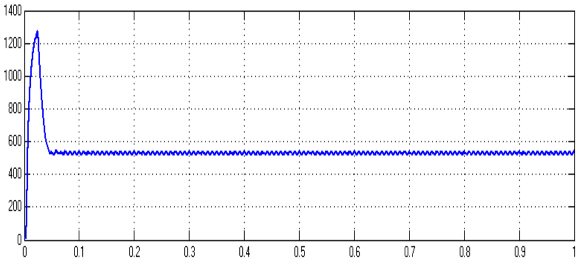

Figure-2(f). output power of the inverter.

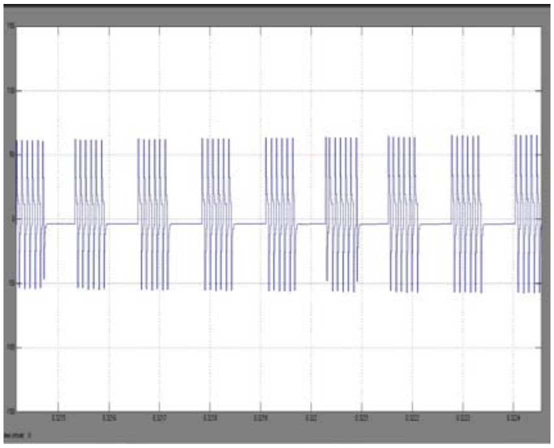

Figure-2(g). Transformer primary voltage waveform.

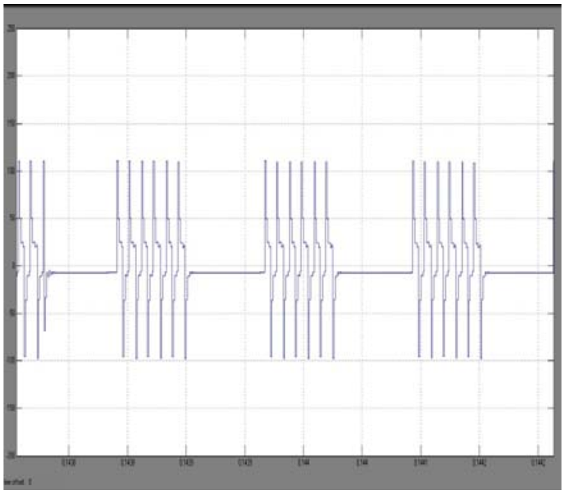

Figure-2(h). Transformer secondary voltage waveform.

The simulation results for the open loop with step change in input waveform are shown in Figure-3 .Input voltage of the rectifier waveform is shown in Figure-3 (a). Output voltage of the rectifier is shown in Figure-3 (b).Output voltage, current of the inverter are shown in Figure-3 (c) and 3(d) and the output power of the inverter is shown in Figure-3 (e).The circuit shown in the Figure-3 is the simulink model of the open loop system with a step change in input voltage. The steady-state error of this circuit is high by giving a change at the input side. The input voltage given to the rectifier is given as 48volts for change given at the input side with a change of 4 volts rise in voltage at 0.4seconds. The input voltage waveform of the inverter is obtained as 108 volts by giving a change in the input side with a change of 4 volts rise in voltage a 0.4seconds. The output voltage waveform of the inverter is obtained as 60 volts by giving a change in the input side The output current obtained by giving step change in theinput side is 25 amps. The output power of the inverter is obtained as 750 watts by giving a step change in the input side. And the error produced is high for the open loop system.

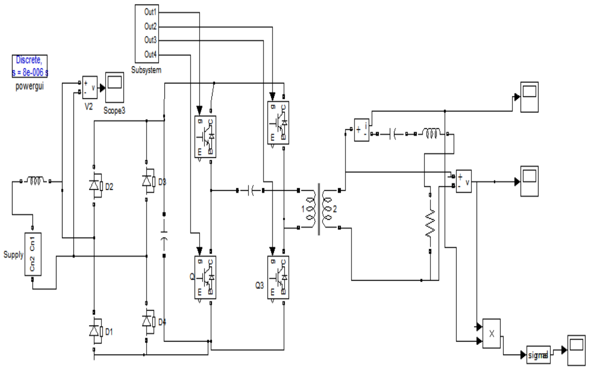

Figure-3. Simulink model of the open loop system with step change in input.

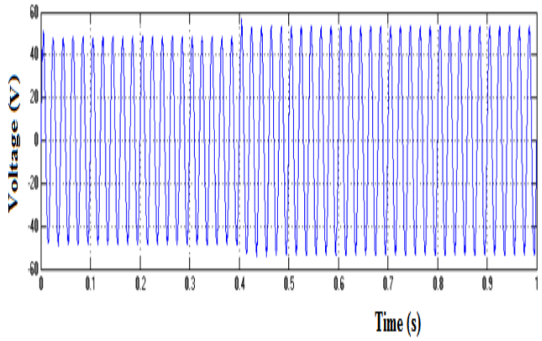

Figure-3(a). Input voltage waveform of the rectifier.

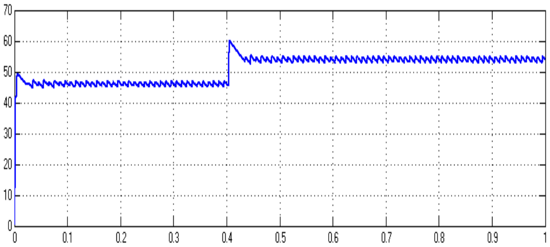

Figure-3(b). DC link voltage waveform of the inverter.

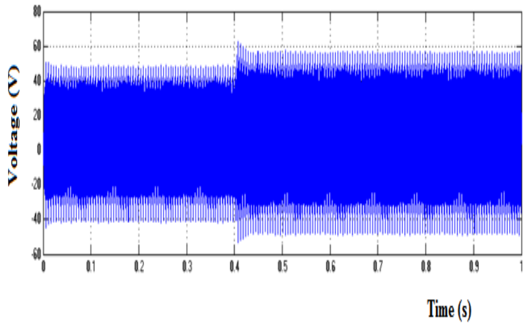

Figure-3(c). Output voltage waveform of the inverter.

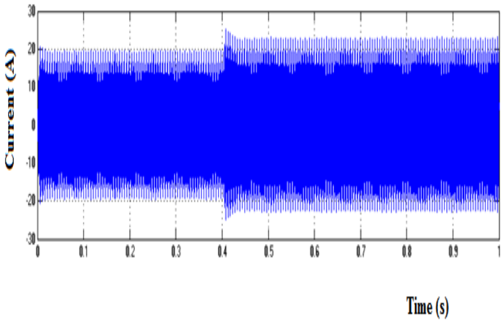

Figure-3(d). Output current waveform of the inverter.

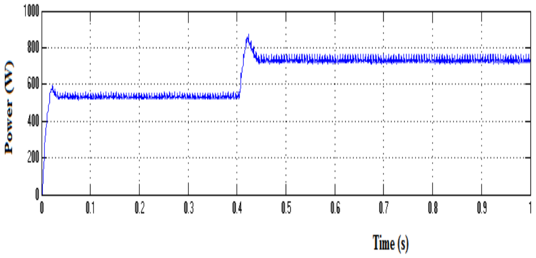

Figure-3(e). Output power waveform of the inverter.

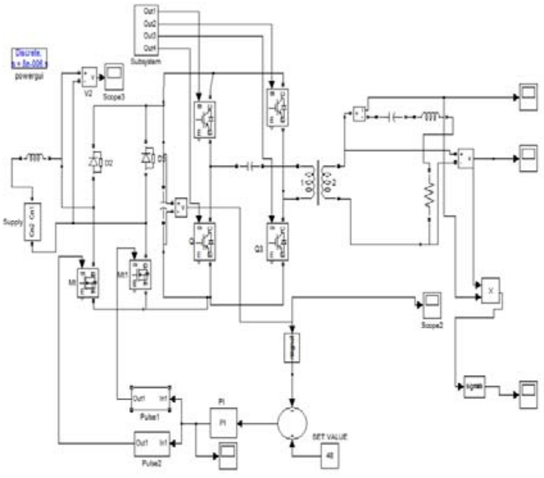

Figure-4. Simulink model of the closed loop system with PI controller.

The closed loop circuit has been simulated with PI controller by giving disturbance at the input side. The steady-state error has been reduced to 3 volts by using PI controller. A change in input has been created in the rectifier part so that the inverter can work under the maximum resonating conditions without any change in the switching frequency. The simulation results for the closed loop system with PI controller is shown in Figure-4. Input voltage of the rectifier waveform is shown in Figure-4 (a). Output voltage of the rectifier is shown in Figure-4 (b).Output voltage, current of the inverter are shown in Figure-4 (c) and 4(d) and the output power of the inverter is shown in Figure-4 (e). The output current obtained with PI controller is 25 amps for the change given at the input The output power obtained with PI controller is 580 Watts for the for a step input given at the input side and the error has been reduced to 3 volts.The input voltage of the rectifier of the rectifier with PI controller is 48 volts by giving a change in the input side. The Input voltage obtained with PI controller is 42 volts by giving a for the change given at the input. The output voltage of the inverter obtained with PI controller is 90 volts by giving a change given at the input side.

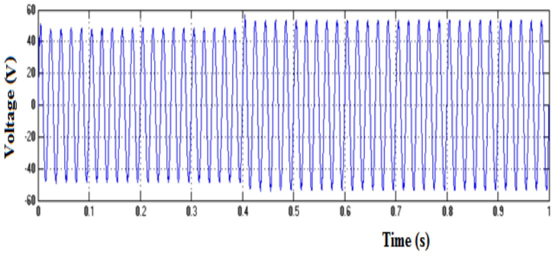

Figure-4(a). Input voltage of the rectifier.

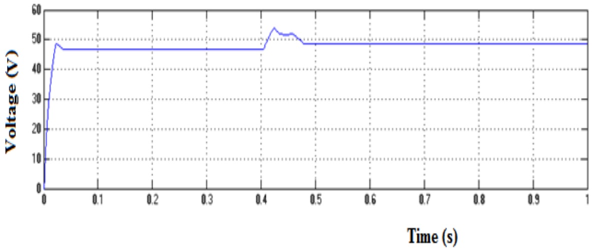

Figure-4(b). DC link voltage waveform of the Inverter

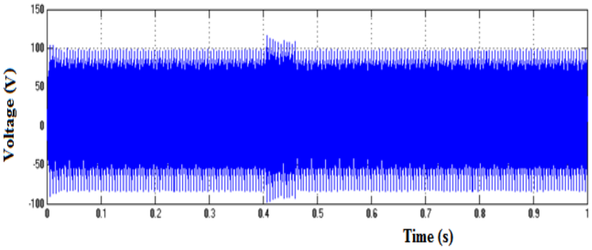

Figure-4(c). Output voltage waveform of the inverter.

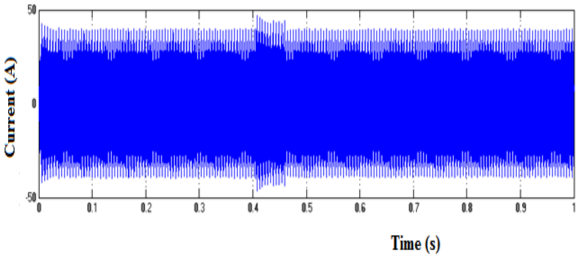

Figure-4(d). Output current waveform of the inverter.

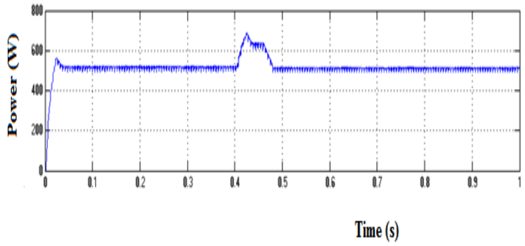

Figure-4(e). Output power waveform of the inverter.

The closed loop circuit has been simulated with fuzzy logic controller by giving disturbance at the input side.The steady-state error has been reduced to 0.05volts by using FLC.The simulink model of the FLC system is shown in Figure-5 and the Input voltage of the rectifier waveform is shown in Figure-5 (a). Output voltage of the rectifier is shown in Figure-5 (b).Output voltage, current of the inverter are shown in Figure-5 (c) and 5 (d) and the output power of the inverter is shown in Figure-5 (e), respectively. The input voltage given to the rectifier with FLC is 50 volts for a change given at the input side. The input voltage obtained for the inverter with FLC is 48 volts for a step input given at the input side. The output voltage obtained for the inverter with FLC is 100 volts for a for a step input given at the input side The output current obtained for the inverter with FLC is 25 amps for a for a step input given at the input side. The output power obtained for the inverter with FLC is 500 watts for a step input given at the input side .The error has been reduced to 0.05 volts.

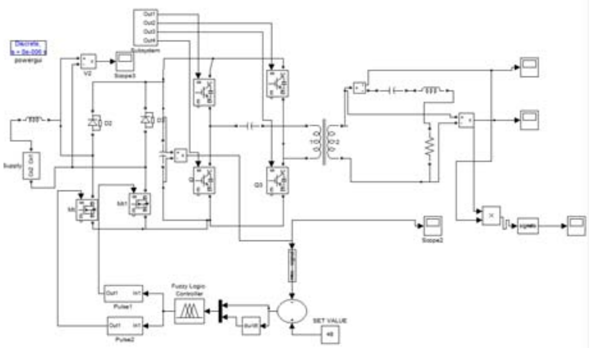

Figure-5. Simulink model of closed loop system with FLC.

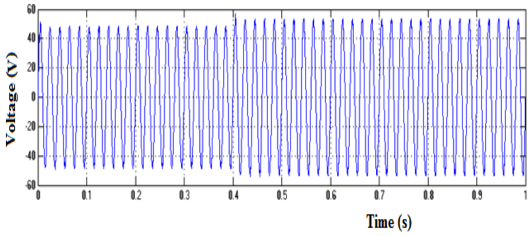

Figure-5(a). Input voltage waveform of the rectifier.

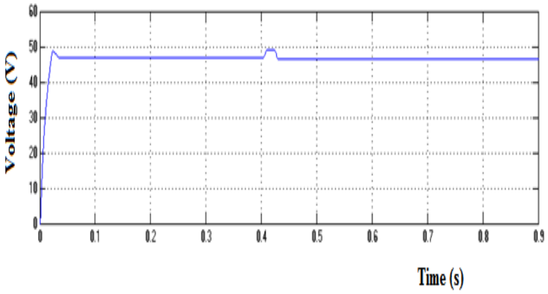

Figure-5(b). DC link voltage waveform of the inverter.

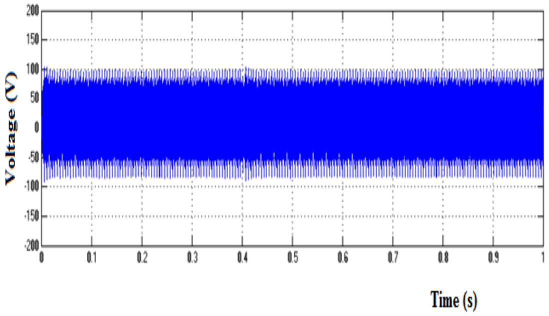

Figure-5(c). Output voltage waveform of the inverter.

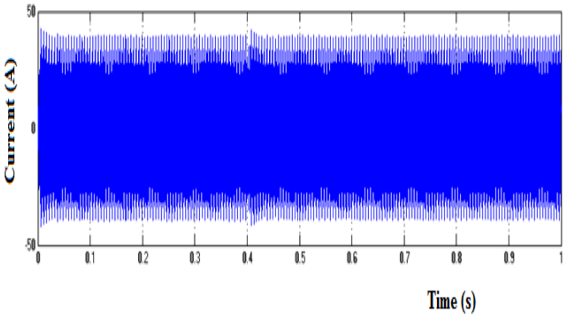

Figure-5(d). Output current waveform of the inverter.

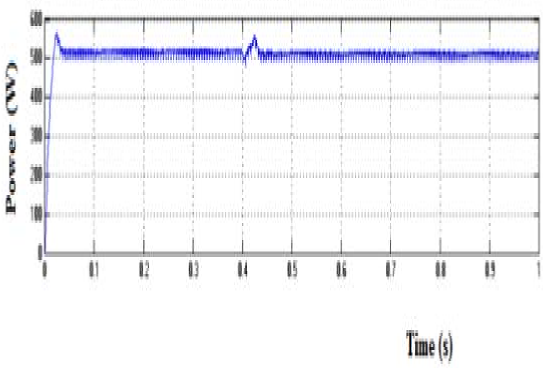

Figure-5(e). Output power waveform of the inverter.

Table-1. Comparison of the steady state error.

Conrollers	**Rise time** (sec)	**Peak time** (sec)	**Settling time** (sec)	**Steady-state error** (volts)
PI controller	0.03	0.06	0.09	3
FLC	0.02	0.03	0.035	0.05

The table shown describes the comparison of PI and FUZZY logic controllers. From the above table we can infer that the steady-state error has been reduced with FLC when compared to PI controller. A smooth response has been achieved by reducing the steady-state error for the FLC system.

6. CONCLUSIONS

High frequency series resonant inverter for induction heater system is designed, modelled and simulated successfully using matlab simulink. The closed loop system with PI controller and FUZZY controller are also simulated. The simulation results indicate that the response of fuzzy based system is superior to PI based system in terms of reduced steady-state error and improved response. This IH system has advantages like high power output, compact size and improved voltage regulation. The present work deals with the comparison of PI and FUZZY systems. The comparison between PI and NEURAL network based controller will be done in future.

REFERENCES

[1] N.-J. Park, D.Y. Lee and D.S. Hyun. 2007. “A power-control scheme with constant switching frequency in class-D inverter for induction-heating jar application,” IEEE Trans. Ind. Electron. Vol. 54, No.3, pp.1252–1260, June.

[2] S. Faucher, F. Forest, J. -Y. Gaspard J.-J. Huselstein, C. Joubert and D. Mont loup. 2007. “Frequency synchronized resonant converters for the supply of multiwinding coils in induction cooking appliances,” IEEE Trans. Ind. Electron. Vol. 54, No. pp. 441–452, February.

[3] V. Esteve, E. Sanchis-Kilders, J. Jordan, E. J. Dede, C. Cases, E. Maset, J. B. Ejea and A. Ferreres. 2011. “Improving the efficiency of IGBT series resonant inverters using pulse density modulation,” IEEE Trans. Ind. Electron. Vol. 58, no. 3, pp. 979–987, Mar.

[4] Bishwajith Saha and Rae-Young Kim. 2014. “High Power Density Series Resonant Inverter Using an Auxiliary Switched Capacitor Cell for Induction Heating Applications,” IEEE Trans on power Electonics. Vol. 29, No. 4, April.

[5] K. Gayathri,S. Devi,V. Hemaand and Mr. A. Sures. 2012. “Analysis of Series Resonant Inverters with PWM and PDM Techniques for Industrial Heating Applications,” International Journal of Power Control Signal and Computation (IJPCSC). Vol. 4, No. 2, April –June.

[6] P. Anitha and P. Shanmugapriya. 2012. “Design and Simulation of Pulse Density Modulation Base Series Resonant Inverter System,” International Journal of Communication Engineering Applications-IJCEA Vol. 03, Issue 01; January-April.

[7] V. Sivachidambaranathan and Subhransu Sekhar Dash. 2012. “A Novel Bi-directional Series Parallel Resonant Converter for Power Factor Correction,” International Journal of Computer Applications Vol. 48, No.2, June.

[8] V. Sivachidambaranathan. 2014. “Bi-Directional Series Parallel Resonant Converter For Power Factor Correction,” International Journal of Applied Engineering Research. Vol. 9, No.21.

[9] Vincente Esteve, Jose Jordan, Esteban Sanchis-Kilders, Enrique J.Dede, Enrique Maset, Jaun B.Ejea and Agustin Ferreres. 2014. “Improving The Reliability Of Series Resonant Inverter For Induction Heating Applications”, IEEE Trans. on Industrial Electronics, Vol. 61, No. 5, May.

[10] Padmanabhan S., Sukhi Y. and Jayashree Y. 2007. “Analaysis Design And Development Of Regulated Power- supply Using Soft-switched Resonant Converter,” Journal Of Applied Sciences Vol. 7, issue 22.