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# Closed Loop Hysteretic Controlled Class E Amplifier Fed Induction Heater System

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**ABSTRACT:** The aim of this work is to improve the dynamic response of closed loop Hysteresis controlled class E based IH system. Circuit modeling, simulation analysis of controlled class E based induction heating system described in the paper. Class -E amplifier is suggested in the present work to generate quick heat in the induction cooker. Class E amplifier is a simple system with single switch and reactive elements. The class E amplifier produces high frequency currents required by the load. Closed loop system with and without HC element are simulated and the corresponding results are presented.

**KEYWORDS:** Closed loop controlled induction heating (CLCIH), Class-E amplifier induction heating system (CEAIHS), Power amplifier (PA), Hysteresis Controlled (HC), and proportional integral controller (PI),

### I. INTRODUCTION

Improving efficiency is a major criterion when working with power amplifiers along with its stability. Class D, Class E power amplifiers are the most used amplifier systems for Induction heating application. Lot of research focused in these power amplifiers in the designing of high power Induction heating (IH) systems everywhere. Design of High power induction heating application is given by J. E. Yeon, K. M. Cho [1]. Procedure to control the temperature of induction heating system for cooking application using class E resonant inverter given by H. Mungikar [2]. Multi cycle modulation for Induction heating systems using Class-E amplifier is given by H.Sarnago [3].

The use of induction heating for domestic applications using Class D/E amplifiers is given by P. Sharath Kumar [4]. Detailed description on self oscillating topology for induction heating systems is given by A. Mediano [5]. New hybrid control system for high power induction heating applications using class-E amplifiers is given by D.Y. Lee [6]. The process of using class-E amplifier for high-frequency induction heating applications is given by S. Hinchliffe [7]. Application of Induction heating using Push-pull Class-E inverter is given by Kamlesh Kumar [8]. Various experimental studies on induction systems using class-E amplifier were given by S.Arumugam [9].

The results of computer simulations and laboratory experiments demonstrate that the proposed methods allow controlling the converter output quantities fulfilling soft switching conditions (zero-current switching) and provide higher efficiency in comparison to other known methods[10]. Cost effective phase shifted pulse modulation soft switching high frequency inverter for induction heating applications is presented by Kifune. Theoretical equations for the soft switching operation region are derived from the practical consideration of the gate pulse control strategy, in which the soft switching operation is limited only by the duration of dead time[11].

Modeling of planar spiral inductors between two multilayer media for induction heating applications is suggested by Acero. We demonstrate the applicability of the model by a variety of examples. We present experimental results to justify the theoretical model[11]. Behaviors of Class-F and Class-F<sup>-1</sup> Amplifiers is given by Moon[13]. Power Amplifier Design Methodologies for Next Generation Wireless Communications is presented by Eswaran[14]. The Continuous Class-F Mode Power Amplifier is suggested by Carrubba. Starting from the standard class-F mode, this work shows that it is possible to maintain constant or even improved output power and efficiency for coupled variations of fundamental and second harmonic impedances[15].

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A current-fed multi resonant converter with low circulating energy and zero-current switching for high step-up power conversion is given by Yuan[16]. Design and Analysis of Class E/F  $\pi$  Power Amplifier with Nonlinear Shunt Capacitance at Nonoptimum Operation is presented by Hayati. Because of the increase in the design degree of freedom, one more relationship can be specified as a design specification [17]. Design equations for suboptimum operation of class E amplifier with nonlinear shunt capacitance is suggested by Kazimierczuk[18]. An example of a design procedure of the class E amplifier is given. The theoretical results were verified with PSpice simulation [19].

A Class-E RF Power amplifier with a flat-top transistor-voltage waveform is presented by Sokal. This work shows a Class-E RF power amplifier designed to obtain a flat-top transistor-voltage waveform whose peak value is 81% of the peak value of the voltage of a "Classical" Class-E amplifier[20]. Suboptimum operation of Class-E RF power amplifiers is suggested by Raab. This paper presents a high-power high-efficiency wideband suboptimum Class-E RF power amplifier based on a packaged high-power GaN HEMT. Direct applications for this amplifier include mobile satellite communications transmitters, envelope elimination and restoration digital audio broadcasting transmitters, and power stages for primary and secondary RADAR transmitters [21].

A design procedure for optimizing the LC resonant converter as a wide output range voltage source is given by Beiranvand[22]. High-efficiency class E, E/F, and E/F inverters is presented by Kaczmarczyk [23]. The class- E/F family of ZVS switching amplifiers is suggested by Kee. Operational waveforms for several implementations are presented, and efficiency estimates are compared to class-E[24]. High efficiency class-E power amplifier design including input harmonic termination is given by Gao[25]. The above literature does not deal with comparison of responses of CEAS with PI and HC controllers. This work proposes HC for the control of CEAS.

## II. SYSTEM DESCRIPTION

The presented induction-heating system utilizing Class-E amplifier is appeared in the Figure 1.1. DC is converted into high-frequency AC utilizing the CEAS.

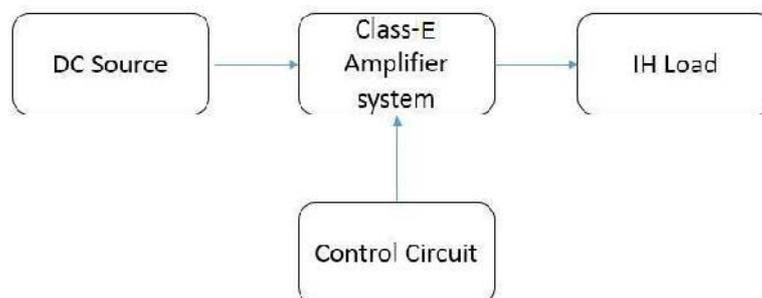


Figure 1.1 Block diagram of the CEA based IH system.

## III. SOFTWARE AND ARTICLE INFORMATION

### 3.1. Existing IH system

The existing system of CEIH (Class E Amplifier based Induction Heating System) is shown in the Fig 1.2. DC is transformed into high frequency AC with help of class-E amplifier. Generated heat is produced due to eddy current losses. Regulating the output voltage is obtained using the PI controller.

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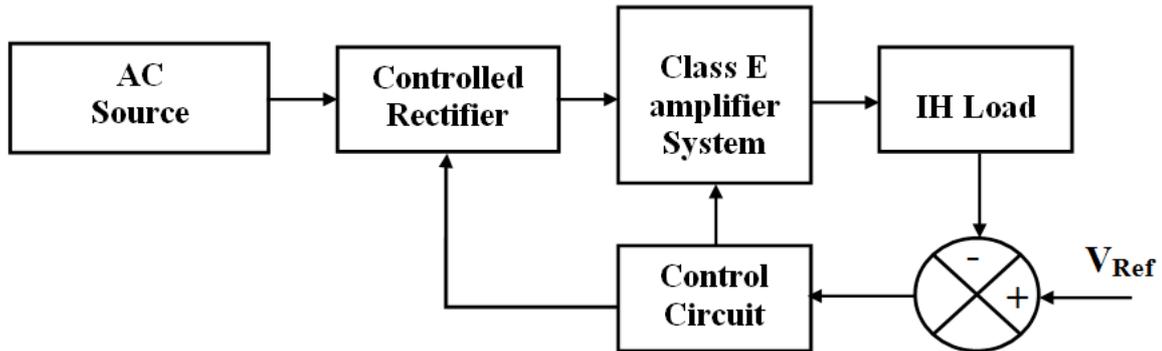


Fig 1.2 Block diagram of the existing IH system

### 3.2 Projected System

Hysteresis Controlled Closed loop Class-E Amplifier system (HCCCEA) is proposed to overcome CEIH is shown Fig 2.1. Low frequency AC is changed into DC with help of the controlled rectifier. The output of the rectifier is manifested into high frequency AC using the class E amplifier. Class-E amplifier is replaced by Class-E amplifier and PI controller is replaced by HC controller to improve the dynamic response.

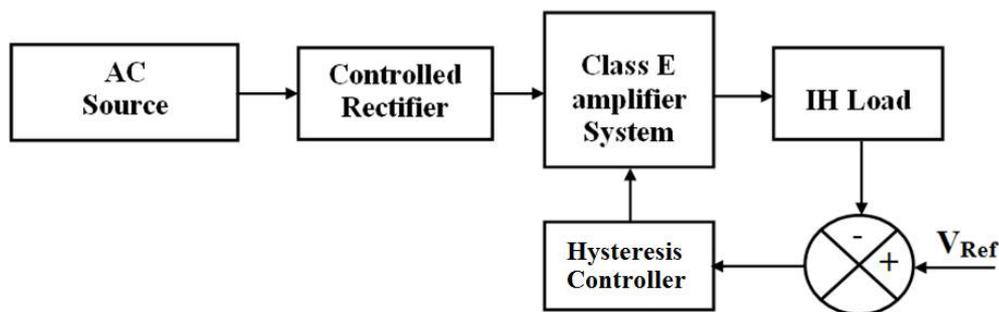


Fig. 2.1 Block diagram of the proposed CEAIHS

### 3.3 Principle Hysteresis Controller

The principle of hysteretic control is given in Figure 2.2. Output voltage is compared with the reference voltage. The error is applied to hysteretic comparator. The output is given to the driver circuit. The driver amplifies the pulses from 5V to 10V. The driver pulses and output voltage. The pulse is applied whenever output voltage is less than  $V_r$ . The pulses is stopped whenever the output is greater than  $V_r + V_h$ .

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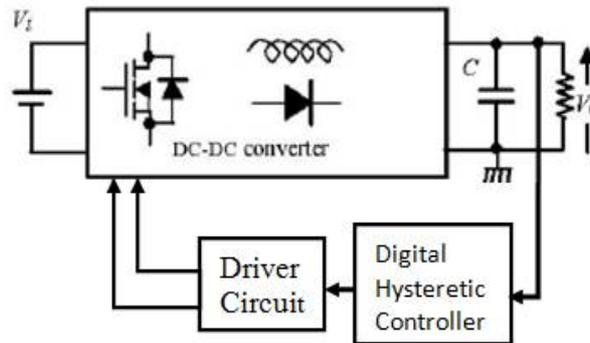


Figure 2.2 Principle of Hysteretic Control

### 3.4 System Analysis

Design calculations are performed using the following equations: The current through the load is

$$I = V_d \sqrt{C/L} e^{-\delta t} \sin \omega t \quad \dots\dots\dots (i)$$

The voltage across the capacitor

$$V = V_d (1 - \cos \omega t) \quad \dots\dots\dots (ii)$$

ZVS period is calculated using equation (ii)

$$r = \frac{1}{4\sqrt{3}fCR} \quad \dots\dots\dots (iii)$$

The value of filter capacitor is determined using the expression for ripple factor given in equation (iii).

## IV. SIMULATION RESULTS

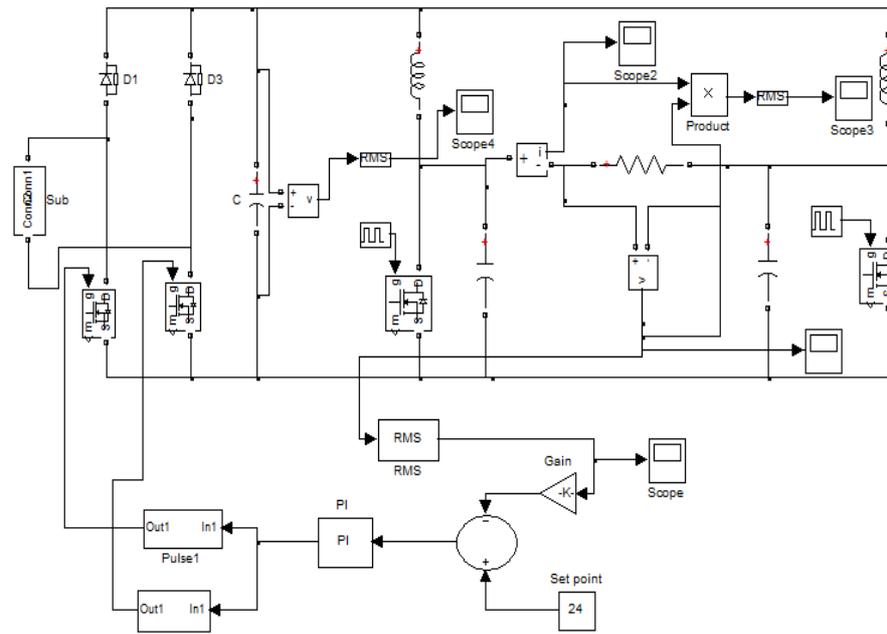
Closed loop with PI controller for CEA system is appeared in Fig 3. The input voltage CEA system is shown in Fig 3a and its value is 55V. The Output voltage of Rectifier CEA system is appeared in Fig 3b and its value is 49V. The output current rectifier CEA system is appeared in Fig 3c and its value is 10.5A. The output current ripple of rectifier CEA system is appeared in Fig 3d and its value is 10.55A. The Output voltage CEA system is shown in Fig 3e and its value is 40 V. The Output current CEA system is shown in Fig 3f and its value is 17A. The output power CEA system is shown in Fig 3g and its value is 300 Watts.

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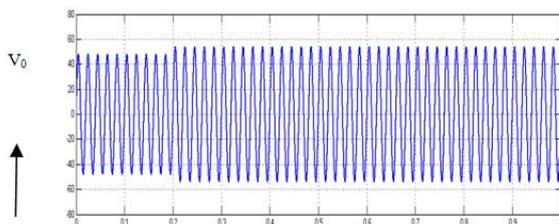
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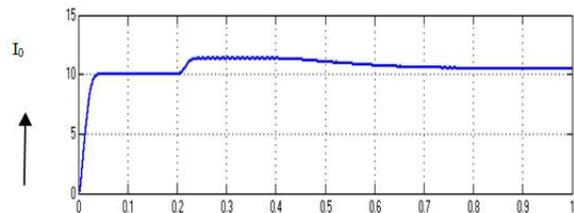
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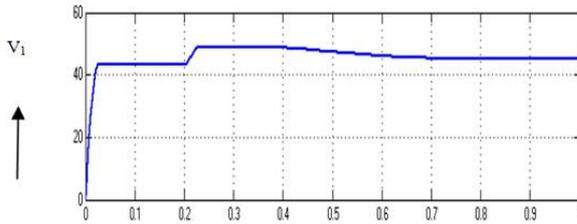
**Fig 3 Circuit diagram of the closed loop CEAS with PI controller**



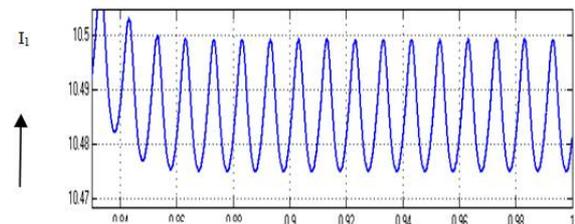
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=20 V **3a**



Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=5 V **3c**



Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=20 V **3b**



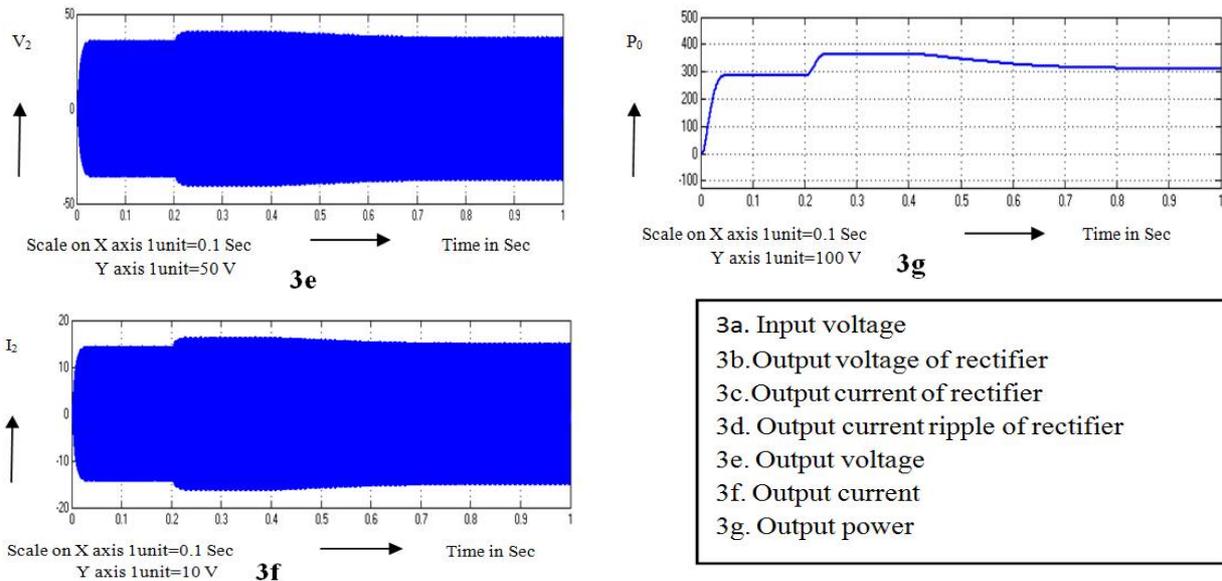
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=10 V **3d**

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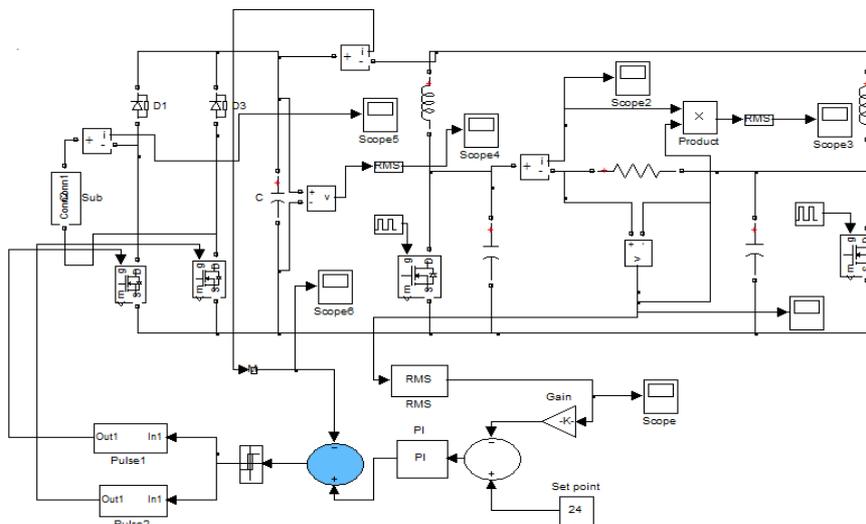
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Closed loop with HC controller for CEA system is appeared in Fig 4. The input voltage CEA system is shown in Fig 4a and its value is 55V. The Output voltage of Rectifier CEA system is appeared in Fig 4b and its value is 48V. The output current rectifier CEA system is appeared in Fig 4c and its value is 12 A. The output current ripple of rectifier CEA system is appeared in Fig 4d and its value is 10.81A. The Output voltage CEA system is shown in Fig 4e and its value is 45 V. The Output current CEA system is shown in Fig 4f and its value is 17.5A. The output power CEA system is shown in Fig 4g and its value is 320 Watts. The Comparison of time domain parameters is given in Table-1. The Comparison of output current ripple of rectifier is given in Table-2.



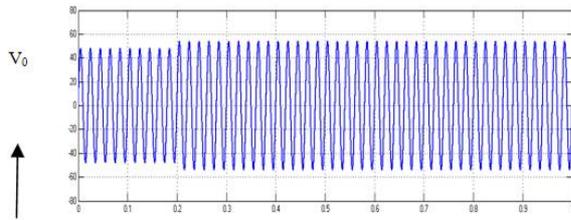
**Fig 4 Circuit diagram of the closed loop with hysteresis controller**

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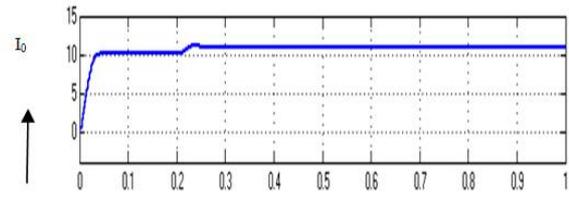
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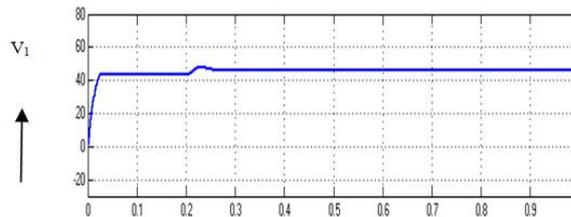
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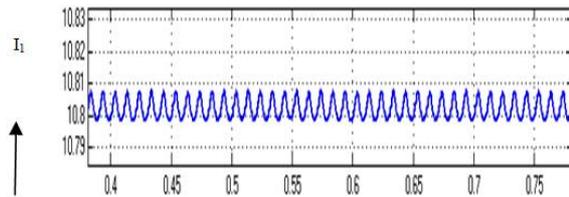
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=20 V **4a** → Time in Sec



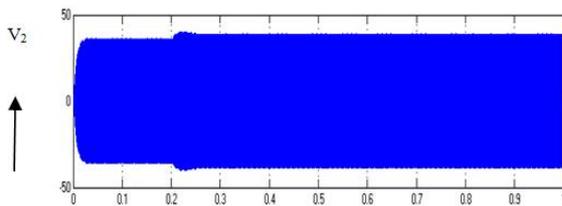
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=5 V **4c** → Time in Sec



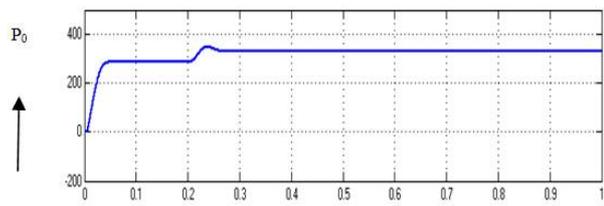
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=20 V **4b** → Time in Sec



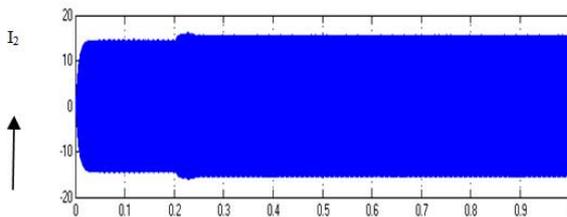
Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=10 V **4d** → Time in Sec



Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=50 V **4e** → Time in Sec



Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=100 V **4g** → Time in Sec



Scale on X axis 1unit=0.1 Sec  
Y axis 1unit=10 V **4f** → Time in Sec

- 4a. Input voltage
  - 4b. Output voltage of rectifier
  - 4c. Output current of rectifier
  - 4d. Output current ripple of rectifier
  - 4e. Output voltage
  - 4f. Output current
  - 4g. Output power

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**Table -1**  
**Comparison of time domain parameters**

Type of controller	Tr	Tp	Ts	Ess
<b>PI</b>	<b>0.23</b>	<b>0.42</b>	<b>0.70</b>	<b>2.80</b>
<b>HYS</b>	<b>0.21</b>	<b>0.22</b>	<b>0.23</b>	<b>0.90</b>

**Table -2**  
**Comparison of output current ripple of rectifier**

Types of controller	Output current ripple of Rectifier
<b>PI</b>	<b>0.02A</b>
<b>HYS</b>	<b>0.01A</b>

### V. CONCLUSION

Class E amplifier system was successfully designed; modeled & simulated using MATLAB and the results of case studies with and without HC system were presented. The induction heater load was shown as series combination of resistance and inductance settling time was reduced to 0.23 sec using HC controller. The steady state error in the output voltage was reduced from 2.80V to 0.90V by introducing HC controller. The Output current ripple is reduced from 0.02A to 0.01A. The results in this paper are clear indication of improvement in dynamic response. The experimental module is implemented to validate the simulation results. The benefits of Class-E system are minimum switching losses, less switching stress and high-power density. The disadvantages of Class- E system is that frequency cannot be varied by wide range.

The scope of this work was the modeling and simulation of Class-E amplifier with HC control. The comparison with FLC controlled system will be done in future.

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