IMPROVED DYNAMIC RESPONSE OF PFC-SEPIC CONVERTER BASED ON INDUCTION HEATER USING FOPID CONTROLLED SYSTEM

Muthu Periasamy[#1], Chandrahasan Umayal*[2]
[#] Research Scholar, [*]Associate Professor
School of Electrical Engineering, VIT University, Chennai, India
* School of Electrical Engineering, VIT University, Chennai, India
[#] E-Mail: muthuvit2007@gmail.com
[*] E-Mail: umayal.c@vit.ac.in

Abstract- T**his 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 FOPID controllers. The analysis and comparison of time responses are presented in this paper. PFC-SEPIC converter is used to improve the output power and the THD of source side current are compared for PI and FOPID 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.**

Keywords - SEPIC Converter; Power Factor Correction (PFC); Induction Heating (IH); VFFBSRI; PI& fractional order PID controller;

I. 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 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 were 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 [2] despite improving the quality of power at inputs. The stress on switches is guarded by making the SEPIC converter to operate in continuous inductor current mode (CICM). Various titles related with modeling and design of domestic induction appliances are analyzed and compiled [3] 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 [4]. The features of induction heating are well advanced compared with the traditional range and has 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 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. This was done by proposing a novel single switch AC-DC PFC topology. 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 in power of 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 nanogrids 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 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 the 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 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 was 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, and 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 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 were 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 techniques for was proposed [19] for a one witch 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 LLCC Resonant inverter functioning in two different operating modes is proposed. This makes the system cheaper in terms of cost and effective. A multiple output, boost resonant AC-AC converter to improve efficiency and have reduced count of components for multiple-load systems [23] have been PI controlled system investigated. A novel voltage fed quasi load resonant inverter with variable power and constant frequency [24] was developed Fractional Order PID Controlled system for 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 [25] performance of sepic converter has been implemented. This applies a sub scheme for regulating power to increase efficiency.

II. PROPOSED PFC-SEPIC CONVERTER BASED IH

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 governs the PI and FOPID controllers. 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.

Conventional Square wave (SW) modulation signifies large switching frequencies to supply low and medium power. To ensure good efficiency size of sink and fan have 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 are applied to improve efficiency and to increase output. Finally, a comparison is made between simulation and hardware results in terms of efficiency. Fig.1 shows the block diagram for the induction heating system.

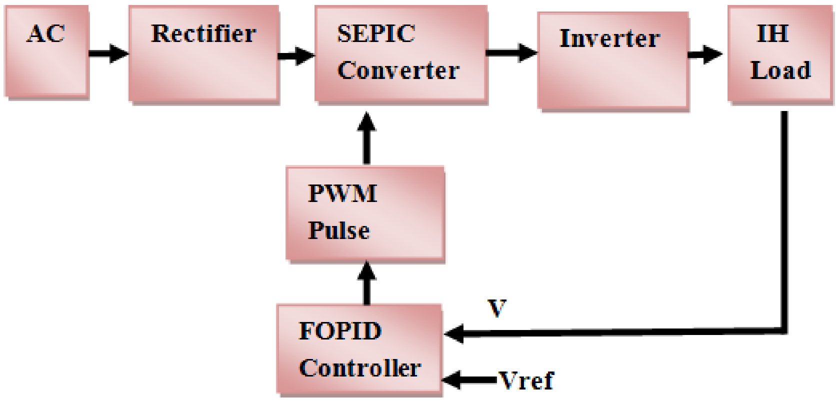

Fig.1. Block Diagram of the Induction Heating System.

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

III. MODES OF OPERATION FOR PFC-SEPIC CONVERTER

Mode-1: In this mode of, the upper switch S is turned on and the energy stored in inductive coil is transferred to load by electromagnetic induction.

Mode-2: This mode of starts when the upper switch S is switched off. As soon as the upper switch is switched off, the resonant current free-wheels its energy through the body diode of lower switch d3, thus enabling it to turn on under ZVS condition.

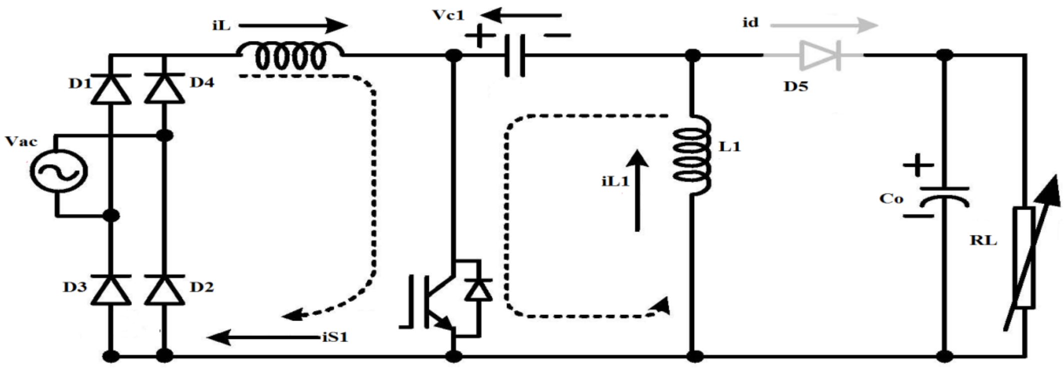

Fig.2. Mode1- Operation of PFC-SEPIC Converter during Ton.

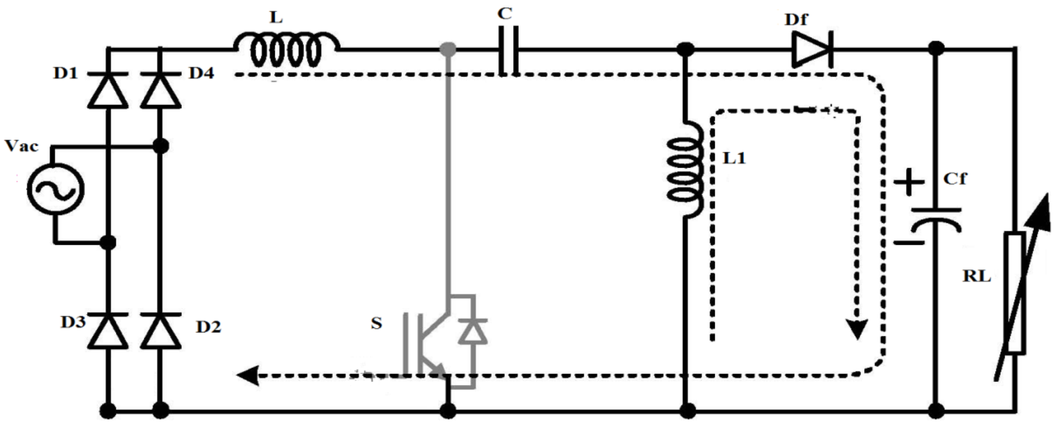

Fig.3. Mode2- Operation of PFC-SEPIC Converter during Toff.

A. *Design of PFC-SEPIC Converter*

The following equation as designed duty cycle ratio of $D_{(t)}$. The inductor and filter capacitor as L, L1, C and SEPIC output capacitor voltage as C_{s0}.

$$D_{(t)} = \frac{V_{so}}{V_{so} + V_{in(t)}} \quad (1)$$

$$D_{(max)} = \frac{V_{so}}{V_{so} + \sqrt{2} * V_{in}} \quad (2)$$

$$\Delta I = \frac{\sqrt{2} * 35\% * P_O}{D * V_{inmin}} \quad (3)$$

$$L = L_1 = \frac{\sqrt{2} * V_{inmin} * D_{min}}{\Delta I} \quad (4)$$

$$C = \frac{V_O}{R * f_s * \Delta V_c} \quad (5)$$

$$C_{s0} = \frac{P_O}{2 * \pi * f_L * Vso\, \Delta V_b} \quad (6)$$

IV. MODES OF OPERATION FOR VFFBSRI SYSTEM

Mode-1: In this stage, the upper switch S1and S2 is turned on and the energy flows from source to the inductive coil is transferred to load by electromagnetic induction.

Mode-2: In this stage, energy in L is returned to d3and d4 to the source.

Mode-3: In this stage, the upper switch S3and S4 is turned on and the energy flows from source to the inductive coil is transferred to load by electromagnetic induction.

Mode-4: In this stage, energy in L is returned to d1and d2 to the source.

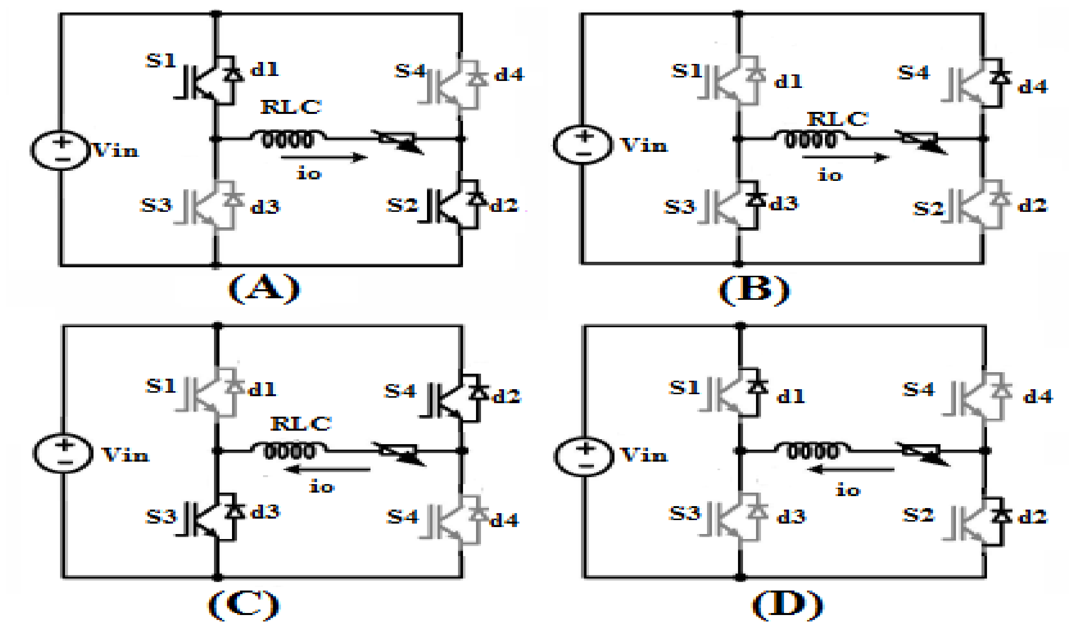

Fig. 4. Operating Modes of VFFBSRI-IH DC-AC Inverter

A. Design of VFFBSRI Converter

The following equation of VFFBSRI Output Resistor (R_R),Peak Current as (I_{Peak}),Output Capacitor as(C_{RC}) and Output Inductor as(L_{RL})

$$R_R = \frac{2\, Vso^2\, Cos^2\, \phi}{\pi^2\, P_0} \quad (7)$$

$$I_{Peak} = \frac{2\pi P_0}{2\pi V_{s0}} \quad (8)$$

$$C_R = \frac{I_{peak}}{2\pi f_r V_{s0}} \quad (9)$$

$$L_{RL} = \frac{1}{(2\pi f_r)^2 C_{RC}} \quad (10)$$

V. SIMULATION RESULTS AND DISCUSSION

5.1 *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 Fig.5. Input voltage and current is shown in Fig. 6. The source current THD is shown in Fig. 7. It shows the THD is 4.98%. Output voltage of SEPIC converter is shown in Fig.8. The full bridge inverter output voltage & current is shown in Fig.9 and Fig10. Output power of induction heating system is shown in Fig. 11.

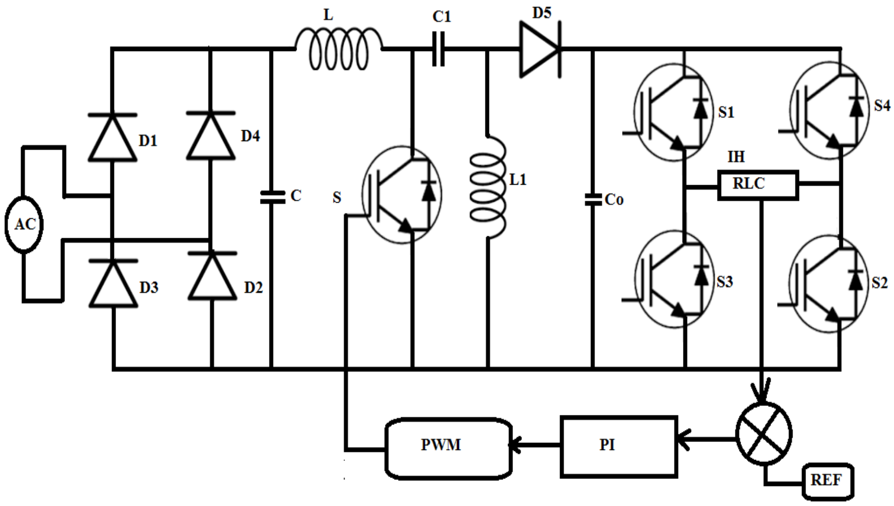

Fig.5. Circuit Diagram of SEPIC with VFFBSRI Closed Loop PI Controller Induction Heating System.

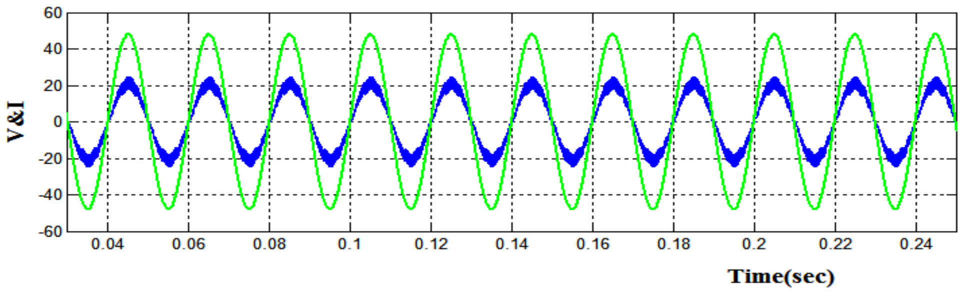

Fig. 6. Input Voltage and Current.

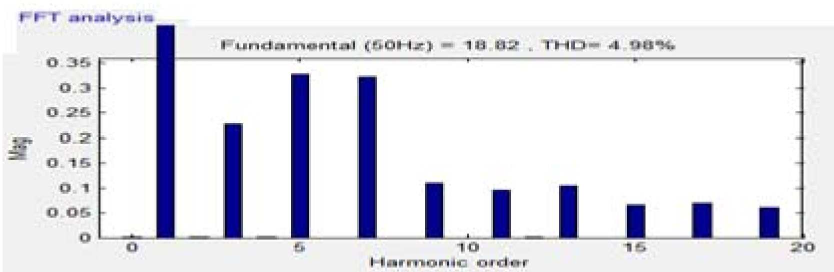

Fig.7. THD Analysis of Input Current of SEPIC Converter with PI controller.

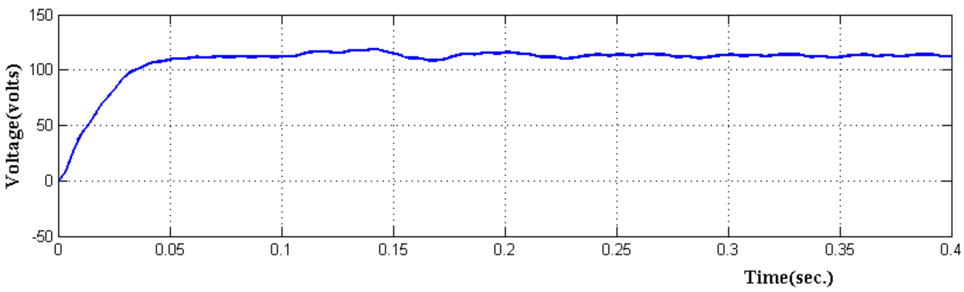

Fig.8. Output Voltage of SEPIC Converter.

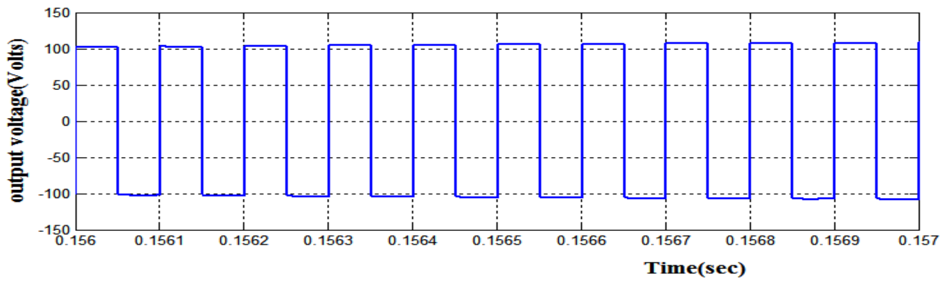

Fig. 9. Output Voltage of Inverter.

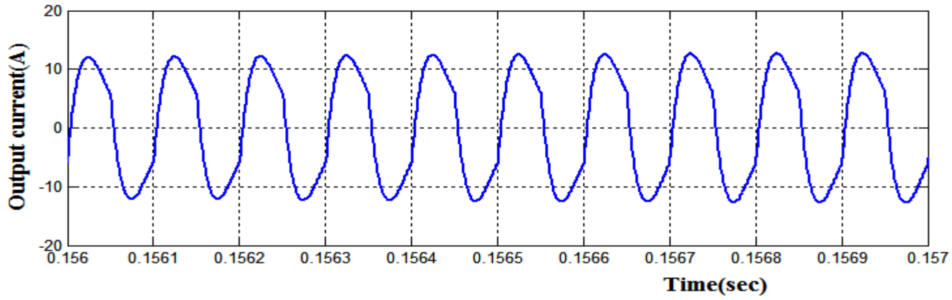

Fig.10. Output Current of Inverter.

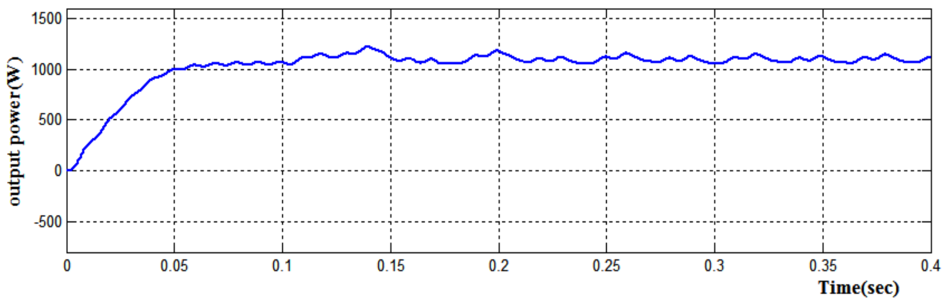

Fig.11. Output Power of Induction Heating System.

5.2 *SEPIC with FOPID controller*

Simulink model of SEPIC with VFFBSRI induction heating closed loop FOPID controller system is shown in Fig.12. Input voltage and current is shown in Fig. 13. The source current THD is shown in Fig. 14. Output voltage of SEPIC converter is shown in Fig.15. The full bridge inverter output voltage & current is shown in Fig. 16-17. Output power of induction heating system is shown in Fig .18.

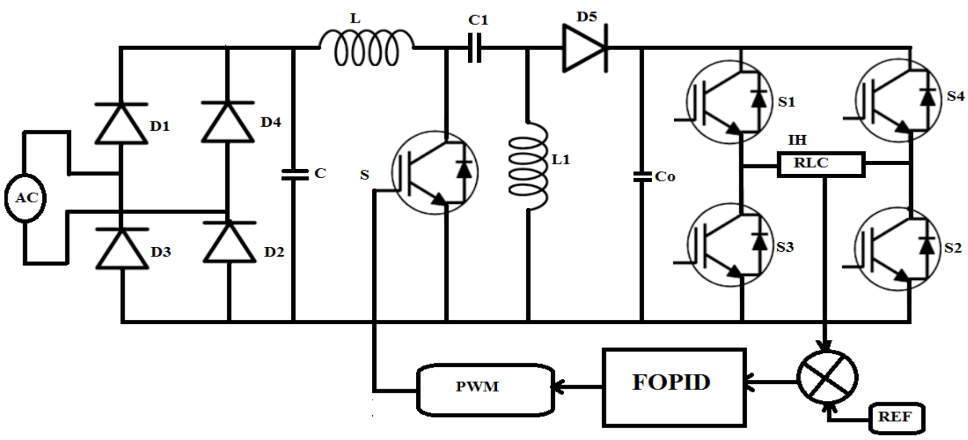

Fig. 12. Circuit Diagram for SEPIC with VFFBSRI Closed Loop FOPID Controller Induction Heating System.

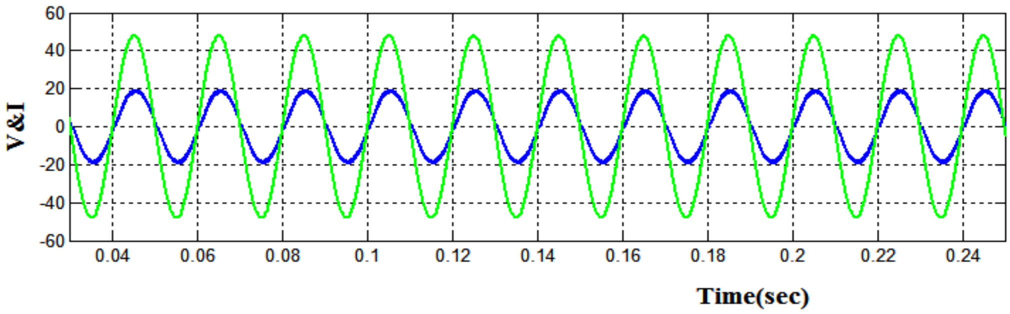

Fig.13. Input Voltage and Current.

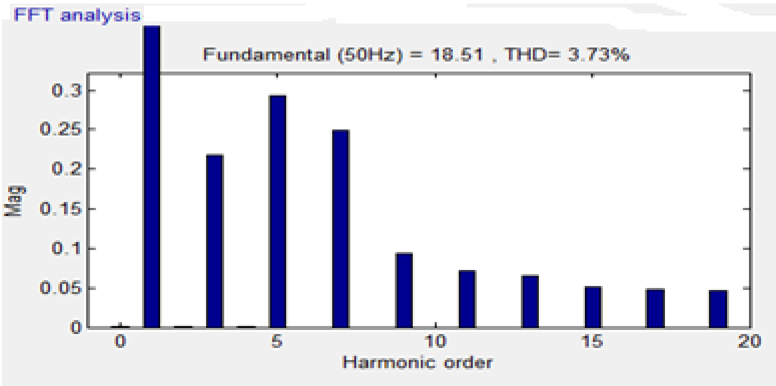

Fig. 14. THD Analysis of Input Current of SEPIC Converter with FOPID controller.

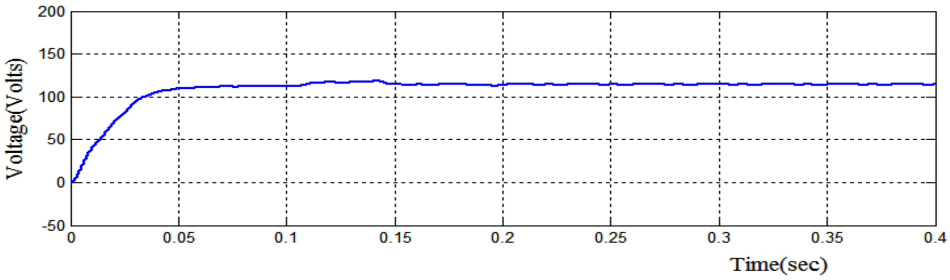

Fig. 15. Output Voltage of SEPIC Converter.

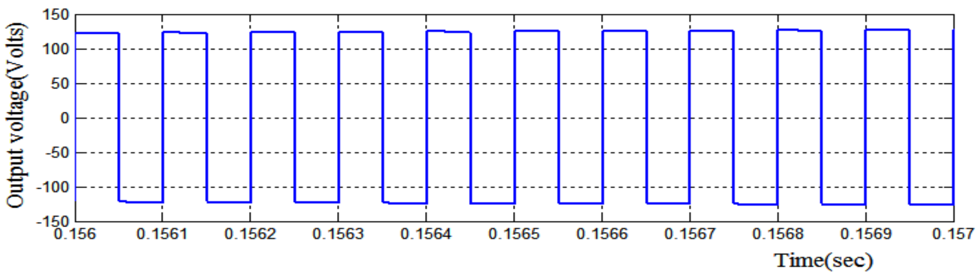

Fig. 16. Output Voltage of Inverter.

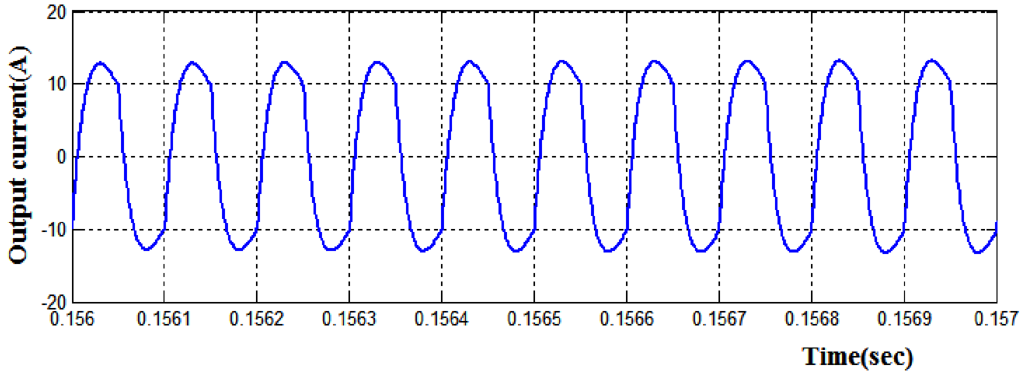

Fig. 17. Output Current of Inverter

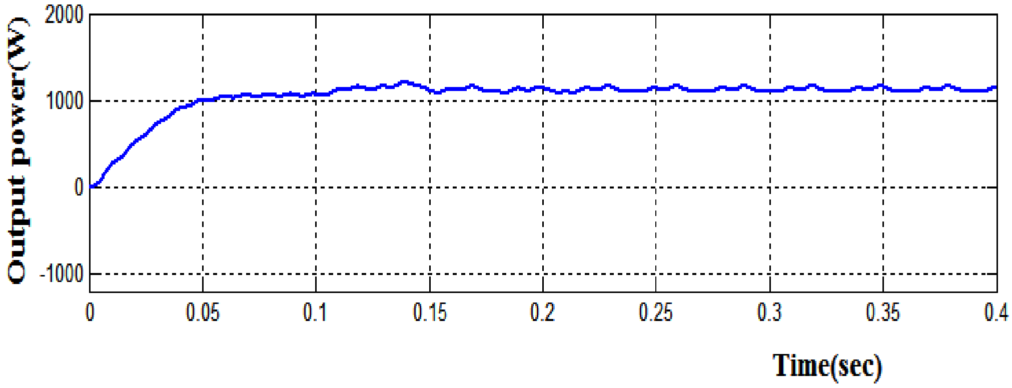

Fig.18. Output Power of Induction Heating System.

Table I. Comparison of Time Domain Parameters

Types of Controller	Rise time (s)	Peak time (s)	Settling time (s)	Steady state error (v)	THD
PI	0.12	0.24	0.14	3.8	4.98%
FOPID	0.11	0.15	0.12	1.8	3.73%

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

VI. EXPERIMENTAL RESULTS

The hardware setup of the prototype whose input voltage is 48V, output voltage is 110V, has output power of 1kW and switching frequency of 10 kHz. Hardware setup of SEPIC with VFFBSRI induction heating system is shown in Fig. 19. The hardware of SEPIC with VFFBSRI system is fabricated and tested in laboratory. The hardware consists of 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 controller is shown in Fig. 20. Fig. 21 shows the system with controller. Output voltage of SEPIC converter is shown in Fig.22. Output voltage of the inverter is shown in Fig. 23. Output current of the inverter is shown in Fig. 24.

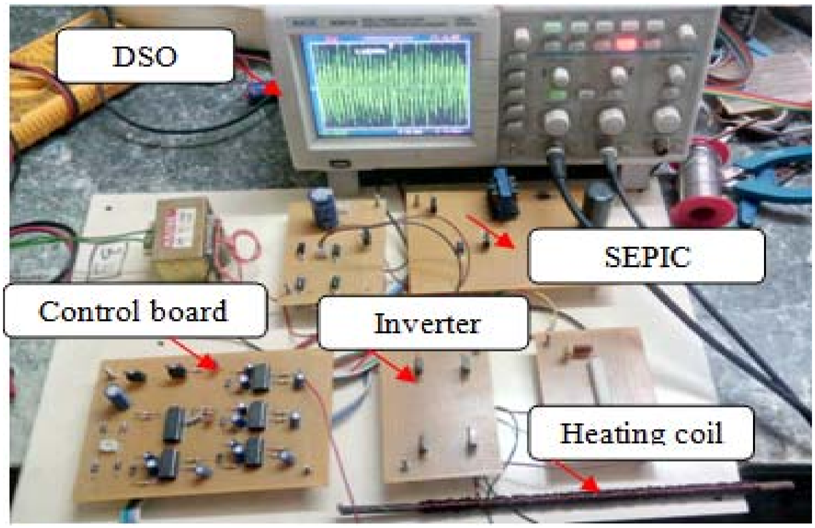

Fig. 19. Hardware Setup of the Prototype System.

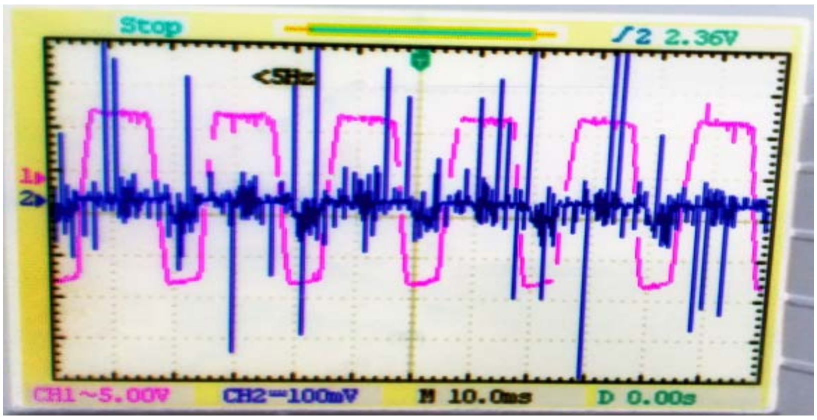

Fig. 20. Input Voltage and Current of the system without controller.

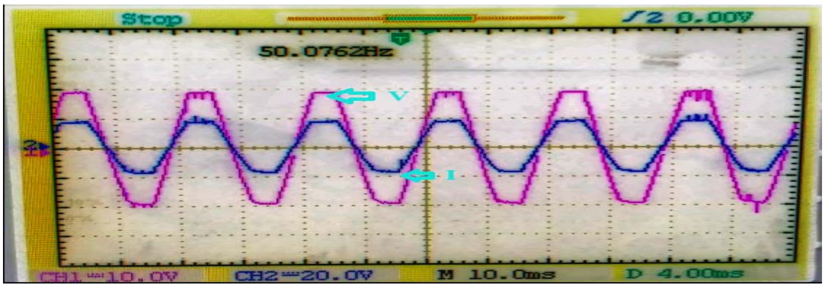

Fig. 21. Input Voltage and Current with Controller.

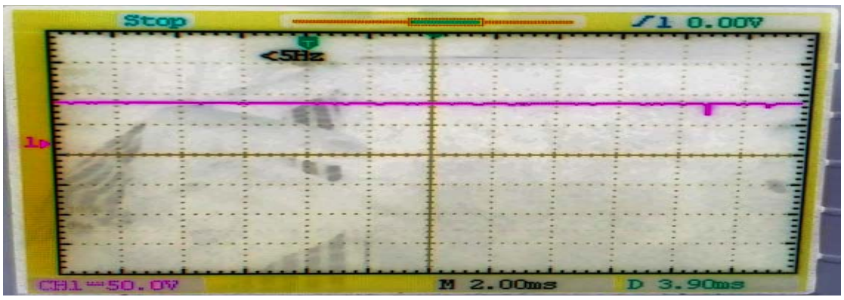

Fig. 22. Output Voltage of SEPIC Converter.

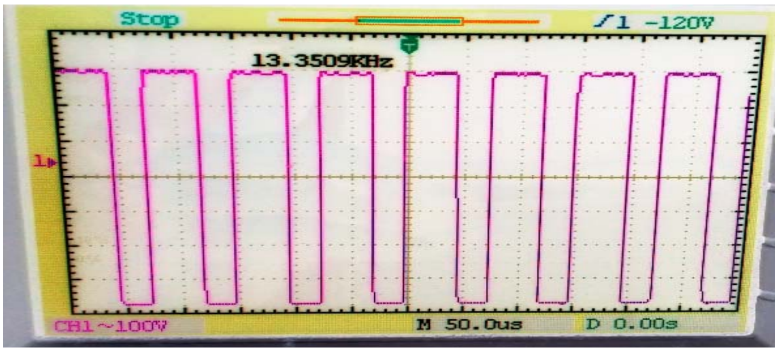

Fig. 23. Output Voltage of Inverter.

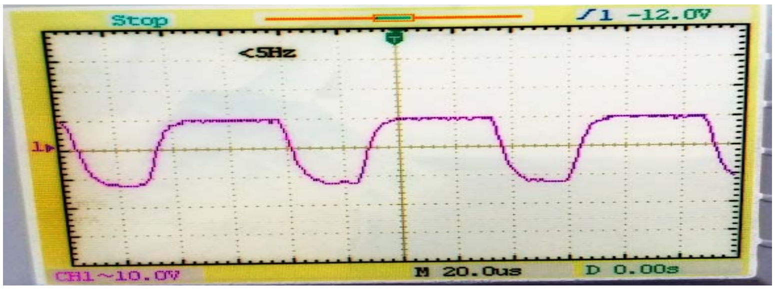

Fig.24. Output Current of Inverter.

Table II. Simulation and Hardware specifications

Description	Simulation	Experimental
Inductance(L)	10µH	12µH
Inductance(L1)	9µH	8µH
Filter capacitance©	1000µF	1000µF
Filter Capacitance(C1)	104µF	104µF
Filter Capacitance(Co)	2200µF	2200µF
Load Resistance (Ro)	3Ω	3.5Ω
Load capacitance (C2)	14µF	15µF
Load side Inductance(L2)	50 µH	48 µH
Input Voltage	48 V	48 V
Switching Frequency	10kHz	10kHz
Output voltage (Vo)	110V	108V
Controller IC	FOPID	PIC 16F84A
Driver IC	-	IR2110
Diode	5408	IN4007
IGBT	12FA-150N	12FA-150N

VII. CONCLUSION

The comparative analysis of SEPIC converter based voltage fed closed loop full bridge series resonant induction heating system with PI & FOPID control strategies was simulated and the results are presented. Also hardware implementation of the inverter fed induction heating system was done. It can be noticed that the time domain parameters and source current THD has reduced from 4.98% to 3.73%. Thus the response of FOPID controlled system is superior to the PI controlled system.

The present work deals with comparison of closed loop PI and FOPID controller systems. The closed loop system PR controller will be done in future.

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Appendix

PFC-SEPIC PI controller gains: Kp=0.06, Ki=0.9; PFC- SEPIC FOPID controller gains: Kp=0.01, Ki=0.04; Kf=0.05, Kd=0.8.

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BIOGRAPHIES OF AUTHORS

P.MUTHU received the B.E. degree in Electrical and Electronics engineering from Dhanalakshmi engineering college Anna University, Chennai, in 2007, and the M.Tech degree in Applied electronics from the Department of Electrical and electronics Engineering, Adhiparasakthi Engineering college Anna University, in 2010. He is currently doing PHD in VIT Chennai campus.

DR.C.UMAYALCHANDRAHASAN 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.