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Improved Time Responses of PI & FL Controlled SEPIC Converter based Series Resonant Inverter-fed Induction Heating System

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ABSTRACT

This work deals with the Power Factor Corrected Single-Ended Primary Inductor Converter (PFC-SEPIC) based voltage fed closed loop full bridge series resonant induction heating system for household induction heating applications. The output voltage of the front end PFC-SEPIC converter fed series resonant inverter governs the controllers, which may be PI controller or Fuzzy Logic Controller (FLC). The analysis and comparison of time responses are presented in this paper. The PFC-SEPIC converter is used to improve the output power and the THD of source side current are compared for PI and FLC controllers. PFC-SEPIC converter maintains improved current and voltage at unity power factor through the input mains. The SEPIC converter based Voltage Fed Full Bridge Series Resonant Inverter (VFFBSRI) converts the voltage at a frequency of 10 kHz to a level suitable for household induction heating. A 1 kW SEPIC converter based VFFBSRI with RLC load is designed and simulated using MATLAB/ Simulink and hardware is fabricated

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1. INTRODUCTION

Induction heating is employed in many domestic and industrial applications due to its various advantages like safeness, cleanness, adaptability and non-contact compared with the other classical methods of heating. Electrical energy supplied from the utility AC supply to the coil is transformed to thermal energy in the work piece by inducing eddy currents at the work piece surface over the electromagnetic field, in the absence of any physical electrical connection to the work piece. At the work piece surface, this induced current intensity is maximal and lowers as the center is approached. This is the function of the ratio of thickness/skin depth. The skin depth and size of the work piece plays a crucial role in the operating frequency selection. A larger percentage of the entire power is exhausted as the ratio increases along the exterior surface and this aspect is termed as skin depth.

The various topologies, which are commonly used for induction heating applications, are the half bridge, full bridge and single switched Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) inverter. The comparative analysis of the above said topologies was discussed earlier [1] by considering similar specifications with several factors. In general, resonant based high-frequency inverters are always preferred in induction heating applications in order to have less switching losses and high power output. Various modulation schemes were developed to have high heating function amidst proper voltage control.

In PFC-SEPIC converter based induction heating, the converter regulates the voltage at the DC link to a much smaller value compared with the traditional PFC boost converter [1] despite improving the quality of power at inputs. SEPIC converter operating in Continuous Inductor Current Mode (CICM) guards the stress on switches. Various titles related to modeling and design of domestic induction appliances are analyzed and compiled [2] focusing on their future trends. The topics include topologies of the inverter, modulation techniques, implementation on digital controllers and design of inductors. The approach, theory and the conceptions of induction heating were discussed way back in 1973 [3].

The features of induction heating are well advanced compared with the traditional range and have remarkable thermal response, safeness, and comfort. These features are achievable only because of electromagnetic induction, which allows the vessel to get heated directly. Analysis of performance of a free biomass induction heating system with SEPIC converter and without the SEPIC converter was dealt [5] to accomplish a better power factor and decreased total harmonic distortion. Proposing a novel single switch AC-DC PFC topology, this was done. It is convinced that Induction heating technology is a promising one both at present and in future [6] by investigating and validating various techniques involved in induction heating systems. To supply medium and high frequency power signals to the inductor a uniquely designed output resonant circuit is used along with an exclusive inverter circuit. The 10-kW dual frequency resonant circuit, which is capable of operation at 10 kHz and 100 kHz, make use of two technologies namely silicon (Si) and silicon carbide (SiC).

Efficiency and loss of power of the inverter using both technologies are compared and listed [7]. Research on the strength of the current control strategy [8] was presented in which a resonant control tracks the correct reference for current. Methods for tuning the controllers were also discussed in detail during very low switching/ sampling frequencies. Home appliances supplied by a DC-based nano-grids form the major portion in recent studies on home appliances. Induction heating was considered [9] as an example for such a study. Here detailed designing, which included power converters, inductor systems were taken into consideration. Implementation of hardware was also done on the performance of converters. An innovative soft-switching high-frequency resonant inverter for the application of induction heating was detailed [10]. This uses a current-phasor control, which adjusts the phase shift angle among a couple of half-bridge inverter units.

By this method, induction heating load resonant current is supervised and controlled at typical intervals using soft switching. Along this efficiency is also improved by a dual mode power regulation method. A different model of a zero voltage soft switching, working at normal frequency utility AC mains to high-frequency AC resonant power converter used in induction heating appliances is discussed [11]. This converter manages the conversion of frequency in the absence of any diode bridge rectifier along with power factor correction. Analysis and design of a novel Ac-AC resonant converter for induction heating applications constituting half bridge resonant converters were discussed [12]. This converter is capable of functioning with zero voltage switching while the switch is ON and OFF. The voltage at the output is doubled with this network thereby reducing the load current. Above all induction-heating appliances need distinct features like increased power levels at the output in a smaller enclosure, increased operating temperature, huge variation in load and cost-effective. A proposal was given [13] with a lesser number of components, cheaper and reliable which make use of a direct AC-AC converter.

This topology has soft switching during both turn-on and turn-off thereby improving efficiency. A straightforward power-control scheme was discussed [14] for a consistent-frequency class-D inverter, which has a variable duty cycle. This is convenient to heat an induction-heating appliance. This method has a vast range of power regulation as well as easy control of output power. Four different topologies of inverters for induction cookers were dealt with [15-16] and their performance with respect to stress on the device, control of frequency, efficiency was compared. A single switch silicon carbide JFET resonant inverter, which is normally ON, is used in an induction-heating appliance [17-18] and a comparison is made with Si IGBTs and results are discussed.

An innovative driving technique for was proposed [19] with zero voltage switching topology, which was claimed to have reduced crisis of peak currents. Usage of Litz-wire planar windings, which has frequency-dependent resistance, in induction appliances, is discussed [20]. A comparative study has been done with various wires for inductors. Since induction appliance with fluctuating induction loads is a threat to designing a resonant converter with more efficiency [21] a variable snubber topology has been proposed. To improvise efficiency over a broader power output, [22] a half-bridge inverter functioning in two different operating modes is proposed. This makes the system cheaper in terms of cost and efficiency. A multiplied output, boost SEPIC PFC AC-DC converter to improve efficiency and have reduced count of components for multiple-load systems [23] has been proposed. A novel voltage fed quasi-load resonant inverter with variable power and constant frequency [24] was developed for SEPIC with fuzzy controlled induction heating appliances. This soft switching inverter, which uses IGBTs, is found to be more applicable for a multiple burner induction heating systems. Another prototype is also presented by using the dual pulse modulation technique and source side harmonic reduction [25] has been implemented. This applies a sub-scheme for regulating power to increase efficiency.

The above literature does not deal with comparison of PI and FL controlled VFFBSRI systems. This work proposes FLC for VFFBSRI system. This work deals with the PFC-SEPIC based voltage fed closed loop full bridge series resonant induction heating system for household induction heating applications. The output voltage of the front end PFC-SEPIC converter fed series resonant inverter is controlled by the PI or Fuzzy Logic Controller (FLC). PFC-SEPIC converter maintains improved current and voltage at unity power factor at the input mains. The SEPIC converter based Voltage Fed Full Bridge Series Resonant Inverter (VFFBSRI) converts the voltage at a frequency of 10 kHz to a level suitable for household induction heating. Figure 1 shows the block diagram of the induction heating system.

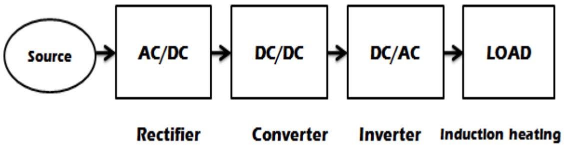

Figure 1. Block diagram of the induction heating system

The source is supplied to the rectifier, which is followed by a DC-DC converter, which is known as the second stage converter. An inverter follows the DC-DC converter, which is further supplied to the induction heating system.

2. DUTY CYCLE MODULATION TECHNIQUE FOR ASYMMETRICAL CONDITION

Conventional Square Wave (SW) modulation signifies large switching frequencies to supply low and medium power. To ensure good efficiency size of the sink, the fan has to be reduced. The main objective of this paper is to propose a modified control algorithm, which improves efficiency while maintaining the same parameters with no hardware changes. To accomplish this asymmetrical and theoretical analysis of duty cycle modulation technique has been carried out. A different operating condition is applied to improve efficiency and to increase output. Finally, a comparison is made between simulation and hardware results in terms of efficiency.

3. PARAMETERS OF INDUTION HEATING

Figure 2 depicts the equivalent circuit model of the heating coil.

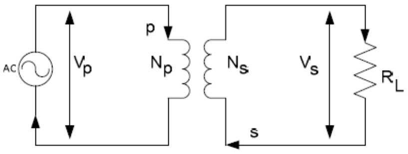

Figure 2. Equivalent circuit model of the heating coil

Where,
V_p = primary voltage (V)
I_p = primary current (A)
N_p= number of primary turns
I_s = secondary current (A)
N_s =number of secondary turns
V_s = secondary voltage (V)
RL =load resistance (Ω)

$$I_pN_p = I_sN_s \tag{1}$$

$N_s = 1$
$I_p N_p = I_s$

Equation (2) gives the power equation in terms of primary current and turns.
$P = I_s^2 R$ Watts

$$P = \frac{(I_p N_p)^2 \pi \rho d}{\delta L} Watts \tag{2}$$

Where $\delta = \frac{\sqrt{2\rho}}{\mu\omega} meters$

δ = the skin depth
ρ = the resistivity of the work piece
μ = the magnetic permeability of work piece
ω = the angular frequency of the varying magnetic field

4. SIMULATION RESULTS AND DISCUSSION

4.1. SEPIC with PI controller

Simulink model of the SEPIC converter based Voltage Fed Full Bridge Series Resonant Inverter (VFFBSRI) induction heating system with closed loop PI controller is shown in Figure 3. Input voltage and current are shown in Figure 4. The peak value of input voltage is 50 V and the peak value of current is 20 A.The THD of the source current is shown in Figure 5 and the THD is 4.98%. The fundamental component is 18.82 and the harmonics are negligible.

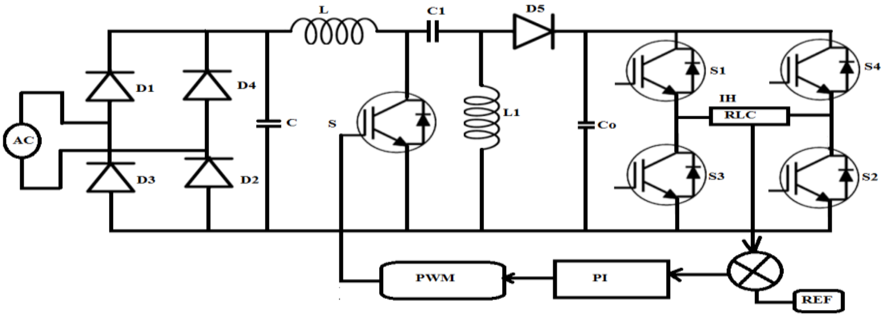

Figure 3. Circuit diagram of SEPIC with VFFBSRI closed-loop PI controlled induction heating system

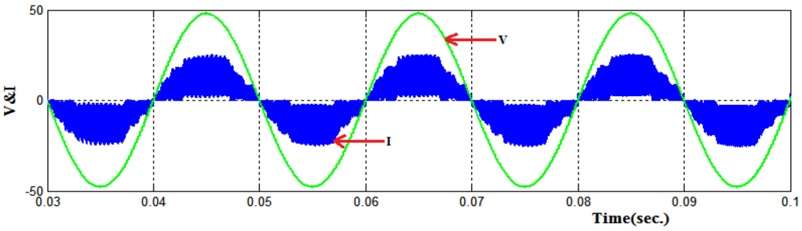

Figure 4. Input voltage and current

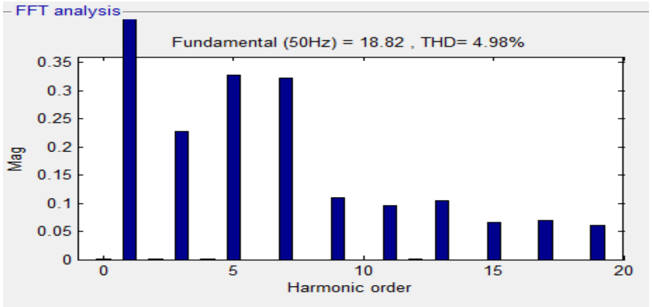

Figure 5. Analysis for input current of SEPIC converter with PI controller

Output voltage of the SEPIC converter is shown in Figure 6 and its value is 110 V. The output voltage & current of the full bridge inverter are shown in Figure 7 and Figure 8 respectively. The peak values of output voltage and current are 120 V and 12 A respectively. Output power of the induction heating system is shown in Figure 9. The output power is 1050 W.

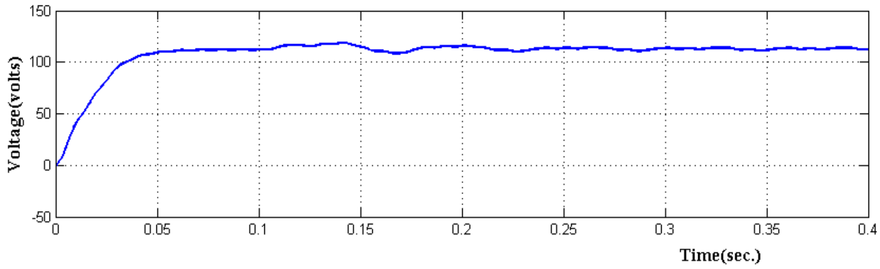

Figure 6. Output voltage of the SEPIC converter.

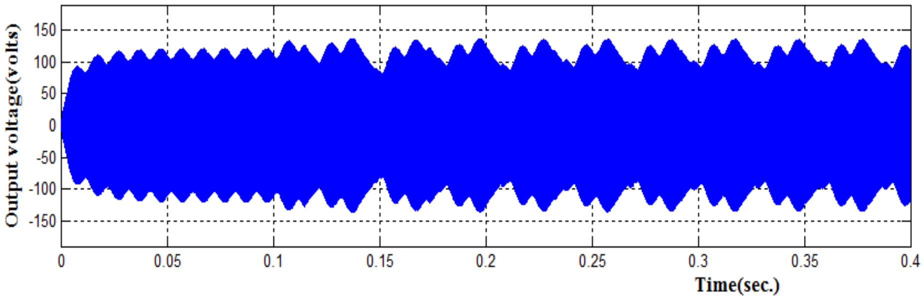

Figure 7. Output voltage of the inverter

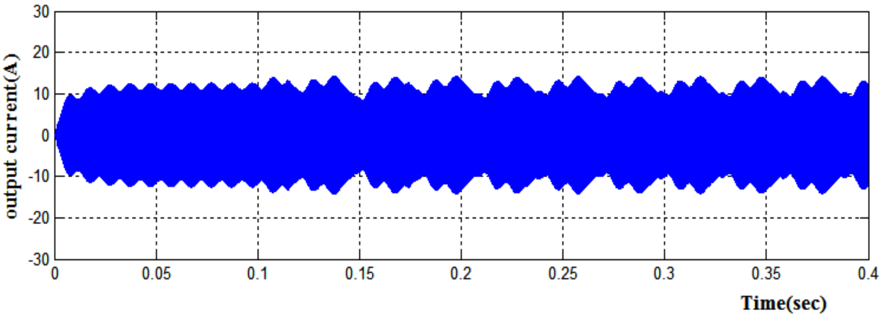

Figure 8. Output current of the inverter

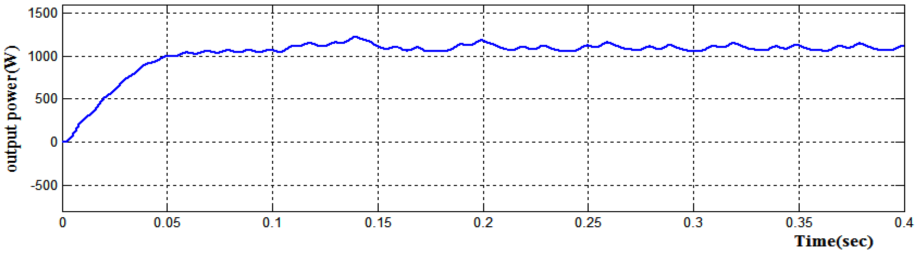

Figure 9. Output power of the induction heating system

4.2. SEPIC with FLC controller

Simulink model of the closed loop FL controlled SEPIC with VFFBSRI induction heating system is shown in Figure 10. Input voltage and current are shown in Figure 11. The peak value of input voltage is 50 V and the peak value of current is 20 A.The THD of the source current is shown in Figure 5 and the THD is

3.48%. The fundamental component is 18.41 and the harmonics are negligible. The THD in the source current is shown in Figure 12. The output voltage of the SEPIC converter is shown in Figure 13. The output voltage & current of the full bridge inverter is shown in Figure 14 and Figure 15 respectively. The peak values of output voltage and current are 120 V and 12 A respectively. Output voltage of the SEPIC converter is shown in Figure 6 and its value is 110 V. Output power of the induction heating system is shown in Figure 16. The output power is 1000 W.

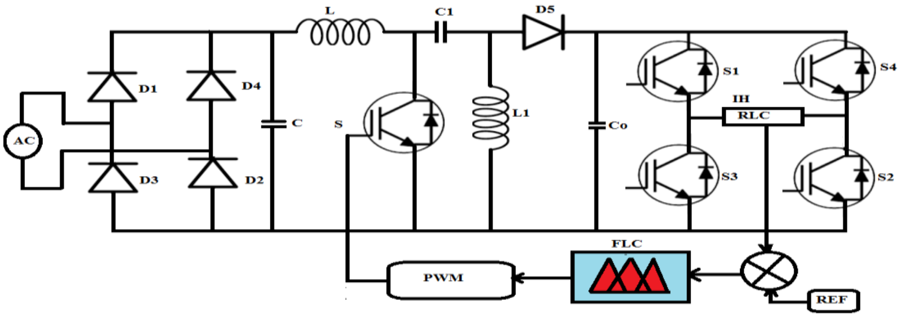

Figure 10. Circuit diagram of SEPIC with VFFBSRI closed loop FLC controlled induction heating system

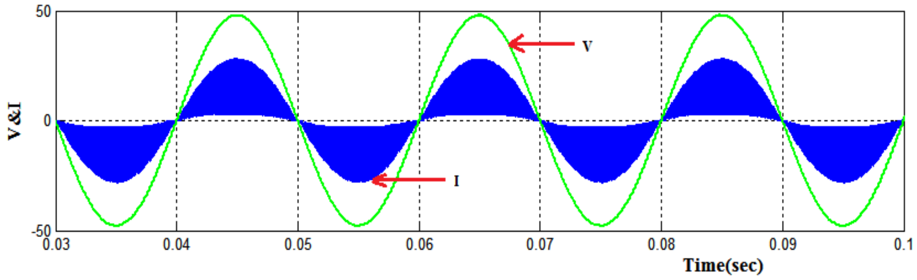

Figure 11. Input voltage and current.

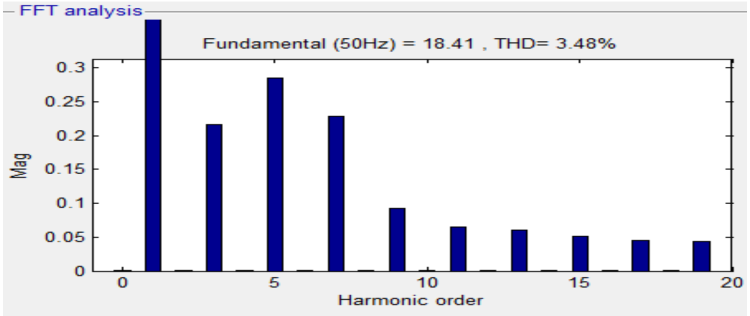

Figure 12. Analysis of THD in the input current of SEPIC converter with FL controller

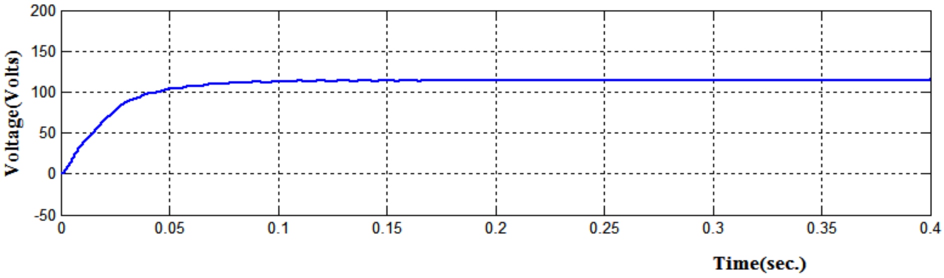

Figure 13. Output voltage of the SEPIC converter.

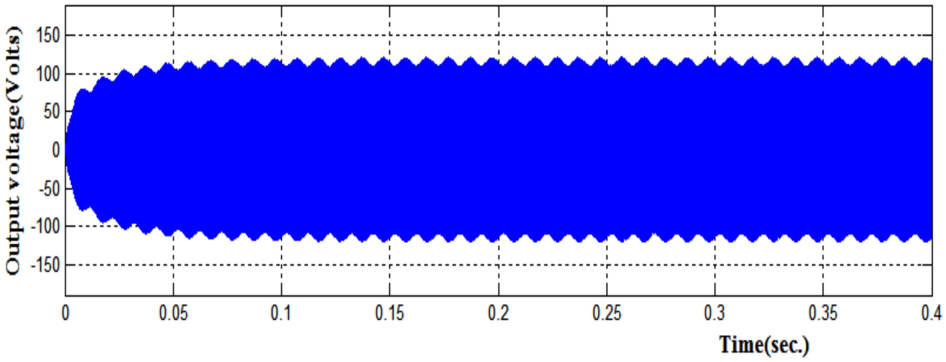

Figure 14. Output voltage of the inverter

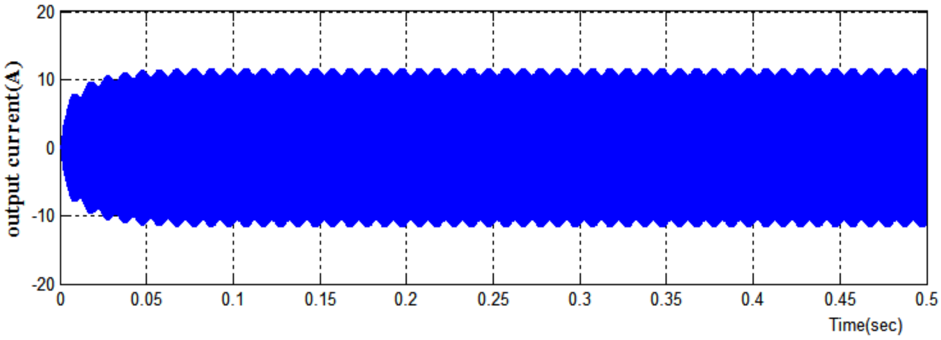

Figure 15. Output current of the inverter

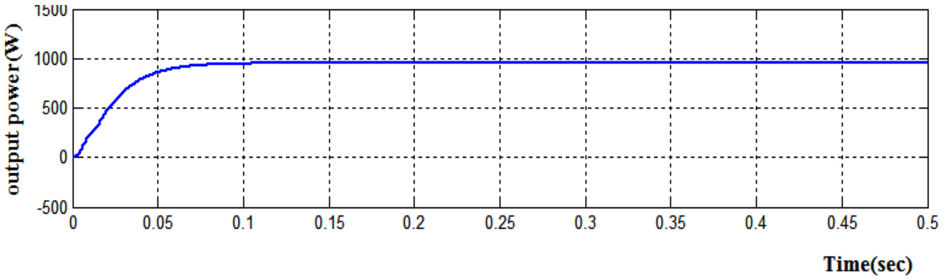

Figure 16. Output power of the induction heating system

Table 1. Simulation Specifications

Parameter	Value
Inductance (L)	10µH
Inductance (L1)	9µH
Filter capacitance(C)	1000µF
Filter Capacitance(C1)	104µF
Filter Capacitance(Co)	2200µF
Load Resistance (Ro)	3Ω
Load capacitance (C2)	15µF
Load side Inductance(L2)	50 µH
Input Voltage	48 V
Switching Frequency	10kHz
Output voltage (Vo)	110V

Table 2. Comparison of Time Domain Parameters

Types of controllers	T_r	T_s	T_p	THD
PI	0.12	0.24	0.13	4.98%
FLC	0.06	0.12	0.11	3.48%

Table 1 displays the specifications used in simulating the system. Table 2 displays the comparison of time domain parameters for a PFC-SEPIC based voltage fed closed-loop full bridge series resonant induction heating system for household induction heating applications with PI and FLC controllers.

5. EXPERIMENTAL RESULTS

The hardware setup of the prototype whose input voltage is 48V, output voltage is 110V, has an output power of 1kW and switching frequency of 10 kHz. Hardware setup of the SEPIC with VFFBSRI induction heating system is shown in Figure 17. The hardware of the SEPIC with VFFBSRI system is fabricated and tested in the laboratory. The hardware consists of a control board, SEPIC converter board & VFFBSRI board. The pulses are generated using PIC 16F84A. They are amplified using driver IC 2110. Input voltage & current of the system without a controller is shown in Figure 18. Figure 19 shows the system with a controller. The output voltage of SEPIC converter is shown in Figure 20. The output voltage of the inverter is shown in Figure 21. The output current of the inverter is shown in Figure 22. The hardware specifications are listed in the Table 3.

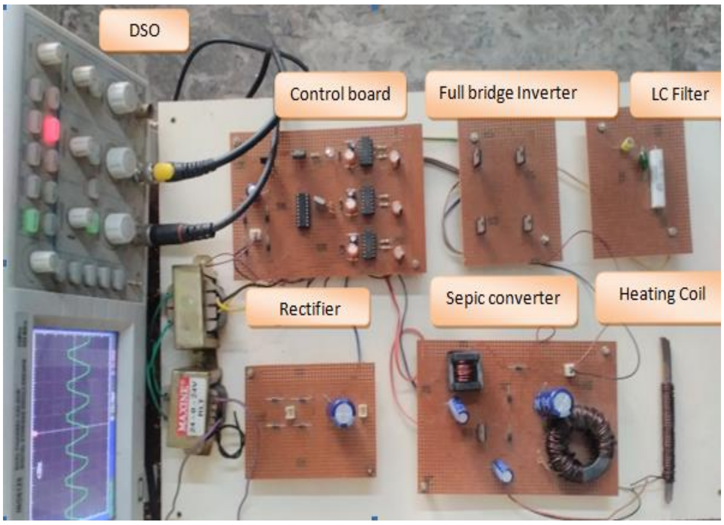

Figure 17. Hardware setup of the prototype system

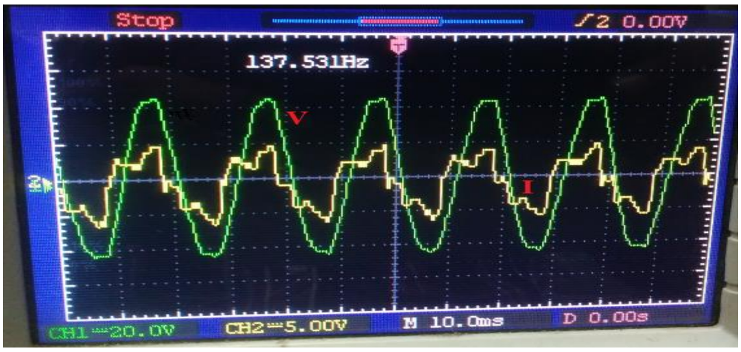

Figure 18. Input Voltage and Current of the system without controller

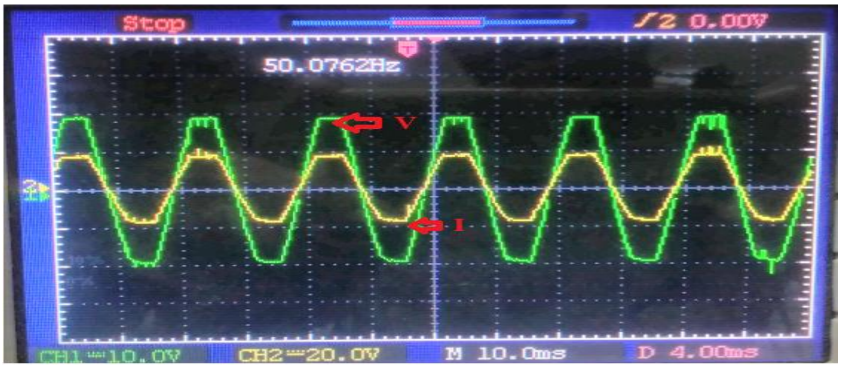

Figure 19. Input Voltage and Current with Controller

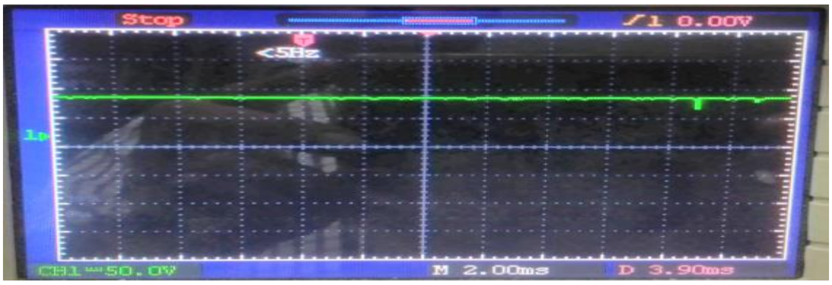

Figure 20. Output voltage of the SEPIC converter

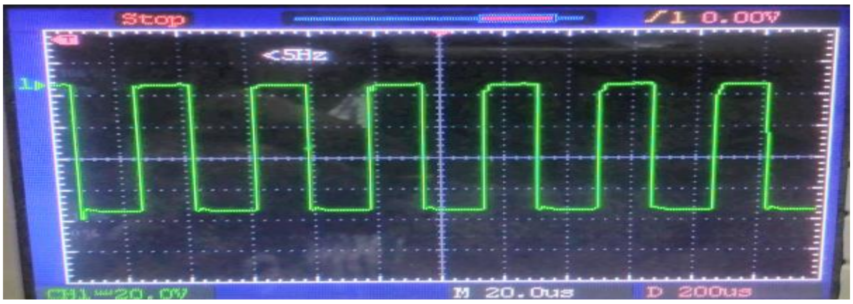

Figure 22. Output Current of the Inverter

Table 3. Hardware Specification

Parameter	Value
Inductance (L)	9.5µH
Inductance (L1)	8µH
Filter capacitance©	1000µF
Filter Capacitance (C1)	104µF
Filter Capacitance (Co)	2200µF
Load Resistance (Ro)	3.5Ω
Load capacitance (C2)	13µF
Load side	48 µH
Input Voltage	48 V
Switching Frequency	10kHz
Output voltage (Vo)	110V
Controller IC	PIC
Driver IC	IR2110
Diode	IN4007
IGBT	12FA-150N

6. CONCLUSION

The comparative analysis of SEPIC converter based voltage fed closed loop full bridge series resonant induction heating system with PI & FL control strategies are simulated and the results are presented. Also, the hardware implementation of the inverter fed induction-heating system was done. It can be noticed that the time domain parameters and THD of the source current have reduced from 4.98% to 3.48%. Thus the response of FL controlled system is superior to the PI controlled system. The present work deals with the comparison of closed loop PI and Fuzzy logic controller systems. The closed-loop system with ANN controller will be done in the future. The hardware for VFFBSRI using DSP will be done in near future.

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C.Umayal has obtained her ME degree from Anna University, Tamil Nadu, India, in the year 2005. She has 12 years of teaching experience and 8 years of Industrial experience. She completed her PhD at ANNA University, Chennai in 2014. She is currently working as Associate Professor in the Department of EEE at VIT University, Chennai.