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Performance Enhancement in Cyclo Inverter based Induction Heating System Using Hysteresis Controller

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Abstract: **Induction heating is a popular non-contact method for thermal processing, valued for its rapid response, uniform heat distribution, and accurate controllability. Improving the dynamic behavior of IH systems particularly with respect to time-domain characteristics, it requires the implementation of effective feedback control strategies. This paper presents a comparative study of two feedback controllers namely, a conventional Proportional-Integral (PI) controller and a PI controller integrated with a hysteresis control mechanism for an IH setup powered by a multi-output cyclo-inverter. The proposed control models are developed and simulated using the MATLAB/Simulink environment. Key performance parameters such as output current ripple and steady-state error are evaluated under varying input conditions. Results indicate that the PI with hysteresis controller significantly outperforms the conventional PI controller, reducing the current ripple from 0.7 A to 0.1 A and achieving a statistical significance level of 0.937. The performance evaluation, conducted using SPSS software with seven samples in each group and a statistical power set at 0.95, validates the enhancement in dynamic response. A 100W experimental prototype of the IH system is also developed and tested using both controllers. The experimental results closely match the simulation findings, demonstrating the efficiency of the suggested control approach. The objective of this study is to improve the dynamic response and precision control of an induction heating system powered by a multi-output cyclo-inverter, through the implementation of a hybrid PI-hysteresis feedback controller.**

Keywords: Induction heating, PI, Hysteresis controller, Cyclo converter, Ripple Factor

I. INTRODUCTION

Induction heating (IH) systems have evolved significantly with advancements in power electronic converters and intelligent control techniques. Numerous researchers have suggested techniques to improve the efficiency, accuracy, and overall performance of these systems by optimizing controllers and refining inverter architectures. In [1], a fuzzy logic-based voltage regulation approach was introduced for Class-D inverters in induction heating systems, leading to notable enhancements in dynamic behavior and power management. [2] introduced an input voltage selection technique for half-bridge resonant inverters with high turn-numbered coils, enhancing thermal efficiency and enabling compatibility with all-metal IH applications. [3] developed an inductive sensor for accurate temperature measurement in IH, emphasizing the importance of non-contact and precise feedback for real-time control.

In [4], harmonic distortion was minimized by choosing suitable power semiconductor switches within a modified half-bridge resonant inverter configuration, thereby enhancing power quality in induction heating applications. [5] designed a high-power-density inverter using multiple MOSFETs, enhancing thermal handling and reliability. [6], [7], [9] have made extensive contributions to cyclo-inverter-fed IH systems. Their experimental and simulation-based investigations demonstrated the feasibility and advantages of multi-output cyclo-inverter architectures, highlighting improvements in dynamic performance, zone control, and harmonic reduction. In addition, their research on PDM-controlled Class-D inverters confirmed efficiency gains and stable output characteristics [10].

[8] utilized phase angle control in multi-inverter systems, facilitating zone-wise control of resonant currents, essential for multi-output IH configurations. Recent works have also focused on advanced converter architectures relevant to the power supply of IH systems. In [11], a power factor correction (PFC) based three-stage interleaved boost converter was designed for renewable energy applications, significantly reducing current ripple, an essential factor in induction heating power circuits. [12] improved the control of multiport boost converters for hybrid systems, reinforcing the need for flexible energy management techniques. [13] analyzed transformer-coupled bidirectional converters, emphasizing dynamic control and energy flow management—features crucial for bidirectional heating and cooling cycles in advanced IH systems. [14] studied PV-fed multilevel inverters for smart grids, and their comparative analysis underlines the importance of low harmonic content and high efficiency, applicable to IH in smart energy environments.

These prior studies establish a strong foundation for the development of optimized control strategies in IH systems. Despite advancements, the combined application of PI and hysteresis controllers in cyclo-inverter-fed IH systems remains underexplored. This study seeks to bridge that gap by introducing a hybrid control strategy that merges the steady-state precision of the PI controller with the rapid response characteristics of the hysteresis controller. The objective is to achieve reduced output current ripple, improved dynamic response, and enhanced system reliability. The organization of the paper is as follows: Section II presents the proposed cyclo-inverter topology integrated with asymmetrical voltage cancellation control. Section III presents the simulation results using the conventional PI controller, PI with Hysteresis controller, along with statistical analySection IV discusses the experimental prototype results. Finally, Section V provides a summary of the overall work.

II.CYCLO-INVERTER TOPOLOGY

The proposed CIFIH arrangement is given in Fig. 1. Half controlled rectifiers composed of 2 diodes and 2 MOSFETs are utilized to rectify the given ac source. Diodes are connected back to back with semiconductor devices in order to provide the high rate of recurrence current to the inductor coil.DC link inductor is of low value so as to allow pulsating dc input to the cyclo-inverter module. The firing module's high frequency pulses are used to sequentially turn on and off the six MOSFET switches, which are also connected to diodes. First leg with third leg devices are operated like a full bridge inverter as first load and second leg with third leg devices are operated as second load.

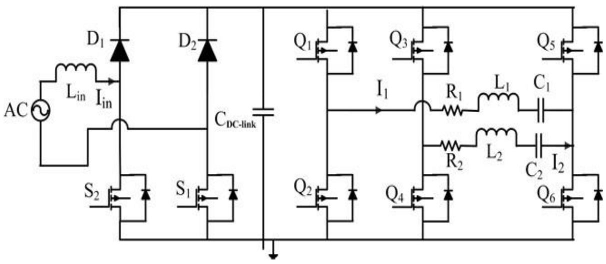


Fig. 1 Proposed system CIFIH

Here the third leg acts as a common leg for both load 1 and 2 so as to share the component requiredfor supplying multiple loads. IH coil gets high frequency eddy currents from the inverter circuit for generating required heating function. MOSFET switching losses are reduced by ZVS. This study aims to identify a suitable control strategy for a CIFIH system, as outlined in the referenced work.IH system is implemented by means of the MATLAB / SIMULINK model. Parameters assigned are: Source voltage is 230 V, 50 Hz, Capacitor used in the DC link (Cdc) is 2200 µF, load inductance (L) is 25 µH, resonant capacitance (C) is 60 µF, and output resistance (R) is 9.5 Ω with a switching frequency of 48kHz. Asymmetrical Voltage Cancellation (AVC) control (Burdio et al. 2004) is the most preferred control technique for multiple output control. In the Asymmetrical Voltage Cancellation (AVC) method, the duty ratios assigned to the switches in the common leg, first leg, and second leg are 50%, 40%, and 20%, respectively. Moreover, the switches are operated with a frequency of 48 KHz. Common leg (3rd leg) with first leg forms load 1 and common leg with second leg forms load 2. The control technique explained in20 is considered for simulation.

III. SIMULATION RESULTS

Feedback control of a system is required to ensure precise control over output parameters. To obtain accurate output, feedback control is mandatory. The evaluation of the proposed system focuses on assessing the closed-loop performance using both PI controllers and a hybrid control approach that integrates PI with hysteresis (PI-Hy) control. The schematic diagrams of the proposed system with traditional proportional-integral (PI) controller and conventional proportional-integral (PI) and hysteresis (H) controller appear in Figures 2 and 3. in both the cases are same as mentioned in section 1. The PI controller, which is a feedback controller, regulates the load power of an induction heating system using a weighted average of the error. The dynamic response is improved, and the steady state error is decreased, using this method frequently. The system's PI tuning and the controller's K_P and K_I parameters are acquired as shown in the table 1. Ref T_1, as well as the sample time (Tsam). One PI-based control method regulates the input voltage; this type of control is voltage-based.

Converter parameter is same as mentioned in section 1. Voltage regulation is accomplished through a PI-based control strategy, in which the PI controller's output functions as the reference current for the inner control loop. The inner loop is a hysteresis based current control. The input current is detected and compared to the reference current. The error signal is then sent to a hysteresis-based controller, which produces pulses of the gate for the switches S_1 and S_2. The system is controlled using a dual control strategy, and the controller parameters K_P and K_I are obtained as below.

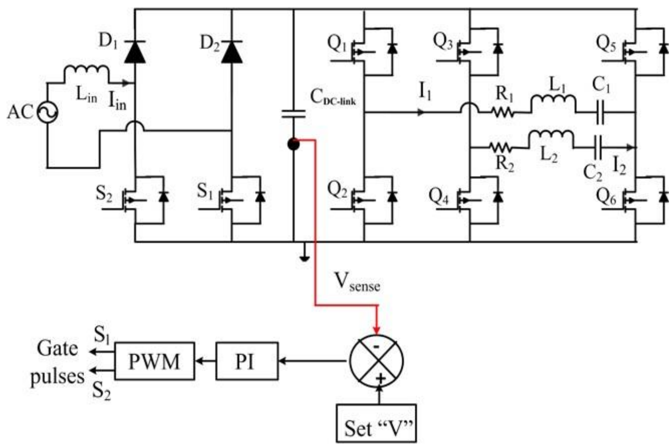


Fig. 2 IH system with conventional PI controller

Converter parameter is same as mentioned in section 1. The voltage is regulated using a PI controller, and its output is utilized as the reference current for the inner control loop. The inner loop is a hysteresis based current control. The input current is detected and compared to the reference current. The error signal is then sent to a hysteresis-based controller, which produces pulses of the gate for the switches S_1 and S_2. The system is controlled using a dual control strategy, and the controller parameters K_P and K_I are obtained as below.

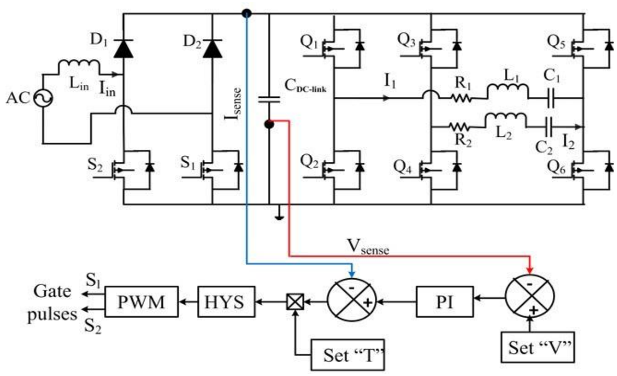


Fig 3. IH system with hysteresis controller

The results of the PI based and Hysteresis based IH system are shown from Fig 3 to Fig 6. The input voltage of the for both system are same and it is 140 V as shown in Fig.4.

Table 1. Controller Parameters

System	Kp	Ki	SampleTime (ms)
PI based IH	0.5	15	15
PI and Hysteresis based IH	0.9	30	50

Figures 5 to 7 illustrate the rectifier output for the induction heating system using both PI and PI-Hysteresis (PI-Hy) controllers. The results indicate that the PI-Hy controlled system achieves more accurate rectifier voltage and current compared to the conventional PI-controlled system.

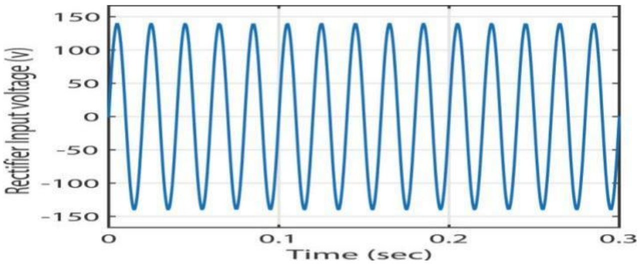
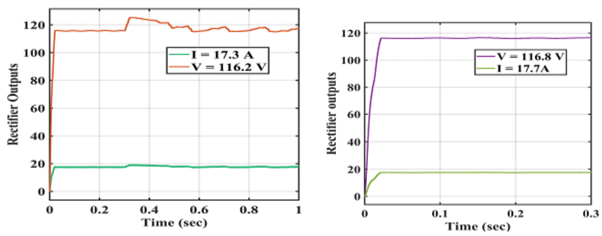


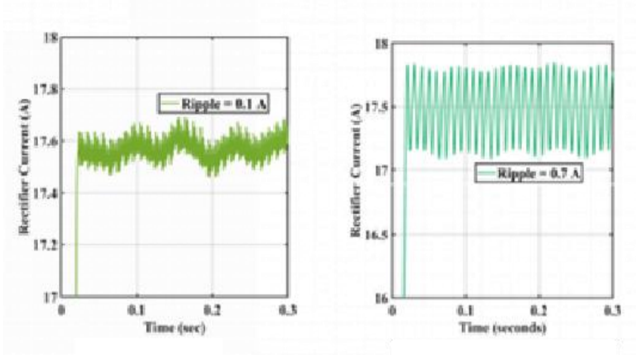
Fig 4. Input voltage of the Rectifier



(a) PI based IH system. . (b) PI-Hy based IH system.

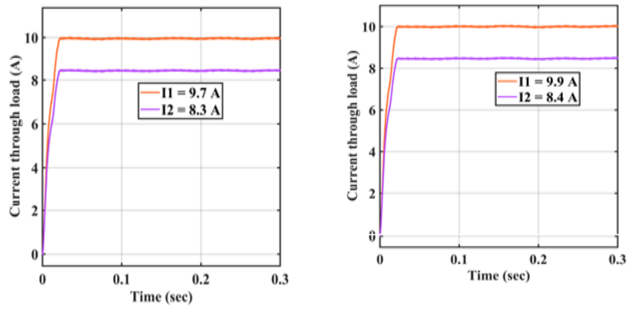
Fig.5. Voltage and Current at the Rectifier Output

Figure 6 illustrates the output voltage and current measurements across two loads in the IH system for each type of controller implementation. It is spotted in Fig.6(b), the output current in PI-Hy based IH system is 2% and 1% higher for load 1 and 2 than the PI based system in Fig. 6(a). The performance of the CIFIH system is improved by integrating a PI controller with a hysteresis control mechanism within the feedback loop.. This approach minimizes output current ripple and steady-state error, thereby improving system stability and dynamic response.

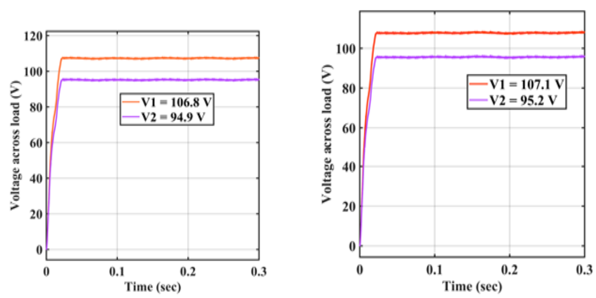


(a) PI and Hysteresis Controller (b) PI Controller

Fig 6. Rectifier Current Ripple of IH system.



(a) Load Current with PI Controller. (b) Load Current with PI-Hy Controller.



(c) Load Voltage with PI Controller. (d) Load Voltage with PI-Hy Controller.

Fig 7. Load Current and Voltage of PI and PI-Hys Controller based IH system.

Similarly, the load voltages for PI-Hy controller based IH system is 9 mV and 3 mV higher than the PI controller based system. On the other hand, the time domain response at the rectifier output current for the IH system with both the controllers is also observed from the simulation results. Table 2 summarizes the recorded metrics, including steady-state error (Ess), peak time (Tp), rise time (Tr), and settling time (Ts), derived from the system's performance observations. From Table 2, it is observed that, the Tr, Ts, Tp and the Ess are lesser in PI-Hy than the PI based IH system.

Table 2. Time Domain Response Comparison for PI and PI-Hy Controllers

System	Tr (Sec)	Ts (Sec)	Tp (Sec)	Ess (%)
PI based IH	0.32	0.47	0.35	2.4
PI and Hysteresis based IH	0.31	0.39	0.32	1.5

The proposed PI-hysteresis controller has moderate complexity, as it combines simple threshold-based switching with conventional PI logic. It is computationally efficient and suitable for real-time implementation on low-cost embedded platforms.

IV. STATISTICAL ANALYSIS OF PI AND PI-HY BASED IH SYSTEM

SPSS software is used to analyze the conventional PI and PI with a Hysteresis controller based IH system. The input voltage levels supplied to the rectifier function as the independent variable while the Load Voltage stands as the dependent variable. For determining the maximum output voltages of the systems two different group tests were conducted using T-testing. The test is carried out with 7 samples (N=7). The test outcomes reveal that the mean values, along with the standard deviation and standard error of the mean for Load 1 and Load 2 in the PI-Hy-based induction heating system, show an 11% decrease compared to those obtained using the PI-based system. Load 1 exhibits a significance value of 0.096 apart from load 2 which shows a value of 0.095 during the input voltage changes in the PI-Hy based IH system. Tables 3 presents the test results.

Independent sample test results are in Table 4. The conventional and PI controllers with hysteresis have different output voltages.

Table 3. T-test comparison of conventional PI & PI with Hysteresis controller by varying input voltage from 110 to 170

System	Groups	N	Mean	SD
PI based IH	Load Voltage 1	7	127.54	14.566
	Load Voltage 2	7	128.30	15.063
PI & Hysteresis based IH	Load Voltage 1	7	113.07	12.904
	Load Voltage 2	7	113.74	13.354

It is evident from the simulation results and also from the statistical analysis that a PI-Hy controller based IH sytem has better performance than PI based system. Therefore, an experimental prototype of 100 W is developed for PI-Hy based IH system and its performance is validated experimentally in the following section.

Table 4. Independent sample test results

Independent Sample Test										
Levene's Test for Equality of Variances						T-test for Equality of Means				
		F	Sig.	t	df	Sig.(2-tailed)	Mean Diff.	Std.Error Diff.	0.95 confidenceInterval of the Difference	
									Down	Up
Load Voltage 1	Assumption of equal variances	.005	.942	.096	12	.925	-.757	7.920	-18.013	16.498
	Equal Variances not assumed			.096	11.987	.925	-.757	7.920	-18.015	16.500
Load Voltage 2	Equal Variances assumed	.007	.937	.095	12	.926	-.669	7.019	-15.961	14.624
	Equal Variances not assumed			.095	11.986	.926	-.669	7.019	-15.963	14.626

V. HARDWARE VALIDATION OUTCOMES

An experimental 100W induction heating prototype utilizing a cyclo-inverter has been built to validate the accuracy of the simulation results. The half-controlled bridge rectifier is constructed by two IN4007 diodes and two IRF840 MOSFETs to supply the input to the Cyclo inverter. control logic of AVC technique was implemented, which gives firing pulses for switching devices present in inverter. IR2110 driver was used to amplify the pulses obtained from firing module. The IH load consists of working coil with 70mm outer diameter and 4mm thickness. A test model snapshot is in Fig. 8a. Cyclo-inverter output power is controlled by asymmetrical voltage cancellation (AVC) and switching frequency. Firing pulses for the first, second, and third legs are illustrated in Figs. 8b to 8d, while the terminal voltage and current waveforms of the induction heating load are displayed in Figs. 8e and 8f.These waveforms confirm the proper functioning of the inverter.

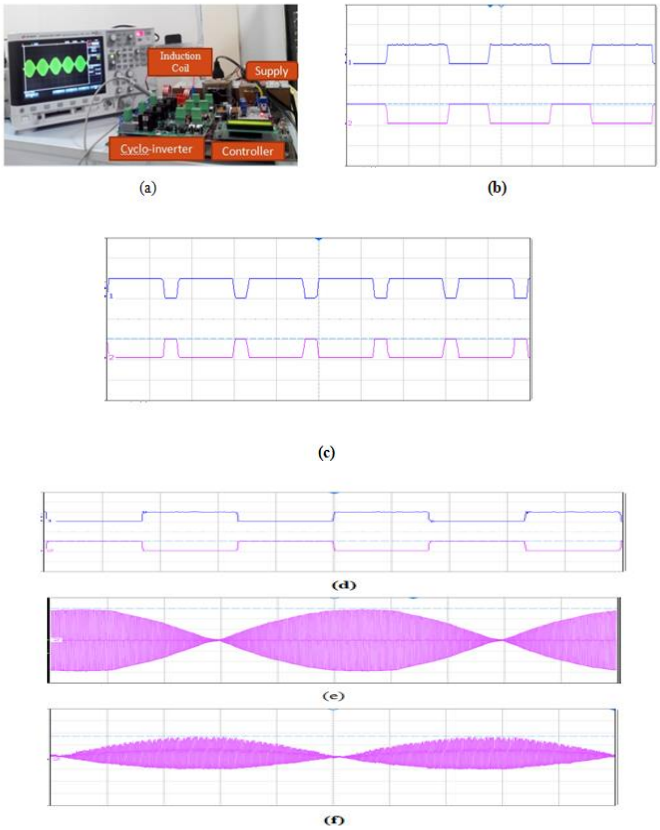


Figure 8 presents the test results for the CIFIH system with AVC control:
(a) Test setup, (b) Firing signals of Q1 & Q2 (X: 9.5 µs/div, Y: 3 V/div), (c) Firing signals of Q3 & Q4 (X: 9.5 µs/div, Y: 3 V/div), (d) Firing signals of Q5 & Q6 (X: 9.5 µs/div, Y: 3 V/div), (e) Terminal voltage waveform (X: 7.8 µs/div, Y: 20 V/div), (f) Load current waveform (X: 7.8 µs/div, Y: 2.5 A/div).

Reliability is achieved by using dual control strategies (PI and hysteresis) that ensure consistent performance under varying input conditions. Additionally, the system's behavior is validated both through MATLAB/Simulink simulations & prototype experimentation, confirming stable & repeatable operation. Error is reduced by integrating hysteresis control with the PI controller, which helps maintain the output current within a defined band, thereby minimizing steady-state error & fluctuations. Precision is improved by using the hysteresis mechanism, which enables tighter control over output current by switching only when deviation exceeds a set threshold. This results in low ripple current (0.1 A) compared to the PI-only system (0.7 A), improving the precision of heating. Accuracy is enhanced through the feedback control loop using PI with hysteresis controller. Statistical validation of performance using SPSS with 7 samples per group, confirming a significant improvement in response (significance of 0.937). And the proposed system has close correlation between simulation and experimental results. The model's effectiveness is demonstrated through simulation and experimental comparisons of output current ripple and steady-state error. Statistical analysis using SPSS further validates the improved dynamic response of the hybrid controller.

VI.SUMMARY

This study investigates the control of a CIFIH system using two different feedback strategies: a conventional PI controller & a PI controller augmented with a hysteresis mechanism. Simulation results demonstrate that the hybrid PI-hysteresis controller significantly improves the system's dynamic performance by minimizing output current ripple & steady-state error. Experimental validation on a 100W prototype confirms these findings, showing consistency between simulated & real-world results. The hysteresis mechanism effectively confines output current within a tight tolerance band, enhancing precision & accuracy while ensuring stable operation across varying conditions. This control approach makes the IH system more reliable & suitable for precision heating applications. Future work will focus on implementing fuzzy logic-based closed-loop controllers to further enhance adaptability and robustness. The design may lead to higher switching frequencies under certain load conditions, requiring careful thermal management. Additionally, the fixed hysteresis band width limits adaptability in highly dynamic heating environments.

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