DESIGN OF FIXED ORDER ROBUST CONTROLLER USING H_∞ -NORM AND EVOLUTIONARY TECHNIQUES: COMPARISONS AND PERFORMANCE ANALYSIS

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ABSTRACT

Robust controllers obtained using H_∞ control theory usually have much higher order than that of the plant and it is complex in nature as well. Moreover, in these design methods the order of controller cannot be fixed a priori to control law design. In industrial applications it is hard to execute these controllers practically. To overcome this problem, this paper proposes the use of evolutionary techniques (i.e. genetic algorithm and immune algorithm) for the designing of a low, fixed order robust controller. To check the effectiveness of the proposed approach, resulting controller parameters are evaluated for performance analysis via extensive simulations. Simulation results and performance comparisons demonstrate the efficiency of proposed approaches.

Key words: *Robust controller, H_∞-norm, Genetic Algorithm, Immune Algorithm*

INTRODUCTION

Robust controllers are acquired from classical design techniques have generally much higher order than that of the plant. As the order of plant can be high, design of full order controller narrows the options of use in industrial application. That is why there has been increasing and considerable interest in designing low, fixed order controllers. However, there are basic difficulties intrinsic to low, fixed order controller design[1], such as to find the best possible values of controller gain and performance criteria which can be optimized.

Many researchers have addressed these problems during the past many years, the fixed order controller design problems were formulated using regional pole assignment[1], convex optimization[2] and Riccati equation approach[3]. However many professionals in the field of control engineering have experienced difficulty in solving industrial control problem with these related methods due to the complexity of these methods.

Robust controllers can be designed using H_∞ control theory. The weakness in these design methods is the order of controller cannot be fixed to a prior value. The design of controllers generally take place in two steps, first the selection of a specific structure and second, the computation of suitable controller parameters. Determination of proper controller parameters mostly depends on the requirements of control system. The typical requirements are: short settling time, small over shoot and small value of cost function[4].

Designing a controller means choosing the suitable gains. The main thing to note is that if the calculated value of gain is too large, the response will vary with high frequency. On the other hand, having too small gains would mean longer settling time. Thus, finding the best possible value for gain is the most important concern in controller design[5]. Generally, the overall design procedure is iterative between controller design and cost function (CF)[a] evaluation. If performance is not satisfactory one has to fine-tune the controller parameters after using Ziegler-Nichols (Z-N)[b] tuning rule, which gives an educated guess for controller parameter values or with adjusting some weighting functions in CF used to synthesis the controller[6].

The H_∞ controller optimization presents an additional intricacy because the focus of optimization is on choice of weighting functions, which are not parameters but transfer functions[7]. Hence, the H_∞ loop shaping design problem can be optimized using evolutionary techniques (ETs). Therefore the H_∞ loop shaping design problem is considered as bench mark problem for comparing the performance of ETs such as, genetic algorithm (GA), particle swarm optimization (PSO) and immune algorithm (IA) etc.

[a] measure of performance

[b] used to tune the PID controller parameters

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Mostly, researchers use GA as a search technique in combination with H_∞ loop shaping design procedure (LSDP)[8]. In H_∞ LSDP pre-compensator and post-compensators are required[9]. GA is used to optimize the cost function and controller parameters that define the structure[10].

In last few years, IA has become an active research area. Optimization computations are also accepted search areas of IA[11]. Researchers have proposed IAs for solving optimization problems in the field of engineering and sciences[12]. The use of IA in engineering applications has increased due to its importance, ability in terms of adoption and robustness to the external disturbances[13]. In ref. 14, a four bus power system case study is investigated to demonstrate the efficiency and success of IA. The IA has attractive characteristics as an optimization instrument and present considerable advantages over conventional optimization methods. In the field of modern control engineering, immune systems learning mechanism present well for successful control design application[15].

Objective of the paper

The objective of this paper is to design a robust controller with fixed lower order simple structure, using evolutionary techniques, in particular GA and IA. Controller performance is indicated by a single CF *i.e.,* stability margin. In this proposed approach, the original plant will be shaped by choosing the weighting functions and minimizing the CF of shaped plant. A set of controller parameters *in* pre-specified low fixed order controller is optimized by using GA and IA. The designed robust controller will be implemented in the original plant and then in perturbed plant.

The main contribution of this paper is the design of low, fixed order robust controllers by GA and IA. Other contribution includes a comprehensive comparison and performance analysis of evolutionary techniques based fixed order robust controllers.

The paper is arranged as follows: following the introduction about background literature presented in previous paragraphs, H_∞ robust control design problem is briefly described in Section 2, LSDP is discussed in Section 3, Section 4 discusses the detailed procedure for proposed scheme for designing of fixed order robust controllers via LDSP, GA and IA, Section 5 presents simulation results, the comprehensive comparison and performance analysis of evolutionary techniques based fixed order controllers is presented in Section 6 and conclusion is summarized in Section 7, followed by the references.

The H_∞ Robust Control Design Problem

Consider a system *P(s)* of Figure 1, with inputs *w*, outputs *z*, measurements *y*, control *u* and controller *K(s)*[16].

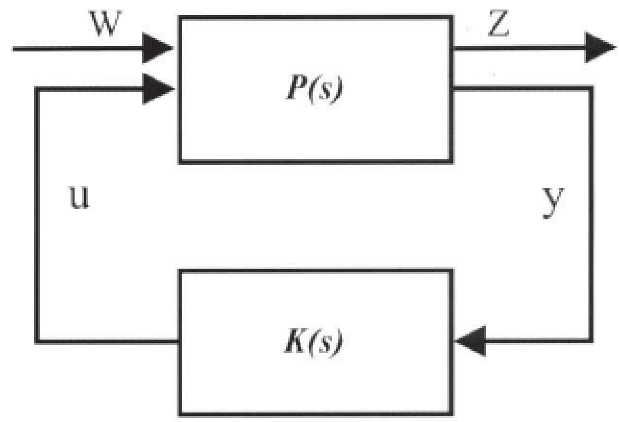

Figure 1: General H_∞ Configuration[16].

Suppose *P(s)* can be partitioned as:

$$P(s)=\begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix}$$

$$\begin{bmatrix} z \\ y \end{bmatrix}=P(s)\begin{bmatrix} w \\ u \end{bmatrix}=\begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix}\begin{bmatrix} w \\ u \end{bmatrix}$$

The closed loop transfer function from *w* to *z* can be obtained directly as given in[17].

$$\begin{aligned} z &= F_l\left[P_{11}+P_{12}K(1-P_{22}K)^{-1}P_{21}\right]w \\ z &= F_l(P,K)w \end{aligned} \tag{1}$$

where $F_l(P,K)$ is called the lower fractional transformation of *P* and *K*. The design objective now becomes, $\left\|F_l(P,K)\right\|_\infty$ and referred as H_∞ optimization problem[18], where $\|.\|_\infty$ represents infinity norm.

The H_∞ loop shaping Design Procedure

The H_∞ loop shaping design procedure (LSDP) proposed in[19] is an efficient technique for design of robust controllers and has successfully been used in different applications. Two stages are involved in LSDP.

In first stage the singular values of original plant are shaped by choosing W_1 and W_2. The original plant G_0 and weighting functions are combined to form a shaped plant G_s as shown in Figure (2). The weighting functions are chosen as:

$$W_1 = K_w \frac{s+\alpha}{s+\beta} \tag{2}$$

where K_w, α, β are positive numbers, β is selected as small number (<< 1) for integral action.

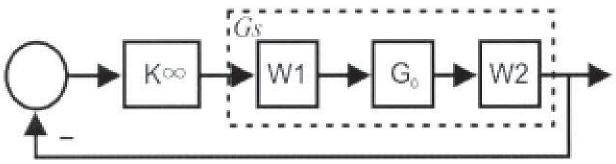

Figure 2: Block diagram of shaped plant[19]

In second stage the stabilizing controller K_∞ is synthesized and stability margin is computed. The final controller is constructed by multiplying K_∞ with weighting functions W_1 and W_2 as shown in eq. (3) and depicted in Figure 3.

$$K(s)_{final} = W_1 K\infty W_2 \tag{3}$$

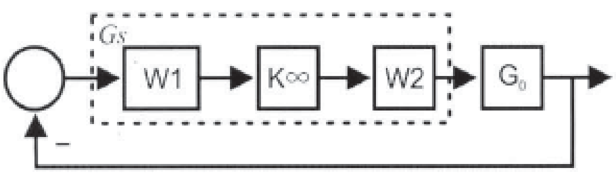

Figure 3: Block diagram of final controller[19].

This organized procedure has its foundation in[20]. Once the desired loop shape is achieved, H_∞-norm of transfer function is minimized to find the overall stabilizing controller K[21].

H_∞ Robust Stabilization

The shaped plant is formulated as a normalized co-prime factor which separates the plant G_s into normalized factors[22].

The normalized co-prime factorization of the shaped plant is $G_s = W_1 G_0 W_2 = NM^{-1}$, then a perturbed plant G_Δ is written as:

$$G_\Delta = (N+\Delta N)(M+\Delta M)^{-1} \tag{4}$$

where, ΔM and ΔN are stable unknown transfer functions representing the uncertainty in the original plant model G_o. Satisfying $\left\|\Delta M \ \Delta N\right\|_\infty \le \varepsilon$, here ε is uncertainty boundary called stability margin.

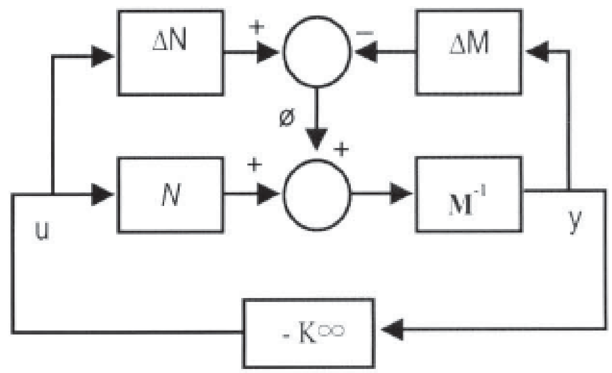

Figure 4: Co-prime factor robust stabilization[8, 22].

The configuration shown in Figure 4, a controller K_∞ stabilize the original closed loop system and minimizes gamma.

$$\gamma = \underset{k}{\overset{\inf}{stab}} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (1+G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{5}$$

Where, γ is the H_∞-norm from ϕ to $\begin{pmatrix} u \\ y \end{pmatrix}$ and $(I+G_s K_\infty)^{-1}$ is the sensitivity function, the lowest achievable value of gamma and corresponding maximum stability margin is calculated by the following equation:

$$\gamma = \varepsilon_{\max}^{-1} = \sqrt{1+\lambda_{\max}(XZ)} \tag{6}$$

where $\lambda_{\max}$ represents maximum eigenvalue, Z and X are the solution to the algebraic Riccati equation[23]:

$$\begin{aligned}(A-BS^{-1}D^TC)+Z(A-BS^{-1}D^TC)^T \\ -ZC^TR^{-1}CZ+BS^{-1}B^T=0\end{aligned} \tag{7}$$

$$\begin{aligned}(A-BS^{-1}D^TC)^T+X(A-BS^{-1}D^TC) \\ -XBS^{-1}B^TX+C^TR^{-1}C=0\end{aligned} \tag{8}$$

where, A, B, C, and D are state space matrices of G, $S = I + D^T D$ and $R = I + DD^T$.

Design of fixed order robust controller using Evolutionary Techniques

Optimization has been essential component of many engineering fields including control systems etc[24]. Recently, some optimization methods have been developed that are theoretically different from the conventional techniques. These methods are labeled as modern ETs. In robust control design problem ETs can be used to optimize both the controller parameters and cost function, while retaining the stability and robustness of the controlled system. The derivative free ETs are: genetic algorithms, immune algorithm, particle swarm optimization, simulated annealing, and ant colony optimization etc.[25]. The approach suggested uses GA and IA to solve the optimization problem defined in eq (12).

GA is a search method, starts the process with randomly initialization of population of individuals. Then the fitness of each individual is calculated. The transmission of one population to next takes place by means of the genetic operators such as *selection*, *crossover* and *mutation*. The process chooses the fittest individual from the population to continue in the next generation. Cross over randomly chooses a locus and exchanges the subsequences before and after that locus between two chromosomes to create two offspring. Mutation operator randomly flips some of bits in the chromosome.

In IA, antigen represents the problem to be solved and an antibody set is generated where each number represents a candidate solution. Also an affinity is the fit of an antibody to the antigen. The role of antibody is to eliminate the antigen. In IA n number of antibodies generated randomly. While affinity of all antibodies is known new population is generated through three steps: *replacement, cloning* and *hypermutation*. In replacement step low antibodies are replaced those with highest affinity are selected by cloning and hypermutation is applied where the mutation rate is inversely proportional to its affinity.

In the block diagram of Figure 1, the H_∞ optimal control problem is to find admittance controller such that H_∞-norm from w to z is minimized in order to stabilize the system. The mathematical model of the plant is given by[26]:

$$G(s) = \frac{551.1e^{-0.12s}}{s^2 + 43.26s + 536.9)} \qquad (9)$$

Assume that $K(p)$ is structure specified controller. The structure of controller is specified before starting the optimization process[27].

The p controller structure is taken as vector p of the controller parameters is given by $p = [k_p, k_i]$. A set of controller parameters p is evaluated to minimize CF.

Since there is a possibility that during the optimal search for PI gains, the response could go unstable, the check is added in coding that ignores the gains for unstable case.

By using eq. (3) controller $K(p)$ can be written as:

$$K(p) = W_1 K_\infty W_2 \qquad (10)$$

It is assumed that W_1 and W_2 are invertible, therefore,

$$K_\infty = W_1^{-1} K(p) W_2^{-1} \qquad (11)$$

W_2 is chosen as identity which implies that sensor noise is negligible. By substituting eq. (11) in eq. (5), the H_∞-norms of the transfer matrix from disturbances to states, which has to be, minimized i.e. CF is written as:

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix} (1 + G_s W_1^{-1} K(p)(1\, G_s) \right\|_\infty \qquad (12)$$

Proposed approach using GA

The steps for designing the fixed order robust controller using GA are:

Step-1 Shape the singular values of the original plant by selecting W_1 and W_2 then calculate gamma using Eq. (6). The returned variable gamma is the inverse of the magnitude of coprime uncertainty. Therefore gamma ≤ 4 is required. If gamma is greater than 4, it shows that weighting function is unsuited with robust stability; the weigh W_1 is adjusted.

Step-2 Initialize several sets of parameters p as first generation, where p is considered as a vector of controller parameters.

Step-3 Specify the controller structure and evaluates the CF of each chromosome using eq. (12).

Step-4 Select chromosomes with lowest CF as solution in present generation. Apply GA operators.

Step-5 if current generation is less than the maximum generation, create a new population by using GA operators and go to step 3, if current generation is maximum generation then stop.

Finally, check the performance in both frequency and time domain. Flow chart of the proposed scheme by using GA is shown in Figure 6.

Proposed approach using IA

The steps for designing the fixed order robust controller using IA are:

Step-1 Shape the singular values of the original plant by selecting W_1 and W_2 calculate gamma using eq. (6). The returned variable gamma is the inverse of the magnitude of coprime uncertainty so the gamma ≤ 4 is required. If gamma is greater than 4, it shows that

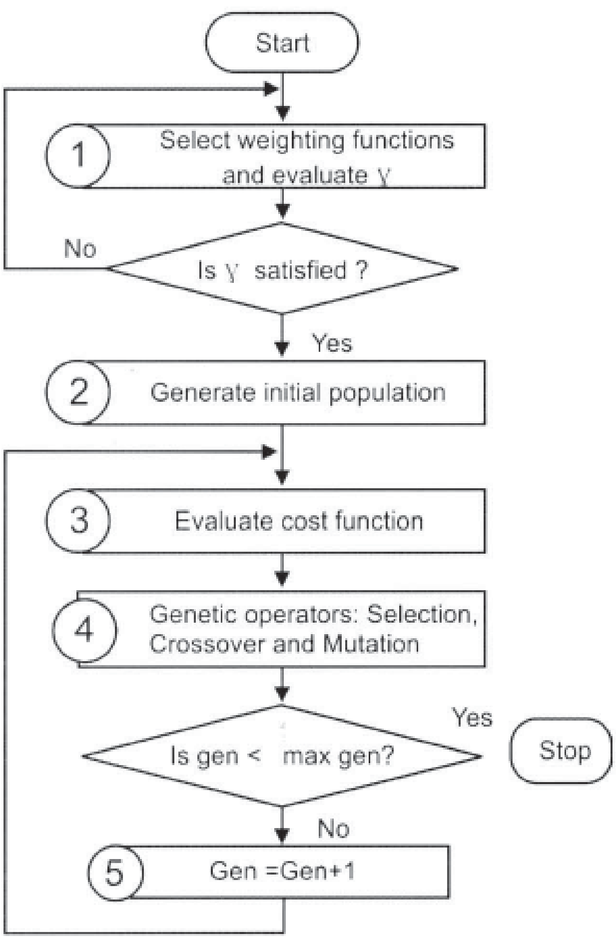

Figure 6: Flow chart for proposed approach using GA.

weighting functions are unsuited with robust stability, the weight W_1 is adjusted.

Step-2 Generate initial sets of parameters p as population of antibodies.

Step-3 Specify the controller structure $K(p)$ where p is considered for each string of antibodies as a vector of controller parameters, evaluate CF of each antibody using eq. (12).

Step-4 Best antibody in the present problem is chosen as an antigen, which has minimum CF, affinity of each antibody can be calculated by using eq. (13).

$$Affinity = \frac{f(antigen)}{f(antibody)} \tag{13}$$

Finally, check the performance in both frequency and time domain. Flow chart of the proposed scheme by using IA is shown in Figure 5.

Simulation Results

The transfer function of original plant is shown in eq. (9). To design the stabilizing controller by using H_∞ LSDP, the weighting functions are chosen as:

$$^{c}W_1 = \frac{0.80s+4}{s+0.001} \quad \text{and} \quad W_2 = I \tag{14}$$

Where I is the identity matrix, with these weighting functions the shaped plant is computed as:

$$G_s(s) = \frac{413.5s + 2205e^{-0.12s}}{s^3 + 43.26s^2 + 536.9s + 0.5369} \tag{15}$$

The stabilizing controller K_∞ is obtained by using H_∞ loop shaping is,

$$K_\infty(s) = \frac{413.5s + 2205}{s^3 + 43.36s^2 + 5369s + 0.5369} \tag{16}$$

By using the H_∞ LSDP the final controller is obtained as:

$$K(s) = \frac{310.1s + 3308s + 8221}{s^4 + 43.26s^3 + 537s^2 + 1.07s + 5.36\times10^{-2}} \tag{17}$$

[c] Selection is weighting function are usually done by few initial trial runs, to do this an engineer relies on his intuition and his past experience

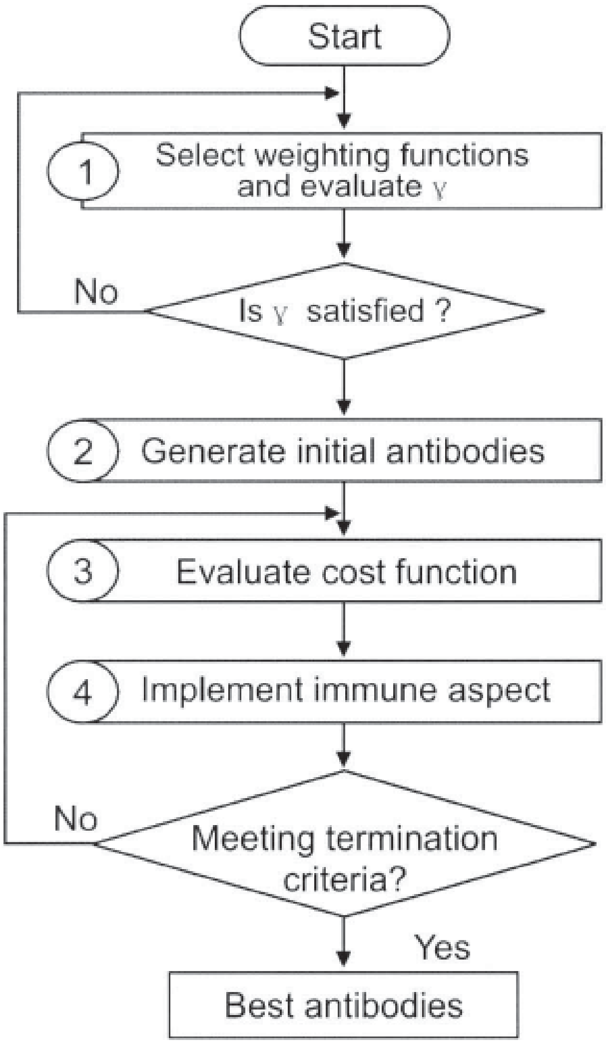

Figure 5: Flow chart for proposed approach using I A.

The controller obtained by H_∞ LSDP eq. (17) is of 4th order which is double than that of the plant and its structure is complex as well. Hence the advantage of fixed structure can be obtained from proposed approach. After that, investigation has been performed for PI controller as a fixed structure controller k_p and k_i are the controller parameters which are evaluated by using GA. The specific controller structure is expressed in eq. (18).

$$K(p) = k_p + \frac{k_i}{s} \tag{18}$$

Investigation by running GA

The simulation was carried out by running GA. The size of initial population was 10; tournament selection and single bit wise mutation was used. GA converged on 4th generation and gave optimal CF of 1.396. Figure 7 shows the plot of convergence of CF versus generations of GA.

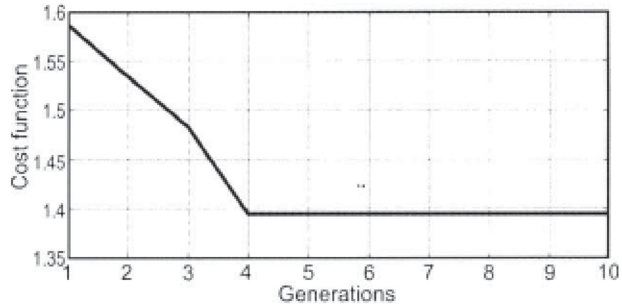

Figure 7: Convergence of CF vs. generations of GA.

The optimal solutions of specified controller parameters were obtained on 4th generation, which has satisfied stability margin of 0.716. It shows that GA can find optimal solution of fixed order controller parameters in several generations. Obtained optimal values of controller parameters are shown in eq. (19).

$$K(p)^* = 0.9991 + \frac{0.584}{s} \tag{19}$$

The step response of the control system which was determined by optimized controller parameters by using GA is shown in Figure 8, the step response present 0.66 seconds rise time, 14% overshoot and the settling time 2.73 seconds, the results obtained clearly shows the effectiveness of proposed scheme.

Investigation by running IA

Afterward, investigation has been performed for PI controller as a fixed structure controller. k_p and k_i are the controller parameters that would be evaluated by using IA. The specific controller structure is expressed in eq. (20).

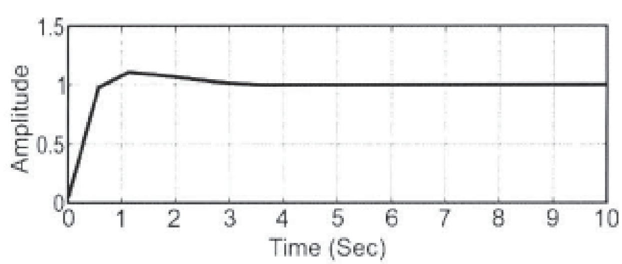

Figure 8: Step response obtained by GA.

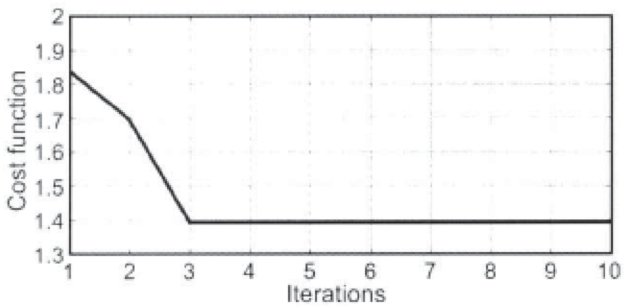

Figure 9: Convergence of CF vs. iterations of IA.

$$K(p) = k_p + \frac{k_i}{s} \tag{20}$$

The simulation was carried out using IA with representation of antibodies. The size of initial population was 10 antibodies, colonial affinity was calculated and single bit mutation was used. IA converged on the 3rd iteration and gave the optimal CF of 1.395. Figure 9 shows the plot of convergence of cost function versus iterations of IA.

The optimal solutions of controller parameters were obtained on 3rd iterations, which has satisfied stability margin of 0.716. It shows that IA can find a global optimal solution of fixed order controller parameters in few generations. Obtained optimal values of controller parameters are shown in eq. (21).

$$K(p)^* = 0.9991 + \frac{0.584}{s} \tag{21}$$

The step response of the control system with optimized controller parameters by using IA is shown in Figure 10; the step response presents rise time 1.06 sec., 2% overshoot and the settling time is about 2 sec. the results obtained clearly shows the effectiveness of proposed scheme.

Investigation by using Z-N technique

To investigate PI controller parameters Z- N technique was employed to find the values of specified

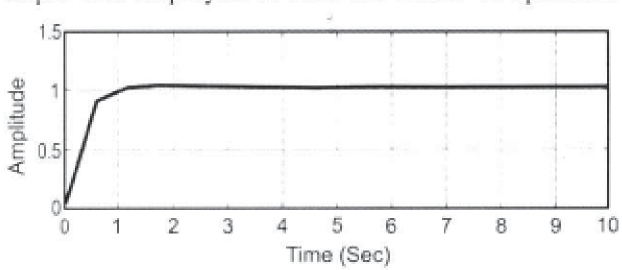

Figure 10: Step response obtained with IA.

controller parameters. The specific controller structure is expressed in eq. (23).

$$K(p) = k_p + \frac{k_i}{s} \tag{23}$$

Controller parameters were obtained experimentally by using Z-N techniques based on the unit step response of the nominal plant. The controller parameters obtained using Z-N technique is shown in eq. (24).

$$K(p)^* = 4.495 + \frac{12}{s} \tag{24}$$

The closed loop step response of the system is shown in Figure 16 present an over shoot of about 58%, rise time 0.25 sec. and settling time 3.7 sec.

A. Robustness check

In order to validate the suitability and robustness of designed controllers, some parameters of the nominal plant in Eq (3) were varied as follows:

$$G_\Delta(s) = \frac{551.1e^{-0.12s}}{(8s^2 + 43.26s + 536.90} \tag{25}$$

The designed optimal controller eq. (20) obtained by running IA was implemented to control the perturbed plant eq. (25).

The step response of perturbed plant is almost same as step response of original plant with some difference in settling time. The result shown in Figure 12 demonstrates that the designed controller from the proposed scheme have reasonably good performance and robustness.

Comparisons and performance Analysis

Results obtained by modern ETs i.e., IA and GA are compared with popular conventional methods H_∞ and Z-N, to verify the value of CF and specified

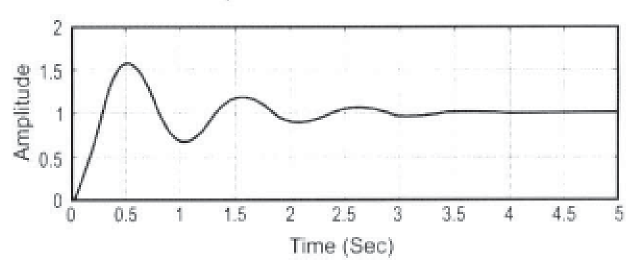

Figure 11: Step response with Z- N.

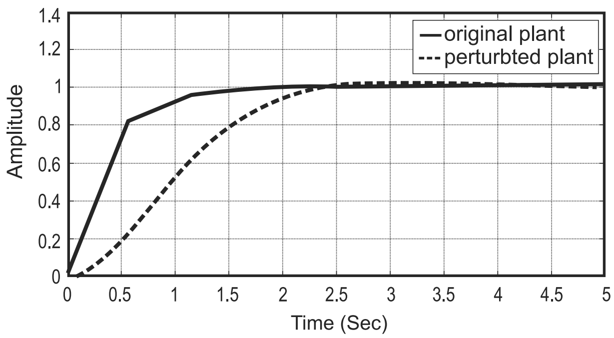

Figure 12: Robust check IA controller.

structure controller parameters. Conventional method is based on solving H_∞-norms that satisfy the stability margin. However, the ETs automatically select controller gain parameters which satisfy the constraints.

Controller structure

The controller obtained from H_∞ LSDP in eq. (16) is of 4th order, double as compared to the original plant under consideration and has complex structure as well. The controllers designed by using IA and GA showing approximately equivalent performances have much lower order, i.e. fixed as first order.

Overall performance

The overall performances of control system were tested for closed loop response with three controllers IA, GA and Z-N, results are shown in Figure 13, the results of overall performance comparison clearly show the advantage of using the IA controller due to its best performance with respect to time domain specifications, and CF value.

Convergence behavior

The comparisons were made in terms of convergence behavior; good cost function convergence values are reflected as shown in cost function versus iteration plots Figure 7 and Figure 9, when evaluate the optimal values of CF obtained using GA and IA. It seems quite clear the benefit of using IA for this type of optimization problem, since it provides optimal CF in fever generations. Moreover the two algorithms almost converge to the same value of CF.

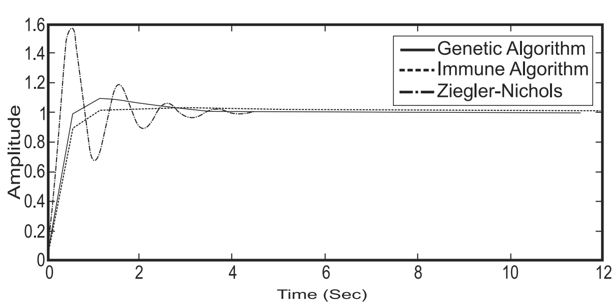

Figure 13: Comparison of step responses for IA, GA and Z-N.

Empirical comparison

Empirical comparison is the key element of such type of comparisons and performance analysis because the time taken by an algorithm to produce/ generate optimal solution cannot be ignored. This raises an important question that which evolutionary algorithm quickly searches for the best initial optimal results. The results shown in Figure 7 and Figure 9 indicate that by given an equal time IA consistently gave better solutions than GA. Moreover it is also noted that IA achieved its solution much quicker.

Optimization of controller parameters and CF

The CF value and the parameters of the controller optimized using GA and IA were compared to that obtained by using Z-N method. Results shown in Table-1, indicates that ETs gave much better solutions than conventional H_∞ and Z–N. The PI gains obtained by using Z-N method are quite high values as compared to GA and IA methods. High controller gains may cause high frequency oscillations and saturation in the controller circuit. Moreover, the CF values of GA and IA are also much better than Z-N method.

The CFs were optimized using H_∞ Z-N, GA and IA. Results shown in Table-1, indicates that ETs gave much better solutions than conventional H_∞ and Z-N. Moreover, optimal results of CF values obtained from GA and IA are equivalent.

Time Domain performance

The aim of control system design is to achieve desired time domain performance of the controlled

Table 1: comparison between optimized parameters.

Parameters	IA	GA	Z-N	H™
k_p	0.9991	0.4629	4.495	—
k_i	0.5894	0.0415	12.0	—
CF	1.395	1.396	2.38	1.474

Table 2: Comparison between Z-N, GA and IA

Parameters	Z-N	GA	IA
Settling time in sec.	3.7	2.73	2.0
Rise time in sec.	0.25	0.66	1.06
Percentage Overshoot	58%	14%	2%

system; usually this action is represented in terms of *percentage overshoot*, *rise time* and *settling time* etc. The comparisons were made in terms of step response.

From above comparisons shown in Table-2, Z-N and GA have higher settling time, higher peak amplitude and higher computational time than IA. So tuning PI controller for plant using IA is more optimal than GA. The controller optimized with IA has provided much better response then controller optimized with GA.

CONCLUSION

In this paper a new approach for designing of fixed order robust controller is proposed. In the proposed approach GA and IA have been used for minimization of cost function and optimization of controller parameters. It is shown that IA provides much better CF values in less iteration. Moreover, in problems where classical techniques cannot be applied, IA is very good alternative to solve an optimization problem. The proposed technique will enable the practicing engineers to employ the techniques for design of robust controller with low, fixed order controllers such as PID controllers, which have high acceptance in industrial applications.

The performances of the proposed approaches were tested with and without disturbances acting on the plant. The proposed techniques showed robust behavior against external disturbances and plant perturbations, hence, promising the use of the algorithms in conditions plant parameters are varying with time.

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