

Hybrid Differential Evolution based Concurrent Relay-PID Control for Motor Position Servo Systems

B.Saritha¹, Dr. L. Ravi Srinivas²P.G. Student, Department of EEE, Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India¹Professor, Department of EEE, Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India²

ABSTRACT: This paper presents the implementation of HDE algorithm for Concurrent Relay-PID (CRPID) controller for motor position servo systems. CRPID is composed of a deadband relay subcontroller which improves the transient performance and the parallel PID subcontroller which improves the steady state performance of the system. Controller is implemented using modern heuristic tuning techniques which are Differential Evolution (DE) and Hybrid Differential Evolution (HDE). The performance of these optimization techniques is evaluated by setting their objective function as Integral Square Error (ISE). Using both DE and HDE optimization techniques comparison of performance has been made between PID and CRPID.

KEYWORDS: PID, CRPID, DE, HDE, deadband relay, servo systems.

I. INTRODUCTION

Electrical servo systems are widely used in robotics, automated factories, electrical vehicles. PID controllers are simple in structure reliable in operation and robust in performance however, they may produce higher overshoots and over oscillatory responses. Hybrid scheme CRPID improves the system performance in terms of transient as well as steady state. CRPID is composed of two controllers one is conventional PID subcontroller which improves the steady state performance and another one is deadband relay subcontroller which improves the transient performance of the system. The goal of PID controller tuning is to attain the optimal control parameters so as to meet the closed loop system performance specifications over a wide range of operating conditions. Improper PID control parameter tuning could lead to cyclic and slow recovery and poor robustness will be the collapse of system operation [1]. To obtain optimal control parameters of PID many strategies has been proposed. Among conventional PID tuning methods Zeigler-Nichols is most popular method however, this may produce large overshoot [2].

Soft computing techniques have been proposed to attain the optimal control parameters. Basic Differential Evolution optimization technique proposed by Storn and Prince[3-4]. DE is a powerful yet simple evolutionary algorithm for optimization of real valued, multi modal functions. DE is generally considered as reliable, accurate and robust optimization technique. However, the algorithm suffers from premature convergence, and large computational time for optimizing the computationally expensive objective functions. Empirical analysis of DE has shown that it may stop proceeding towards a global optimum even though the population has not converged to a local optimum [5]. The situation when the algorithm does not show any improvement though it accepts new individuals in the population is known as stagnation. Besides this, DE also suffers from the problem of premature convergence due to loss of diversity in the population. The entire population converges to a point which may not even be a local optimal solution. Hybrid Differential Evolution has proposed in this paper to overcome the limitations of DE.

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This paper is organised as follows. Section II describes the proposed control strategy and section III describes the mathematical model of the plant. Section IV describes design pattern of two subcontrollers. Section V illustrates simulation result. Conclusion has been made in section VI.

II. CONTROL STRATEGY

The block diagram of proposed controller CRPID has been shown in Fig. 3. Control strategy consists of two subcontrollers. The PID subcontroller is a conventional PID controller. The deadband relay, lead compensator and an auxiliary limited integrator makes up a deadband relay subcontroller. When the system has large error deadband relay automatically turns on and produces either positive or negative maximum controller output until its error becomes small. Whenever the error reaches deadband limit deadband relay automatically turns off and the corresponding output becomes zero and PID subcontroller alone handles the system regulation around the steady state. The limited integrator is to aid the PID subcontroller with near steady state regulation. The integrator in the PID subcontroller may not accumulate sufficient strength to maintain the system output due to fast response of the deadband relay subcontroller in the transient state after the deadband relay subcontroller switches off. Limited integrator provides an initial value for system regulation near the steady state where only the PID subcontroller is in effect. Inclusion of auxiliary limited integrator reduces the settling time. While designing the plant unavoidable modeling errors occurred this may lead the system unstable. Lead compensator improves the relative stability of the resultant closed loop system.

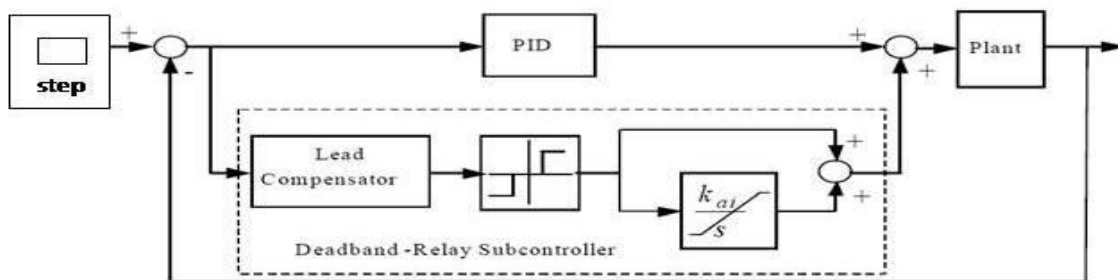


Fig. 1 Block diagram of CRPID

Here controllers are tuned by Differential and Hybrid Differential Evolution techniques and the comparison has been between these techniques. Tuning of controllers are briefly described in the design pattern which is in the following sections.

III. MATHEMATICAL MODEL OF THE PLANT

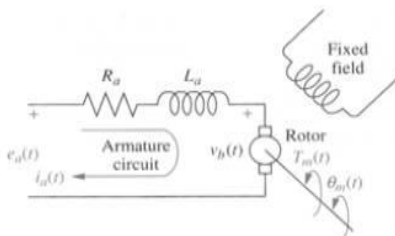


Fig. 2 Block diagram of dc servo system

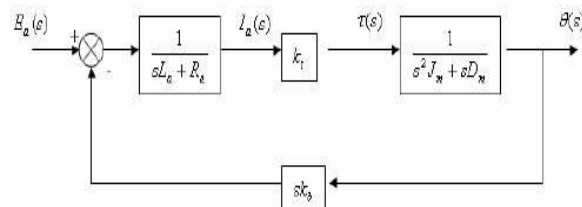


Fig. 3 Time domain block diagram representation of dc servo system

Block diagram of dc servo system is shown in Fig.2 and the time domain block diagram is represented in Fig. 3. From figures $\theta(s)$ is the position and it can be controlled using concurrent relay PID controller by tuning the controller with different tuning techniques.

The open loop transfer function of armature controlled dc servo system from Fig. 3 is obtained as follows [6]

$$\frac{\theta_m(s)}{E_a(s)} = \frac{\left(\frac{K_t}{R_a J_m}\right)}{s^2 + \frac{1}{J_m} \left(D_m + \frac{K_t K_b}{R_a}\right) s} \quad (1)$$

Where

J_m = motor equivalent inertia constant= $30 \times 10^{-6} \text{kgm}^2$

K_b =back-emf constant= $60 \times 10^{-3} \text{vsrad}^{-1}$

K_t =motor torque constant= $17 \times 10^{-3} \text{NmA}^{-1}$

R_a =armature resistance= 3.2Ω

D_m =motor equivalent viscous density =small (neglected)

L_a =armature inductance=small (neglected).

The open loop transfer function of the dc servo system is

$$G(s) = \frac{\theta_m(s)}{E_a(s)} = \frac{177.0833}{S^2 + 10.625 S} \quad (2)$$

IV. DESIGN PATTERN

1. Design of PID subcontroller: Controller PID and CRPID are implemented using modern heuristic tuning techniques Differential Evolution (DE) and Hybrid Differential Evolution (HDE).

The transfer function of the controller is

$$G_p(s) = Kp + \frac{Ki}{s} + Kd * s \quad (3)$$

Where Kp = proportional gain; Ki = Integral gain; Kd = Derivative gain.

1.a. Differential Evolution: DE is a stochastic population based search technique. The algorithm has been used in many practical causes because of its good convergence and global optimization capability. DE can search for the optimal condition very fast with minimal control parameters such as initialization, mutation, crossover and selection. All these operations are briefly described in HDE technique. Mutation, crossover, selection continued until stopping criterion is reached as shown in Fig. 4. The main disadvantage of DE is premature convergence. HDE overcomes this limitation by performing migration operation.

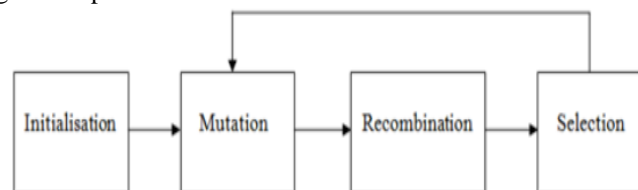


Fig. 4 Flowchart of Differential Evolution

1.b. Hybrid Differential Evolution: Migration strategy is mainly added to original DE to perform Hybrid Differential Evolution by Chiou and Wang. HDE is an effective reliable optimization technique to obtain the optimum control parameters of the controller where the fitness value ISE is minimized [7].

Fitness Function:

$$ISE = \int_0^T \{e(t)\}^2 dt \quad (4)$$

The performance index ISE reduces the large error quickly and makes the response fast.

The proposed method is described briefly below

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Step 1. Initialization:

Initialize upper and lower bounds of each control variables and size of the population. The initial populations are chosen randomly in the interval $[X_{\min}, X_{\max}]$ by uniform probability distribution. Fitness value has been calculated for each set of control variables. Generation of control variables has been made using below formula.

$$X_i^0 = X_{\min} + \rho_i (X_{\max} - X_{\min}), i = 1, \dots, N_p \quad (5)$$

Where $\rho_i \in [0, 1]$ is a random number. The initial process produces N_p individuals of X_i^0 randomly.

Step 2. Mutation Operation:

Mutation expands the search space. A mutant vector is generated based on the present individual X_i^G as follows

$$Y_i^{G+1} = X_i^G + F((X_{r1}^G - X_{r2}^G) + (X_{r3}^G - X_{r4}^G)) \quad (6)$$

The mutation factor was selected as $F \in [0, 1.2]$, and the upper limit of 1.2 for F was determined empirically; r_1, r_2, r_3 and r_4 are randomly selected and distinct.

Step 4. Crossover Operation:

Mutant vector Y_i^{G+1} and a present individual X_i^G are chosen by a binomial distribution to progress the crossover operation to generate an offspring. The diversity of population has been increased. Each gene of the j^{th} individual is reproduced from the mutant vector $Y_i^{G+1} = (Y_{i1}^{G+1}, Y_{i2}^{G+1}, \dots, Y_{ki}^{G+1})$ and the present individual $X_i^G = (X_{i1}^G, X_{i2}^G, \dots, X_{ki}^G)$. That is

$$Y_{hi}^{G+1} = \begin{cases} X_{hi}^G, & \text{if a random number} > C_r \\ Y_{hi}^{G+1}, & \text{otherwise} \end{cases} \quad (7)$$

Where $i=1, 2, \dots, N_p$; $h=1, 2, \dots, n_c$; n_c is the dimension of decision parameters; K is the no of genes; and the crossover factor is set to be $C_r \in [0, 1]$.

Step 4. Estimation and Selection:

The parent is replaced by its offspring if the fitness of the offspring is better than that of the parent. Contrarily, if the fitness of the offspring is worse than that of the parent then parent is retained for the next generation. Two forms are presented as follows

$$X_{hi}^{G+1} = \arg \min \{ F(X_i^G), F(Y_i^{G+1}) \} \quad \& \quad X_b^{G+1} = \arg \min \{ F(X_i^{G+1}) \} \quad (8)$$

Where $\arg \min$ means the argument of the minimum and X_b^{G+1} is the best individual.

Step 5. Migration If Necessary:

Migration strategy is to diversify a population that failed in certain tolerance besides escaping from local optimal and prevents premature convergence. The new populations are based on the best individuals X_b^{G+1} . The h^{th} gene of the i^{th} individuals as follows

$$X_{hi}^{G+1} = \begin{cases} X_{hb}^{G+1} + \rho_1 (X_{h\min} - X_{hb}^{G+1}), & \text{if } \rho_2 < \frac{X_{hi}^{G+1} - X_{h\min}}{X_{h\max} - X_{hb}^{G+1}} \\ X_{hb}^{G+1} + \rho_1 (X_{h\max} - X_{hb}^{G+1}), & \text{otherwise} \end{cases} \quad (9)$$

Where ρ_1, ρ_2 are randomly generated numbers uniformly distributed in the range of $[0, 1]$; $h= 1, \dots, n_c$. The migration in HDE is executed only if a measure fails to match the desired steadiness of population diversity. This measure is defined as follows

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$$\rho = \sum_{\substack{i=1 \\ i \neq b}}^{N_p} \sum_{j=1}^{n_c} X_{ji} / n_c (N_p - 1) < \varepsilon_1 ; \quad X_{ji} = \begin{cases} 1, & \text{if } \left| \frac{X_{ji}^{G+1} - X_{jb}^{G+1}}{X_{jb}^{G+1}} \right| > \varepsilon_2 \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

$\varepsilon_1 \in [0,1]$ and $\varepsilon_2 \in [0,1]$ respectively express the desired steadiness for the population diversity and the gene diversity with respect to the best individual.

Step 6. Repeat step 2 to step 5 until desired ISE is reached as shown in Fig. 5.

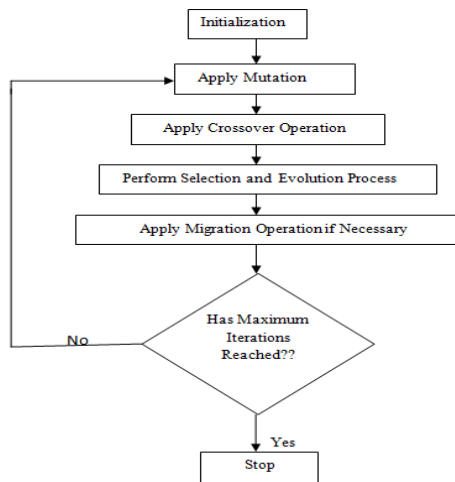


Fig. 5 Flow char of Hybrid Differential Evolution

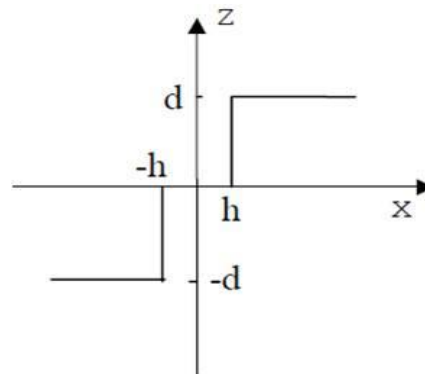


Fig. 6 Input-Output characteristics of the deadband relay

2. Design of Deadband Relay: The input-output characteristics of deadband relay have been shown in Fig. 6. From fig output is zero if the input of the deadband relay is within deadband limit and is positive or negative maximum controller output if deadband relay exceeds the threshold limit. Where d is the relay output amplitude and h represents the threshold value. Nonlinear systems can be analysed using describing function analysis.

Describing function of the deadband relay can be derived as [8, 9]

$$N(X) = \frac{4d}{\pi X} \sqrt{1 - \left(\frac{h}{X}\right)^2} \quad (11)$$

Where N(X): describing function of the deadband relay, d : relay output amplitude, h: half of the deadband width threshold, x represents input .

Inverse describing function of the deadband relay is

$$\frac{1}{N(X)} = \frac{\pi X}{4d \sqrt{1 - \left(\frac{h}{X}\right)^2}} \quad (12)$$

It has a minimum value at some point in the admissible set of $X : \{X | X > h\}$. The minimum value of the inverse describing function can be found at $X = \sqrt{2h}$. The threshold value must be selected in the range $0 < h < |e|_{\max}$

Where $|e|_{\max}$: maximum absolute error.

The minimum value of the describing function is

$$\left[\frac{1}{N(X)} \right]_{\min} = \frac{\pi h}{2d} \quad (13)$$

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3. Design of Limited Integrator: In order to reduce the settling time of the transient response of the system limited integrator is used after the deadband relay. The purpose of limited integrator is to complement the integrator already present in the PID subcontroller for fast settling-down of the system. Hence, the gain of the limited integrator should be some way related to the integral gain of the PID subcontroller.

Empirical formula for calculating the gain of the limited integrator is

$$K_{ai} = \frac{6K_i}{d} \tag{14}$$

Where

K_{ai} : gain of the limited integrator, K_i : integral gain of the PID subcontroller.

Large gain could adversely affect the settling time of the entire system so diligence is always required while determining the gain of the limited integrator.

4. Design of Lead Compensator: The lead compensator is to improve the relative stability of the resultant closed loop system. The block diagram of the closed-loop system in terms of transfer functions /describing function is shown in fig. 7.

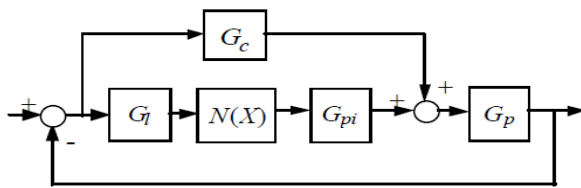


Fig. 7 Block diagram of closed loop system

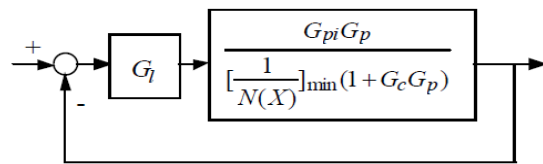


Fig. 8 Equivalent system for the design of lead compensator

Where $G_c(s)$: transfer function of the PID subcontroller, $G_l(s)$: transfer function of the lead compensator, $G_p(s)$: transfer function of the plant, $G_{pi}(s)$: transfer function of pseudo-PI controller, $N(X)$: describing function of deadband relay. The transfer function of the pseudo-PI controller following the deadband relay, which is given by

$$G_{pi}(s) = \frac{s + K_{ai}}{s} \tag{15}$$

Figures 7 and 8 describes that the design of lead compensator for the deadband relay subcontroller is equivalent to the design of lead compensator for a plant with the transfer function of

$$\frac{G_{pi}G_p}{\left[\frac{1}{N(X)}\right]_{\min} (1 + G_c G_p)}$$

A lead compensator with unit static gain is of the form

$$G_l(s) = \frac{TS + 1}{\alpha TS + 1} \quad (0 < \alpha < 1) \tag{16}$$

Where, T represents time constant of the numerator, α represents ratio of time constants.

V. SIMULATION RESULT

Let us consider positive /Negative maximum controller output is -2.2/2.2(volts). The output amplitude of the deadband relay is set to 2.2 volts due to the maximum controller output(d) is 2.2 volts and the threshold(h) of the deadband relay is considered as 0.15. the minimum value of the describing function for the deadband relay[10] is 0.107.

Tuning Ranges: Population=10, $k_{p_{\min}}=0$, $k_{p_{\max}}=4$, $k_{i_{\min}}=0$, $k_{i_{\max}}=2$, $k_{d_{\min}}=0$, $k_{d_{\max}}=0.5$, Rate of crossover (c_r)=0.8, Mutation Factor (F)=0.5, $\epsilon = 0.2$, $\phi_{lead} = 55\text{deg}$.

Case A: The transfer function of dc servo motor is represented by

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$$G(s) = \frac{\theta_m(s)}{E_a(s)} = \frac{18.3}{S(0.1S + 1)} \quad (17)$$

Mathematical model is developed in [9] and the optimal control parameters of the controller are obtained by Hybrid Differential Evolution optimization technique. Control parameters obtained using ZN method for both PID and CRPID are $k_p=0.85$; $k_i=2.83$; $k_d=0.057$.

Optimal control parameters for PID with HDE technique are $k_p=0.855$; $k_i=2$; $k_d=0.0706$ and CRPID with HDE technique are $k_p=3.3075$; $k_i=1.2284$; $k_d=0.1233$ and $\phi_{lead}=55\text{deg}$.

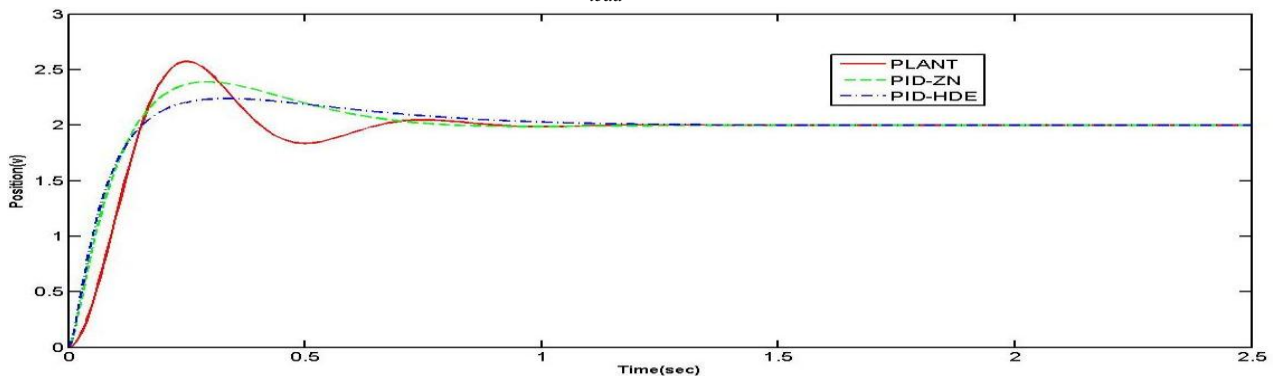


Fig. 9 Step responses of PID with ZN and HDE

Fig. 9 shows that the performance has been improved by tuning PID controller with HDE optimization technique. Overshoot decreases compared with ZN method.

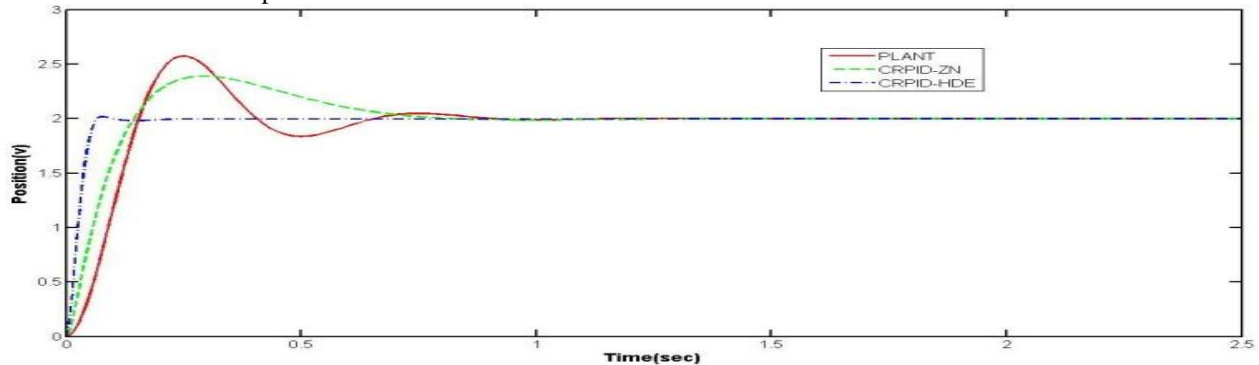


Fig. 10 Step responses of CRPID with ZN and HDE

Fig. 10 shows that the performance has been improved by tuning CRPID with HDE optimization technique in all control aspects like settling time, rise time, peak overshoot and steady state error. Hence CRPID is more effective compared with PID.

Case B: The transfer function of dc servo motor is represented by

$$G(s) = \frac{\theta_m(s)}{E_a(s)} = \frac{177.0833}{S^2 + 10.625S} \quad (18)$$

Optimal control parameters are obtained by tuning the controller with DE and HDE optimization techniques.

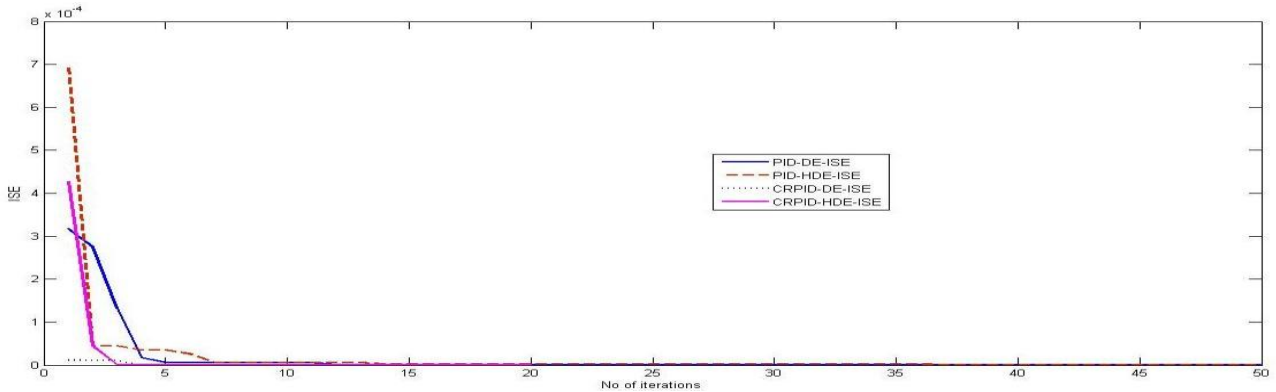


Fig. 11 Convergence graphs of PID, CRPID with DE and HDE tuning techniques.

Fig 11 shows that minimization of ISE with no of iterations. ISE converges fast by tuning controllers with HDE technique and especially with CRPID.

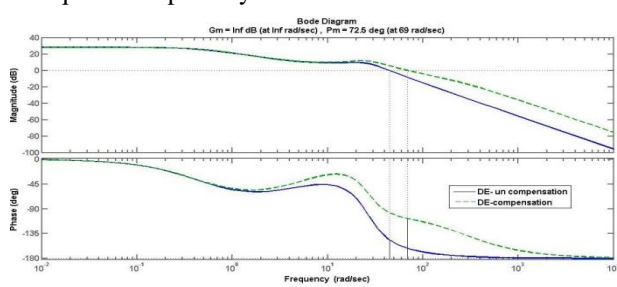


Fig. 12 Frequency response of lead compensator with DE

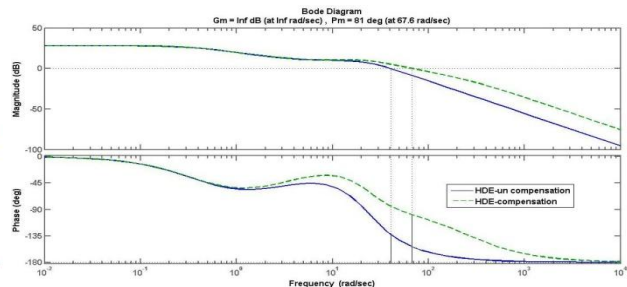


Fig. 13 Frequency response of lead compensator with HDE

Fig 12 and 13 shows the frequency response of lead compensator with DE and HDE. Relative stability has been greatly improved while tuning CRPID with HDE optimization technique.

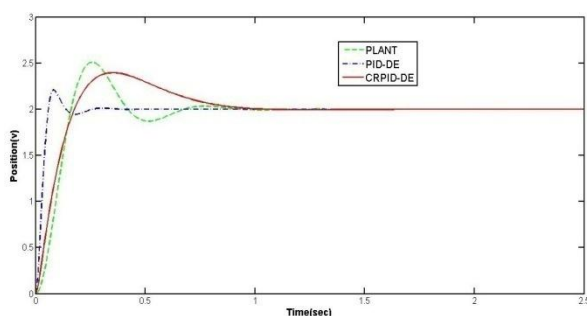


Fig. 14 Step responses of PID and CRPID with DE

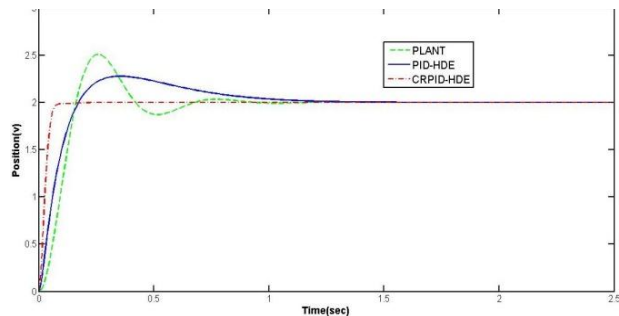


Fig. 15 Step responses of PID and CRPID with HDE

Fig 14 shows the step responses of PID and CRPID controllers by tuning with DE technique. The performance characteristics of CRPID has been greatly improved in all control aspects. Fig 15 shows the step responses of PID and CRPID controllers by tuning with HDE optimization technique. From both plots the performance is improved for CRPID in all control aspects compared with PID. Hence system performance has been improved with CRPID by tuning with HDE Optimization technique.

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Tab. 1: Characteristics of step response with ISE objective function

Parameter Specifications	PID-DE	PID-HDE	CRPID-DE	CRPID-HDE
KP	0.7235	0.8073	4	3.1779
KI	2	1.8164	1.8898	1.2126
KD	0.0446	0.0581	0.0772	0.1274
Rise Time(sec)	0.1273	0.1193	0.0402	0.0437
Settling Time(sec)	0.8451	0.9755	0.2089	0.0734
Peak Overshoot(%)	19.7453	13.8510	9.7941	0.0103
Steady State Error	1.3559e-05	1.0664e-06	1.7882e-06	1.6992e-06
ISE	2.4642e-08	3.1042e-09	1.7395e-09	1.8042e-10

Above table shows the optimal control parameters values and step response characteristics by tuning PID, CRPID with DE and HDE optimization techniques. The above values represents the performance of the system has been effectively improved with CRPID controller by tuning with HDE optimization techniques.

Tab.2: Specifications of lead compensator

Parameters	Phase Margin (db)	Gain Margin (db)	Ω_{gc} (rad/sec)	Ω_{pc} (rad/sec)
DE – Un Compensation	33.6	inf	44.5	inf
DE Compensation	72.5	inf	69.2	inf
HDE-Un Compensation	47.5	inf	39.7	inf
HDE Compensation	81.3	inf	66.5	inf

Table shows the specifications of lead compensator by frequency domain technique bode plot. From the above values phase margin greatly improved with compensation over without compensation for both DE and HDE controller tuning techniques. Hence the design of lead compensator for CRPID with HDE optimization technique improves the relative stability of the system.

VI. CONCLUSION

It has been demonstrated that the tuning of PID and CRPID controllers using Hybrid Differential Evolution technique for motor position servo systems is highly effective over Differential Evolution. From simulation results CRPID is more effective than PID controller in all performance aspects and the relative stability of the resultant closed loop system has been greatly improved.

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