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PARAMETER OPTIMIZATION OF MULTI OBJECTIVE ROBUST PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER WITH FILTER USING MULTI OBJECTIVE EVOLUTIONARY ALGORITHMS

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Key words: Robust proportional integral derivative (PID) controller, Evolutionary algorithms, Non dominated sorting genetic algorithm (NSGA)-II, Modified non dominated sorting genetic algorithm (MNSGA)-II.

In this paper, robust PID controller parameters like proportional gain K_P, integral time constant T_i, derivative time constant T_d and filter time constant T_d/N are optimized for single input single output (SISO) process by utilizing multi objective evolutionary algorithms. The SISO processes considered are phase locked loop (PLL) structure with motor control and magnetic levitation system. Moreover to get better output, a filter structure is introduced with robust PID controller design. The robust stability and closed performance like set-point tracking, load disturbance rejection and control energy are considered as multi objectives and hence, the multi objective algorithms are utilized. The performance of the controller is optimized by non dominated sorting genetic algorithm –II and modified non dominated sorting genetic algorithm –II and the results are compared. The comparison results show that MNSGA-II algorithm is better than NSGA –II in both the SISO processes.

1. INTRODUCTION

Amidst the technological reforms happening in process and control industry, PID controllers are the most accepted controllers which are widely employed in industries even today. The main reasons for the usage of such controllers are their simple design and effective performance [1–10]. PID Tuning refers to the achievement of optimal values of proportional, derivative and integral gains so that; the controller can give its best possible control action for the given process [6]. It also means that the controller gain values are adjusted to experience the operational specifications like robustness to uncertainties in model, tracking of set point, rejection in load disturbance and control energy [3].

In tuning the parameters, there exists a tradeoff between the robustness and the other three performance measures namely set point tracking, load disturbance rejection and control energy. When the robustness of the controller is improved, the performance measures are found to be decreased. Hence, the PID tuning problem discussed in this paper has been reviewed as a multi objective issue with robustness and performance specifications as conflicting objectives. The performance index used here is integral absolute error (IAE) [6].

Few decades ago, design engineers have concentrated on evolutionary approaches to increase the existing design theories and found the optimal design outputs for PID controllers parameter tuning. The main weakness of genetic algorithm (GA) among the evolutionary based approaches is its lack of guarantee in which the global optimum is evaluated in a limited time period. The design specifications of a closed loop system mainly depend on the proper selection of PID parameters. Closed loop systems design specifications consists of least or no overshoot, least rise time, least steady state error and settling time. By considering constraints, genetic algorithms and differential evolution techniques are utilized to evaluate optimal parameters of PID controller [5].

A multi objective problem has been handled by two different kinds of solving methodologies. These are aggregate objective function approach and generate first choose later approach. Multiple conflicting objectives were considered in PID tuning. The tradeoff between robustness/performance has been discussed in [8]. Single objective optimization algorithm like particle swarm optimization has been improved and the enhanced version PSO is able to take up multi objective problems. The reason for using multi objective particle swarm optimization (MPSO) is due to its high speed of convergence [9]. Therefore, the tuning of PID controller as a multi objective optimization has been effectively performed by utilizing evolutionary algorithms [7].

In this research, non dominated sorting genetic algorithm -II (NSGA-II) employs non dominate sorting technique for fitness calculation. The individuals that are not dominated by any other individuals are given priority and assigned in the first front. If the selection of an individual has to be done from two different fronts, then the individual with least front number is selected. Modified non – dominated sorting genetic algorithm-II (MNSGA-II) is a evolutionary algorithm with multi objective that employs dynamic crowding distance and controlled elitism concepts to achieve optimal solution [11–18]

This paper has been classified as given. Section 2 presents structure of robust PID controller. Section 3 depicts the problem formulation and Section 4 briefly enumerates the multi-objective optimization using evolutionary algorithms. Section 5 focuses the test system of robust PID controller. The obtained results are elaborated in Section 6. Finally, proposed work conclusion is provided in Section 7.

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2. CONTROL STRUCTURE OF A PID CONTROLLER WITH FILTER

The PID transfer function incorporated with filter is given as

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + \left(\frac{T_d}{N}\right)s}\right), \quad (1)$$

where K_p – gain of the controller,

T_i – integral time constant,

T_d – derivative time constant ,

$\frac{T_d}{N}$ – filter time constant.

In order to improve the operation a derivative filter is added with the robust PID controller. In some cases, the absence of a derivative filter amplifies the noise signal and causes damage to the actuator. The differential equation form of the PID controller without derivative filter is expressed in equation (2). The zeros of the PID controller without derivative filter are expressed in equation (3). Similarly, differential equation of PID with derivative filter is expressed in equation (4) and the PID controller zeros with filter are obtained using equation (5).

$$T_i T_d s^2 + T_i(s) + 1 = 0. \quad (2)$$

The zeros are

$$Z_{1,2} = \frac{\frac{1}{2} - T_i\sqrt{T_i^2 - 4T_i T_d}}{T_i T_d}. \quad (3)$$

After application of derivative filter, zeros of the controller are the equation solution.

$$T_i T_d\left(1 + \frac{1}{N}\right)s^2 + \left(T_i + \frac{T_d}{N}\right)s + 1 = 0. \quad (4)$$

The zeros are

$$\overline{Z_{1,2}} = \frac{\frac{1}{2} - T_i N - T_d \pm \sqrt{(T_i N - T_d)^2 - 4T_i T_d N^2}}{T_i T_d (1+N)}. \quad (5)$$

In PID controller filter improves the operation of load disturbance rejection with a moderate control energy increase [14].

2.1 STRUCTURE OF A ROBUST PID CONTROLLER WITH FILTER

A robust PID controller is the one which gives satisfactory performance, when the plant is subjected to perturbation and the parameters of the plant are varied with respect to time. In Fig. 1 a control system is exhibited.

In Fig. 1 process transfer function is $P(s)$, $\Delta P(s)$ denotes plant modification, $G_c(s)$ is the transfer function of controller, $r(t)$ is the set point variable, $u(t)$ is the control for input, $e(t)$ is the signal for error, $d(t)$ is the disturbance from external and $y(t)$ is the process variable of the system.

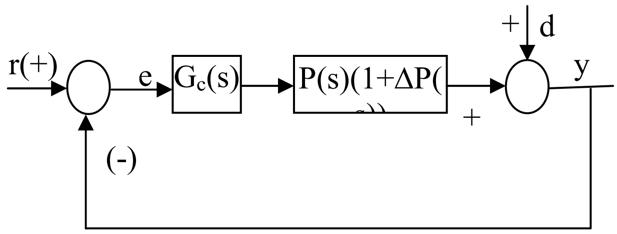

Fig. 1 – Structure of a robust PID controller.

In the above control system, the plant uncertainty $\Delta P(s)$ is predicted to be bound by the boundary conditions as given below. In the absence of generality loss, the plant perturbation $\Delta P(s)$ is bound by balanced function matrix $W_1(s)$ [13].

$$\bar{\sigma}(\Delta P(j\omega)) \le \bar{\sigma}(W_1(j\omega)), \forall_\omega(0,\infty), \quad (6)$$

where $\bar{\sigma}(A)$ indicates the matrix A's highest singular value.

The controller to be designed is considered as $G_c(s)$ and is asymptotically stable. Further, the nominal closed loop system is characterized by $\Delta P(s) = 0$ and $d(t) = 0$. The performance of robust stability against model uncertainty index of controller is considered as J_a and the disturbance attenuation performance of the designed controller is considered as J_b. These performance measures of the controller should satisfy the following inequalities. The robust stability operation must equalize the given inequality

$$J_a = \|W_1(s)T(s)\|_\infty < 1 \quad (7)$$

and the disturbance attenuation performance should satisfy the following inequality

$$J_b = \|W_2(s)S(s)\|_\infty < 1. \quad (8)$$

With $\Delta P(s)$, closed loop system is balanced where $W_2(s)$ is a balanced matrix weighting function identified by authors. $S(s)$ and $T(s) = 1 - S(s)$ are complementary and sensitivity functions

$$S(s) = (1 + P(s)G_c(s))^{-1}, \quad (9)$$

$$T(s) = P(s)G_c(s)(1 + P(s)G_c(s))^{-1}. \quad (10)$$

H_∞ norm in (7) and (8) is given as

$$\|A(s)\|_\infty = aX_\omega \bar{\sigma}(A(j\omega)). \quad (11)$$

The problem of robust PID design recline how good the stability in robustness and disturbance attenuation are minimized simultaneously.

$$\text{Minimize } J_1 = \left|\|W_1(s)S(s)\|_\infty + \|W_2(s)T(s)\|_\infty\right|^{\frac{1}{2}}, \quad (12)$$

where J_1 – robustness uncertainties in model and disturbance attenuation,

J_a – uncertainty of model in H_∞ norm,

J_b – disturbance attenuation in H_∞ norm,

with respect to the constraints in eqns. (7) and (8).

3. **PROBLEM FORMULATION**

The major issues faced in present work involves robust PID controller tuning to get the required response. In the developed work, PID is tuned to strike a balance between the robustness concerning uncertainties in model and the operational specifications. The performance specification parameters are tracking of set point, elimination of load disturbance and control energy. Robustness and performance parameters are considered as conflicting objectives and a balance is achieved by tuning the robust PID controller by using multi objective algorithms like NSGA II and MNSGA II.

3.1 SET POINT TRACKING

In set point tracking, the initial error of step change in set point is weighted and is expressed as the integral performance index J_2. The error is defined as the differentiation in between process variable (PV) and a user defined reference trajectory. This reference trajectory connects the actual process variable PV and the set point. The most significant set point changes in other applications are motion control [2, 16].

$$J_2 = \int_0^{\infty} \left| y(t) - r(t) \right| \mathrm{d}t \ , \tag{13}$$

where $y(t)$ – output process variable,

$r(t)$ – reference input .

3.2 LOAD DISTURBANCE REJECTION

The major objective of the control problem is to achieve good rejection of load disturbances [4, 17].

$$J_3 = \int_0^{\infty} \left| d(t) - y(t) \right| \, \mathrm{d}t, \tag{14}$$

where $d(t)$ = unit step disturbance.

3.3 MEASUREMENT OF CONTROL ENERGY

Control energy measurement is the fourth operational criteria. Measurement of control energy is evaluated by robust PID controller is J_4 which requires energy to settle down the disturbance and set point tracking [18]. To evaluate the control energy, $U(t)$ is computed by input total variation (TV) and it is the addition of all its moving up and down.

$$\mathrm{TV} = \left| U\left(k+1\right) - U(k) \right| \ . \tag{15}$$

If vast and smooth response is provided to a control system input changes exhibits high degree of performance.

3.4 OBJECTIVE FUNCTION

Tuning of robust PID by utilizing multi objective optimization problem, the objective function is first defined. The objective function is defined as a minimization function. Two functionalities are chosen for the minimization function and these two are conflicting in nature. The first objective is robustness with respect to uncertainties J_1 and the second one is the performance specifications of robust PID controller J_5. The operational specifications considered here are tracking of set point, rejection in load disturbance and control energy.

$$\text{Minimize } \{J_1, J_5\}, \tag{16}$$

Where J_1 – uncertainties in model robustness and disturbance attenuation,

$J_5 = J_2 + J_3 + J_4$ – performance specifications of robust PID controller.

4. **MULTIOBJECTIVE OPTIMIZATION USING EVOLUTIONARY ALGORITHMS**

Evolutionary algorithms have been emerging increasingly popular in solving realistic engineering problems. Many real world engineering issues conflict with one another and thereby, multi objective analysis is required to assist in identifying compromising solutions [19–21]. In order to reduce each criteria functions of objective design multi-objective optimization is utilized. Minimization of one objective function increases the emergence of an alternate objective function as there is more constraints in objective function. The outcome of optimized multi-objective is Pareto optimal solution and this solution is possible to improve any of the objective function by increasing at least one of the other objective functions. Improvisation of any criterion in pareto optimality cannot made without degenerating a value of at least one other criterion. A number of Pareto optimal solutions are present in general. There is an equally acceptable solution of the problem for every Pareto optimal point. Nevertheless, the aim is generally desirable to obtain one point as a solution. The main application of multi objective evolutionary algorithms is to find out solutions to the problems which are i) close to the Pareto front and ii) diverse.

4.1 NSGA – II APPROACH

NSGA II is an efficient multi objective algorithm which reduces the multi objectives into a single fitness by creating non dominated fronts. It takes into account both rank and distance for making diverse solution [8]. The proposed approach is explained in the following steps:

Step 1	:	Start generation count as $t = 0$
Step 2	:	Generate a parent population with size P which is uniformly distributed
Step 3	:	Depending on the principle of non-domination, the individuals in the population are sorted
Step 4	:	Allocate a rank to each solution based on minimum fitness
Step 5	:	Generating an offspring population with size P using binary tournament selection, simulate binary crossover and polynomial mutation
Step 6	:	Form an extended population with size $2P$ by combining the parent and offspring population
Step 7	:	Again based on non-domination sort, extend the population
Step 8	:	Fill the new population of size P with best individuals

Step 9 : Create diversity in population using the concept of crowding distance

Step 10 : Updation of generation numbers, $t = t+1$

Step 11 : Steps 3 to 11 are iterated til stopping criterion is established

NSGA-II method, first uniformly distributed parent population is generated with the user specified size P between the lower and upper bounds. Here, population means a set of PID controller design parameters such as K_p, T_i, T_d, and T_d/N. The parent population is evaluated using the multi-objective function given in the equation 16. After evaluation depending on the principle of non-domination, the individuals in the population are sorted. A rank to each set of controller parameters *i.e.* population is assigned based on the evaluated minimum fitness. An offspring population of size *P* is created using binary tournament selection, simulate binary crossover and polynomial mutation. Combination of parent and offspring populations is created into an extended population. Again based on non-domination sort, extend the population. Fill the new population of size *P* with best individuals. Create diversity in population using the concept of crowding distance. The procedure is iterated till stopping criterion is met. At the end PID controller design parameters are obtained that gives the best minimum fitness value.

4.2 MNSGA-II APPROACH

NSGA-II fails to maintain uniform distribution of non dominated solutions and lateral diversity. The solution will be optimum only if the non dominated solutions cover the entire Pareto front. Controlled elitism concept is adopted by MNSGA-II to maintain the lateral diversity and thereby, the optimum solution is achieved [12]. The proposed MNSGA-II approach is detailed in below steps:

Step 1 : Generation of initial population randomly of size N with limits in control variable and generation set count $t = 0$.

Step 2 : Create an offspring population using crowded tournament selection

Step 3 : Perform non dominated sorting to both initial population and offspring population

Step 4 : Apply the concept of controlled elitism and maintain the number of individuals in all non dominated fronts

Step 5 : If non dominated set *M* size is higher than size of population *N*, then *M-N* individuals are removed using dynamic crowding distance algorithm or else go to step 2

Step 6 : Stop the process, if the maximum generation count is reached

MNSGA-II technique, first initial population *i.e.* a set of PID controller design parameters such as K_p, T_i, T_d, and T_d/N. is generated randomly of size *N*. An offspring population is created using crowded tournament selection. Non dominated sorting to both initial population and offspring population is performed. The concept of controlled elitism and maintain the number of individuals in all non dominated fronts is applied. If non dominated set *M* size is higher than size of population *N*, then *M-N* individuals are removed using dynamic crowding distance algorithm or else create an offspring population using crowded tournament selection. The above process is stopped if the maximum generation count is reached. At the end a set of PID controller design parameters are obtained that gives the best minimum fitness value.

5. TEST SYSTEMS

The robustness of the developed PID controller is validated by considering two SISO systems with filter. In this work, the SISO systems considered are PLL motor speed control system and Magnetic Levitation System.

5.1 TEST SYSTEM 1

Test system 1 transfer function *i.e.*, PLL motor speed control method [19] is represented as

$$P(s) = \frac{68.76}{s(1+0.05s)}. \quad (17)$$

Also, the framework experiences an external disturbance $d(t) = 0.1\ e^{-0.1\ t} \sin(0.8\pi\ t)$ and the plant perturbation transfer function is exhibited as

$$\Delta P(s) = \frac{0.6}{s^2 + 0.2s + 8}. \quad (18)$$

Transfer function of plant uncertainty is bound between two weighting functions denoted as $W_1(s)$ and $W_2(s)$

$$W_1(s) = \frac{0.6}{s^2 + 0.2s + 8}, \quad (19)$$

$$W_2(s) = \frac{0.5s + 0.05}{s^2 + 0.2s + 6.3265}. \quad (20)$$

Transfer function of controller is exhibited by

$$K(s) = K_p \left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + \left(\frac{T_d}{N} \right) s} \right). \quad (21)$$

5.2. TEST SYSTEM 2

The magnetic levitation system technique is considered as test system 2 and linearized model with equilibrium point of $y = 0.018$ is exhibited as

$$P(s) = \frac{7.147}{(s-22.55)(s+20.9)(s+13.99)}. \quad (22)$$

PID controller transfer function is

$$K(s) = 10^{x_1} \left(1 + \frac{1}{10^{x_2} s} + \frac{10^{x_3} s}{1 + 10^{(x_3 - x_4)} s} \right), \quad (23)$$

where $X = (x_1, x_2, x_3, x_4)^T$ represents parameter design vector.

The search space design vector for parameter is represented by $D = x \in R^4 (2,-1,-1,2)^T \le x \le (4,1,1,3)^T$.

In proposed work, it is to be found that the design parameter x fulfill the given multiple H_∞ constraints given in (3) and (4). The plant perturbation is unknown, but it is bound by given known stable function. [20, 21]

$$W_T(s) = 4.3867\times10^{-7}(s+0.066)(s+31.4)(s+88)\left(\frac{10^4}{s+10^4}\right)^3.$$

6. SIMULATION RESULTS

The operation of developed multi objective evolutionary algorithm is evaluated by utilizing two different types of test systems. Known as phase locked loop motor speed control system and magnetic levitation mechanism. To determine best parameter design The evolutionary algorithmic techniques utilized are NSGA-II and MNSGA-II. The developed coding is implemented by utilizing MATLAB 7.10.0 software on Pentium 4 PC 2.16 GHz with 2 GB RAM.

As the results gained by utilizing multi objective evolutionary algorithms are probabilistic, a number of trials with initialized independent population are utilized for evaluating the operation stability of the algorithmic techniques. There are four design parameters, the size of population is set as 40. In the developed technique, 20 independent experiments are made and the maximum functional evolution is fixed as 4000.

6.1. TEST SYSTEM 1 SIMULATION RESULTS

To evaluate robust controller design parameters x_1, x_2, x_3, x_4 are optimized by optimization methodologies. Each elements of chromosome population inside search space are initialized non uniformly by lower and upper bounds.

Table 1

Chromosome of robust PID controller parameter with filter

x_1	x_2	x_3	x_4
K_P	T_i	T_d	T_d/N

The evaluation parameters like proportional gain K_P, integral time constant T_i, derivative time constant T_d and filter time constant T_d/N acquired for PLL system by utilizing NSGA-II and MNSGA-II are represented in Table 2.

Table 2

PLL system design Parameters by utilizing NSGA-II and MNSGA-II

Sl. No	Algorithm	Design parameters (x_1, x_2, x_3, x_4)			
		K_P	T_i	T_d	T_d/N
1.	NSGA-II	0.0209	48.539	9.8537	42.161
2.	MNSGA-II	2.1099	0.0411	0.0139	2.1042

The response of Pareto front is acquired by utilizing MNSGA-II for PLL system is exhibited in Fig. 2. Consider two points in Fig.2, let the points be P_1 and P_2 where P_1 has lowest value of J_1. While P_2 has lowest value of J_5.Henceforth the two points are non dominated like all the points in the solution are obtained Pareto front are non dominated objectives J_1, J_5 are considered conflicting in nature has been verified.

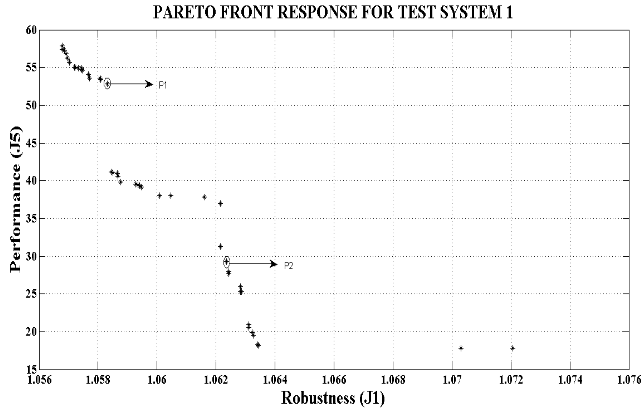

Fig. 2 – PLL system Pareto front acquired by utilizing MNSGA-II.

Table 3

Robustness and Performance comparison of design parameters of PLL

Sl. No	Algorithm	J_1	J_2	J_3	J_4	J_5
						$J_2 + J_3 + J_4$
1.	NSGA-II	1.6166	0.9797	42.448	4.6159	48.0436
2.	MNSGA-II	1.0632	0.0478	0.0255	18.738	18.8113

In Table 3 by utilizing NSGA-II and MNSGA-II tuned controllers the response of robust system J_1 with plant uncertainty $\Delta P(s)$ and the operational specification of the system J_5 are represented.

The output response characteristic curves are plotted by utilizing NSGA-II and MNSGA-II. From Fig. 3, it is noticed that the output response of PLL system tuned by robust PID controller using MNSGA-II gives better performance than the controller tuned by NSGA-II.

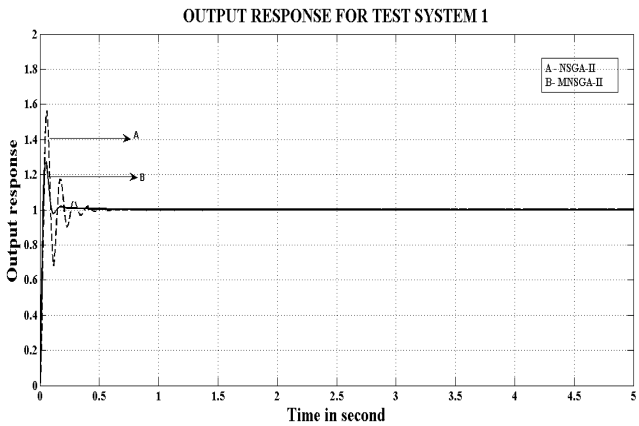

Fig. 3 – Output response of PLL system.

6.2 TEST SYSTEM 2 SIMULATION RESULTS

In Table 4 NSGA-II and MNSGA-II is utilized for MLS technique for evaluating design parameters like proportional gain K_P, integral time constant T_i, derivative time constant T_d and filter time constant t_d / N is exhibited below.

The PID structure controller in magnetic levitation system is shown by eqn. (23), where $x = (x_1, x_2, x_3, x_4)^T$ which represents parameter design vector. Here, $K_p = 10^{x1}$, $T_i = 10^{x2}$, $T_d = 10^{x3}$ and $t_d/N = 10^{(x3-x4)}$. In Table 4 by substituting the calculated design parameters by utilizing

NSGA-II and MNSGA-II, for robust PID with filter the modified transfer function obtained is shown.

Table 4
Parameters of MLS system acquired by utilizing multi objective evolutionary algorithms

Sl. No	Algorithm	Design parameters (x_1, x_2, x_3, x_4)			
		K_P	T_i	T_d	T_d/N
1.	NSGA-II	3.2241	–0.8480	–0.7868	2.3606
2.	MNSGA-II	3.2155	–0.8135	–0.8051	2.3966

Table 5
Robust PID transfer function with filter acquired by utilizing design robust controller parameters tuned by NSGA-II and MNSGA-II

Sl. No	Algorithm	Transfer function of robust PID with filter acquired by utilizing design parameters from Table 3
1.	NSGA-II	K(s)=1675.3*(1+(1/0.1528s)+(0.1633s/ (1+(7.1219*10^{-3})s))
2.	MNSGA-II	K(s) = 1705.68*(1+(1/0.1536s)+ (0.1566 / (1+(6.2849*10^{-4})s))

Robustness response of the technique (J_1) with plant perturbation and the operational specifications of MLS system ($J_5 = J_2 + J_3 + J_4$) by utilizing NSGA-II and MNSGA-II tuned robust controllers are exhibited in Table 6. It is evident that MNSGA-II gives preferred execution over NSGA-II.

Table 6
Operational specifications of robust PID acquired by utilizing NSGA-II and MNSGA-II for MLS

Sl. No	Algorithm	J_1	J_2	J_3	J_4	J_5
						$J_2 + J_3 + J_4$
1.	NSGA-II	1.4822	0.3888	0.00026	9.6664	10.0554
2.	MNSGA-II	1.4554	0.3780	0.00015	9.4450	9.8231

The Pareto front acquired by utilizing MNSGA-II for MLS process are exhibited between the robustness J_1 and performance J_5 of robust PID controller is exhibited in Fig. 4.

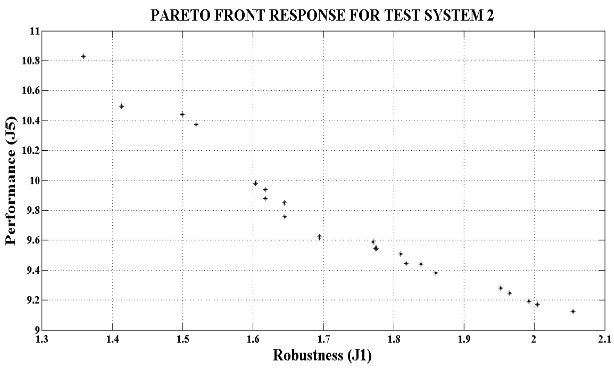

Fig. 4 – Pareto front response by MNSGA-II for MLS.

From the Fig. 5, it is noticed that the output response of MLS system tuned by MNSGA-II gives better results than the controller tuned by NSGA-II for the same system.

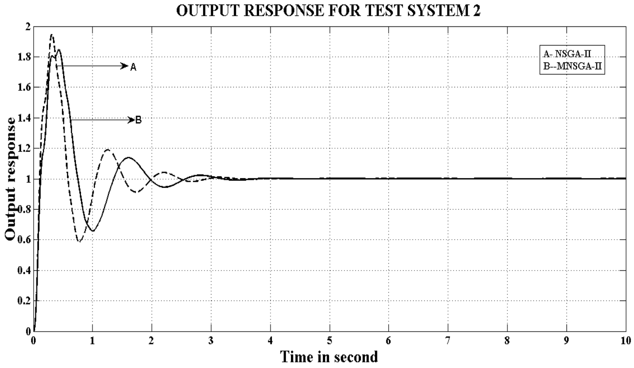

Fig. 5 – Output response of MLS.

7. CONCLUSION

The operation of robust PID controller tuned by multi objective algorithms like NSGA-II and MNSGA-II is studied and it is evaluated that MNSGA-II tuned Robust PID controller provides better solutions than the NSGA-II tuned robust PID controller. In this work, the robustness and the performance specifications are considered as conflicting objectives and a tradeoff is achieved to get the desired optimal solution. The output response of the controller tuned by NSGA-II and MNSGA-II iterates that though the overshoot is high in the case of MNSGA-II for MLS system, it settles down quickly with less number of oscillations. In PLL, the responses of tuned PID by NSGA-II and MNSGA-II are similar but magnitude of oscillations is less in case of MNSGA-II. Hence, MNSGA-II tuned robust PID controller performs better than NSGA-II tuned robust PID controller for both PLL and MLS.

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