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A Fuzzy PID Controller for Induction Heating Systems with LLC Voltage Source Inverter

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ABSTRACT

The Proportional-Integral-Derivative (PID) controller is the most popular control strategy in the process industry. The popularity can be attributed to its simplicity, better control performance and excellent robustness to uncertainties that is found through the research work on such controllers so far. This paper presents the design and tuning of a PID controller using Fuzzy logic for industrial induction heating systems with LLC voltage source inverter for controlling the induction heating power. The paper also compares the performance of the Fuzzy PID controller with that of a conventional PID controller for the same system. The system and the controllers are simulated in MATLAB/SIMULINK. The results show the effectiveness and superiority of the proposed Fuzzy PID controller.

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1. INTRODUCTION

Induction heating is one of the precise and fastest heating methods in domestic, medical and industrial applications [1]. A high frequency electrical power source and a work coil (inductor) that generates the alternating magnetic field are required to implement an induction heating system. The coil is included in series or parallel resonant tank circuits to minimize the loss in the supply resonant inverter. These days, the focus is on development of control strategies for controlling the output power of the induction heating systems by leveraging high switching frequencies with series resonant inverters, parallel quasi resonant inverters [2]-[3], while eliminating the switching loss of semiconductor devices through soft switching.

The Proportional-Integral-Derivative (PID) controllers are widely used in induction heating systems [4]-[5]. With such conventional PID controllers, it is difficult to achieve the desired control results. So, in this paper, fuzzy logic has been used to set the control parameters of a PID controller to achieve a self-tuned Fuzzy PID power controller for the induction heating system. The performances of conventional PID controller and Fuzzy PID controller have been studied in this paper. The Fuzzy PID controller appears to be a better controller for the induction heating system. This paper is organized into following sections: Section 2 describes the system configuration for the induction heating system. Section 3 discusses about the controllers. Section 4 outlines the simulation and results. This paper is concluded in Section 5.

2. SYSTEM CONFIGURATION

A typical induction heating system is shown in Figure 1. The main power source (AC input) provides the energy to the induction coil. The input AC voltage is rectified by a bridge rectifier to convert the alternating current (AC) to the direct current (DC). This direct current gets filtered by the DC link circuit and is fed to the voltage source inverter with resonant parallel load (LLC) [6]. The induction coil produces an alternating magnetic field from high-frequency current of the inverter and the field induces eddy currents and causes hysteresis effect to heat up the workpiece. At the inverter output, a matching inductance can be used to achieve the maximum transfer of the power from the power supply to the workpiece.

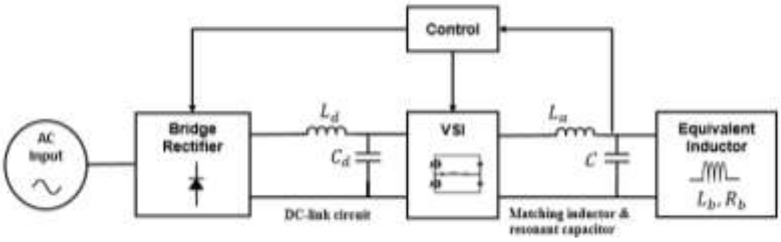


Figure 1. Typical induction heating system

The equivalent circuit of the induction coil and heated workpiece (with inductance L_b and resistance R_b) in parallel with the compensation capacitor C comprise the parallel resonant load. A matching inductor of inductance L_a and resistance R_a is added to the inverter output for maximizing the power transfer to the induction coil.

The control system will handle the operation of the induction coil in parallel with a compensation capacitor at the desired resonant frequency, so the current through the induction coil will be sinusoidal. The parallel resonant circuit is damped when the workpiece is inserted into the induction coil by introducing additional losses into the system and increasing the current drawn from the inverter. To ensure zero-current switching, the switching frequency of the inverter is kept slightly higher than the resonant frequency of the equivalent circuit consisting of induction coil-workpiece in parallel with the resonant capacitor.

This paper focuses on designing and tuning of a Fuzzy PID controller to control the power transferred to a workpiece in the induction heating system through a voltage source resonant inverter. The specification mentioned in Table 1 has been considered to design the controller.

Table 1. Design Specification

Parameters	Symbol	Value
DC-link resistance	R_d	0.1 (Ω)
Inductance of the DC-link circuit	L_d	0.1 (mH)
Capacitance of the DC-link circuit	C_d	2000 (μF)
Equivalent resistance of the matching inductor circuit	R_a	0.1 (Ω)
Equivalent inductance of the matching inductor circuit	L_a	45 (μH)
Equivalent resistance of the induction coil	R_b	12 (Ω)
Equivalent inductance of the induction coil	L_b	47 (μH)
Capacitance of the resonant capacitor	C	0.6 (μF)
Resonant frequency	f_r	32500 (Hz)
Switching frequency	f_s	34000 (Hz)
Input voltage	V	230 (V)

The design specification mentioned in Table I, has resulted in the transfer function of the system [7] given by Equation 1. The transfer function in Equation 1 supplies the system information needed to design the control strategy.

$$P_s = \frac{621.5}{2.826\times10^{-17}s^4 + 2.835\times10^{-11}s^3 + 9.126\times10^{-8}s^2 + 2.044\times10^{-4}s + 0.314} \quad (1)$$

3. DESIGN AND TUNING OF THE CONTROLLERS

3.1. Designing PID Controller

The Proportional-Integral-Derivative (PID) controller is a feedback controller, which controls the induction heating system (plant) through a weighted sum of the error (difference between the output and the desired set point [8]. Figure 2 represents a typical PID controller. It is widely used to enhance the dynamic response and reduce the steady state error. A PID controller consists of the Proportional, Integral and Derivative controls. The PID controller is applied to the induction heating system and is used to control the load power of the induction heating system.

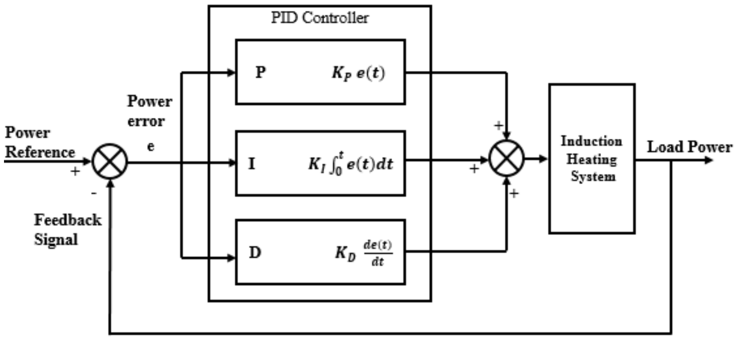


Figure 2. Block diagram of the conventional PID controller

Implementation of such PID controller is usually done through following Equation:

$$u_{pid}(t) = \left[K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \right] \tag{2}$$

Here, K_P, K_I, K_D are the proportional, integral and derivative gains of the controller. To design the PID controller, a set of gains (K_P, K_I, K_D) are found that improves the transient response of a system by overshoot reduction and reduction in settling time. The pid tuning functionality of MATLAB/SIMULINK has been used here to tune the PID controller and the parameters (K_P, K_I, K_D) are adjusted using the tool until a desired set of values are found. Table 3 indicates the values obtained through simulation.

3.2. Designing Fuzzy PID Controller

An effective feedback control mechanism can be implemented for the induction heating system using Fuzzy logic. The Fuzzy tuner will tune the coefficients of conventional PID controller to accomplish the Fuzzy PID controller. It comprises a fuzzification interface, a knowledge base, decision making logic and a defuzzification interface. Its numerical input values are converted into fuzzy values along with the rule base that are fed into the inference engine to produce the control values. The fuzzifier performs measurement of input variables, scale mapping and fuzzification. In fuzzy rule base, different rules are defined as per the problem requirements. The control values are converted to numerical output values using the defuzzifier. Figure 3 shows the block diagram of the proposed fuzzy logic based PID controller which modifies the induction heating power output by optimum fuzzy logic tuning. In this case the controller uses two dimensional fuzzy controller models.

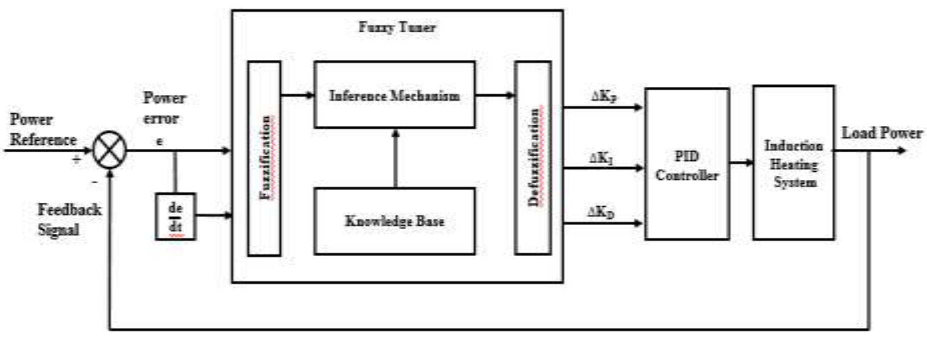


Figure 3. Block diagram of the Fuzzy PID controller

The fuzzy tuning unit will process two input variables and will generate three output variables to achieve the desired level of control. The error (e) and error change rate (ec = de/dt) are the two input variables. Error is the difference between the reference set point and the output, whereas error change rate (ec) is the difference between the error at time t and (t-1). The three outputs variables (ΔK_P, ΔK_I, ΔK_D) will tune the proportional, integral and derivative gains (K_P, K_I, K_D) of the PID controller. All the variables are divided into fuzzy sets [9]. Triangular membership function has been considered for this research work. The fuzzy PID control can be expressed as Equation 3:

$$y_{fpid}(k) = K_P e(k) + K_I \sum_{j=0}^{k} e(j) + K_D\left[e(k) - e(k-1)\right] \tag{3}$$

Also,

$$K_P = K_{P0} + \Delta K_P \tag{4}$$

$$K_I = K_{I0} + \Delta K_I \tag{5}$$

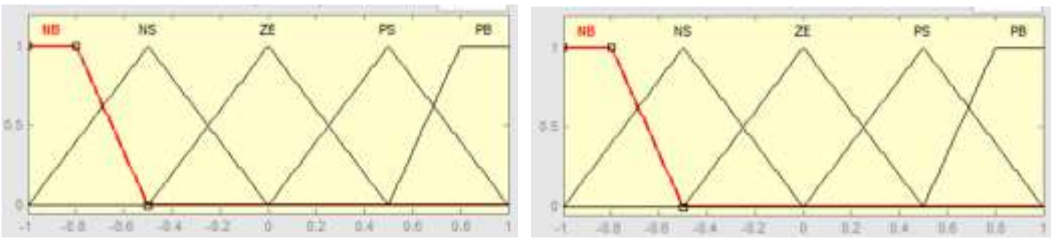
$$K_D = K_{D0} + \Delta K_D \tag{6}$$

$$\Delta K_P = f_1(e, ec) \tag{7}$$

$$\Delta K_I = f_2(e, ec) \tag{8}$$

$$\Delta K_D = f_3(e, ec) \tag{9}$$

K_{P0}, K_{I0}, K_{D0} are the initial values of PID controller and (ΔK_P, ΔK_I, ΔK_D) are the self-tuned PID parameters achieved through fuzzy reasoning. The universe of discourse of each input variable is divided into five overlapping fuzzy sets: Negative Big (NB), Negative Small (NS), Zero Error (ZE), Positive Small (PS) and Positive Big (PB). The fuzzy subset is e = ec = {NB, NS, ZE, PS, PB}. The grade of membership distribution for error (e) and error change rate (ec) are given in Figures 4(a) & 4(b).



(a) (b)

Figure 4. Membership functions: (a) for error e , (b) for error change rate ec

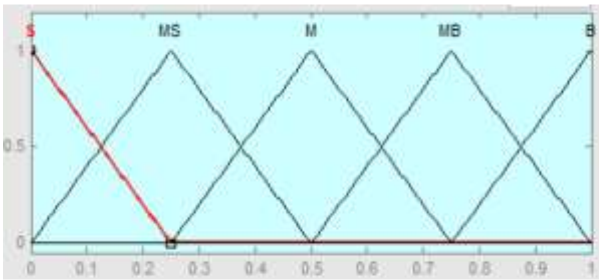


Figure 5. Membership function for ΔK_P, ΔK_I, ΔK_D

The universe of discourse of each output variable (ΔK_P, ΔK_I, ΔK_D) is divided into five overlapping fuzzy sets: Small (S), Medium Small (MS), Medium (M), Medium Big (MB), Big (B) as shown in Figure 5 with the fuzzy subset {S, MS, M, MB, B}. The rule base is based on a set of linguistic IF-THEN rules having two antecedences and one consequence, as expressed in the following form:

$R_{i,j,k}$: IF $e=A_i$ and $\Delta e=B_j$ THEN $u=C_k$

where $1 \leq i \leq 5$, $1 \leq j \leq 5$, $1 \leq k \leq 5$. It generates 25 IF-THEN rules and the set is represented as a matrix, called a fuzzy rule matrix, as shown in Table 2.

Table 2. Fuzzy Rules

e \ ec	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

The decision-making output calculated by the center of gravity (COG) method of defuzzification. In this method the weighted average of the membership function or the center of gravity of the area bounded by the membership function curve is computed as the most typical crisp value of the union of all output fuzzy sets:

$$y_c = \frac{\int y\mu_A(y)dy}{\int \mu_A(y)dy}$$

Here y is the output variable and μ_A the membership function. The fuzzy toolbox of MATLAB has been used to design the fuzzy inference. The proposed fuzzy logic tuner uses Mamdani's fuzzy inference method. This controller has the advantage of driving the load at its resonance frequency, any change in resonance frequency will affect output power. The system performance is indicated by the performance indices as defined [10]:

a. Integral Squared Error (ISE)

$$= \int_0^\infty e^2(t)dt$$

b. Integral Absolute Error (IAE)

$$= \int_0^\infty |e(t)|\, dt$$

c. Integral Time-weighted Squared Error (ITSE)

$$= \int_0^\infty te^2(t)dt$$

d. Integral Time-weighted Absolute Error (ITAE)

$$= \int_0^\infty t\,|e(t)|\, dt$$

4. SIMULATION RESULTS AND DISCUSSION

The performance of the closed loop induction heating system with Fuzzy PID controller has been studied and compared with that of the conventional PID controller. Simulation has been done using the design specification mentioned in Table 1. The controllers have been designed using MATLAB/ SIMULINK blocks and the sets of gains (K_P, K_I, K_D) are determined through simulation. Table 3 provides the controller gains for conventional PID and Fuzzy PID controllers.

Table 3. Controller gains

Controller	K_P	K_I	K_D
PID	0.59×10^{-4}	7.00×10^{-1}	0.20×10^{-6}
Fuzzy PID	1.29×10^{-5}	1.98×10^{-2}	1.05×10^{-8}

Figure 6 displays the step response for the given induction heating system with PID controller, whereas Figure 7 displays the step response with Fuzzy PID controller implementation.

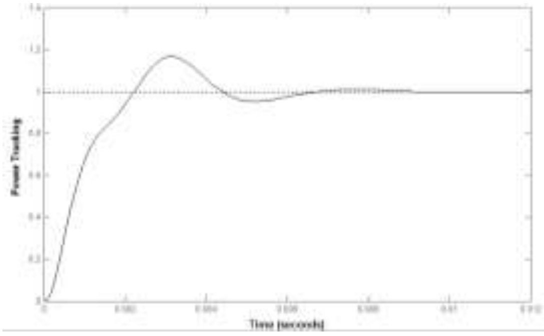


Figure 6. Step response of the induction heating system with conventional PID controller implementation

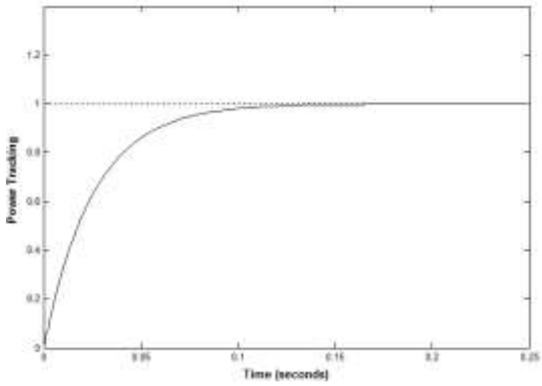


Figure 7. Step response of the induction heating system with Fuzzy PID controller implementation

The corresponding performance parameters such as rise time, settling time and overshoot are listed in Table 4. The performance indices of the controllers are mentioned in Table 5.

Table 4. Performance Parameters for the Controllers

Controller	Rise Time t_r (sec)	Settling Time t_s (sec)	Overshoot M_p (%)
PID	0.0016	0.0061	16.17
Fuzzy PID	0.0559	0.0997	0

Table 5. ISE, IAE, ITSE, ITAE for the Controllers

Controller	ISE	IAE	ITSE	ITAE
PID	1.518×10^{-2}	1.458×10^{-2}	2.518×10^{-2}	3.458×10^{-2}
Fuzzy PID	1.276×10^{-4}	2.556×10^{-4}	1.291×10^{-4}	2.615×10^{-4}

From Table 4, we understand that the conventional PID results in 16.17% overshoot, while Fuzzy PID controller has reduced the overshoot to zero. The rise time and settling time of the conventional PID controller seem to have better values though.

5. CONCLUSION

This paper describes the concept of a Fuzzy self-tuning PID controller to control the output power of an induction heating system with LLC Voltage Source Inverter. Its performance has been analyzed and compared with that of a conventional PID controller. Study shows that conventional PID controller results in higher overshoot, whereas the Fuzzy PID controller reduces the overshoot to zero and it also results in smaller ISE, IAE, ITSE, ITAE values. The reported work presents a systematic approach, which can be easily extended to other inverter topologies. Further analysis can be performed to study the feasibility of designing PID controllers using evolutionary algorithms for such induction heating systems.

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Arijit Chakrabarti received his M.Tech. degree in Radio Physics & Electronics from the Institute of Radio Physics and Electronics, University of Calcutta, West Bengal, India. He is currently working as a Consultant in IBM India Private Limited. His research interest includes Power Electronics, Adaptive Control, Renewable Energy, Cognitive Solutions, Artificial Intelligence, Machine Learning, IoT.

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