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Conference Paper · May 2014

DOI: 10.1109/ENERGYCON.2014.6850610

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Optimal PID Control of Magnetic Levitation System Using Genetic Algorithm

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***Abstract*—Due to its inherent nonlinearities and highly unstable nature with many practical applications i.e. high speed train, frictionless bearings, levitated wind tunnel etc., the Magnetic Levitation System (MLS) is considered as a good test-bench for design and analysis of control systems. This paper presents the design of PID controller for MLS based on an efficient method of tuning controller parameters using Genetic Algorithm (GA). PID controller was designed for MLS. In order to achieve the optimal performance indices, controller parameters were tuned using GA. Performance of the proposed controller was analysed and results are presented in comparison to the conventional PID tuning method i.e., Ziegler Nichols (Z-N). Simulation results showed that performance of PID controller tuned using GA were better than the conventionally tuned PID controller.**

***Keywords:* Genetic Algorithm, Magnetic Levitation System, Mutation, PID Controller, Ziegler Nichols method.**

I. Introduction

PID controllers are extensively used in many control systems due to their simplicity and robustness. PID controllers take the name from its subparts naming, the proportional gain K_P, the integral gain K_I and the derivative gain K_D. These gains need to be accurately and carefully found in order to make PID controllers perform desirably, i.e., reducing the steady state errors, reasonable overshoot and settling time.

Number of methods are available for tuning PID controller parameters. Few examples of these well-known methods are; the Ziegler-Nichols (Z-N) method [1], the Cohen-Coon method [2], Integral of Squared time weighted Error (ISE) rule [3], Integral of Absolute Error rule (IAE) [4], Internal Model Control (IMC) based method [5], and gain-phase margin method [6]. Based on the transient response, which actually include the overshoot, setting time and steady state error, Ziegler and Nichols designed rules for tuning of PID controllers [1]. Minimizing the appropriate performance criterion were the base of method presented by Zhuang and Atherton for automatic tuning of PID controllers [3].

Main disadvantage of Z-N method is that it requires prior knowledge of plant model and dynamics. Once tuned controller using Z-N method gives good performance but optimum system performance is not achieved. If plant dynamics change then transient response of the system can be worse. As many plants have time varying dynamics due to external/environmental disturbances, addition of new features for enhancing the performance capabilities of PID controllers is highly desired [7]. Thus the interest in different random search methods is increased tremendously during recent past because of their very good capabilities in finding the global optimum solution in problem space [8].

In literature, a lot of studies are available on designing a PID controller for not only Magnetic Levitation System (MLS) but also other systems. In [9] Matlab based genetic algorithm for determination of the optimal PID parameters of the Automatic Voltage Regulator systems was used. The authors analyzed the impact of the mutation and the population number on the value of PID parameters. Differences between actual MLS based system and its conventional model has been discussed in [11]. This study of the system experiencing the un-modeled dynamics and their impact on stability of simulated system were also given. In the end, PID controllers are proved efficacious in regulating the set point and hence tracking the changing output. System linearization principle for nonlinear model of MLS is proposed in [12] which primarily take the advantage of expanding the Fourier series and preserving the first order term. For maintaining the better stability in a levitated ball assembly, the controller for unstable nonlinear system is designed by employing system linearization and phase-lead compensation with cancellation of virtual pole, is explained in [13]. Such MLS with small operating ranges have been proposed and studied in the literature.

Classical optimization methods are based on assumptions such as differentiability, convexity of the cost function and constraints that must be satisfied. As these assumptions are hard to satisfy by the constrained optimization and to reduce complexity of tuning controller parameters, several new heuristic methods such as Ant Colony Optimization [14], Particle Swarm Optimization [15], fuzzy logic [8] have been developed. Due to its high potential for global optimization, Genetic Algorithm (GA) has attracted great attention of researchers in control systems in order to figure out the optimal values for PID controller parameters. Although GA has extensively been applied to many control systems, its natural genetic operations would still result in massive computational efforts [10]. In this paper, the basic GA has been applied to the MLS as a plant for tuning the PID controller parameters. The results for settling time, overshoot

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and steady state error are validated by comparing with the Z-N rule.

The paper is structured as follows; the section II briefs about the description of MLS, while system dynamics and modeling has been given in section III. Design of PID controller for the MLS plant is detailed in section IV, followed by the overview of GA in section V and simulation results for the test system in comparison to Z-N method of PID tuning in section VI.

II. Description of Magnetic Levitation System

Ferromagnetic ball suspended in a voltage-controlled magnetic field compose the MLS being considered in this paper and is schematically shown in Fig. 1 [16].

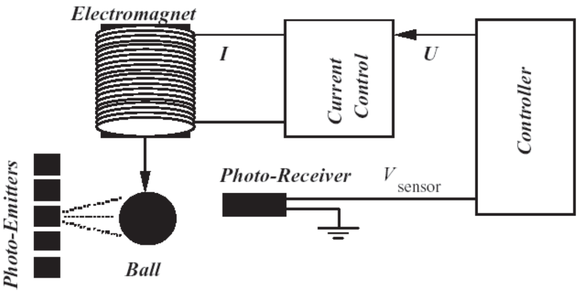

Fig. 1. Schematic Diagram of Magnetic Levitation System

The electromagnet actuator, which takes the controlled current I, specifies the position of the ball being sensed by an optoelectronic sensor and fed back to the controller as V_{sensor} signal. The output of main controller is the set point for current control block and is represented as U in the Fig. 1. Electromagnetic force on steel ball, in upward direction, is adjusted to be equal to the weight of the ball by controlling the input electric current to the coil. In this way the ball is levitated in equilibrium state. In open loop, it is highly unstable and nonlinear system so a challenging effort for designing a controller with optimum performance is needed.

III. System Dynamics and Modelling

This section explains the dynamics and modeling of the plant under study. Dynamic behavior of MLS can be modeled by the study of electromagnetic and mechanical sub systems. Here, the mathematical modeling of this nonlinear electromechanical system is presented, followed by a linear model.

A. Nonlinear Model

The nonlinear model of MLA can be represented by below mentioned differential equation. This model is based on the electro-mechanical modeling and is explained in [16].

$$v = \frac{dx}{dt} \tag{1}$$

$$m\ddot{x} = mg - C\left\{\frac{i}{x}\right\}^2 \tag{2}$$

$$u = iR + L\frac{di}{dt} - C\left\{\frac{i}{x}\right\}^2\frac{dx}{dt} \tag{3}$$

Where, v is the velocity of the suspended ball, x is the position of the ball, m is the mass of ball, C is the magnetic force constant, g is gravitational constant, L and R are the coil's inductance and resistance, i is the current in electromagnetic coil and u is the applied voltage to the system.

Taking $x = x_1, v = x_2$ and $i = x_3$ Equations (1), (2) and (3) can be written as matrix format while considering position as output;

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix} x_2 \\ g - \frac{C}{m}\left\{\frac{x_3}{x_1}\right\}^2 \\ -\frac{R}{L}x_3 + \frac{2C}{L}\left\{\frac{x_2x_3}{x_1^2}\right\}\end{bmatrix} + \begin{bmatrix}0\\0\\\frac{1}{L}\end{bmatrix} \tag{4}$$

$$y = [x_1 \quad x_2 \quad x_3]^T = [1 \quad 0 \quad 0] \tag{5}$$

$$\dot{x} = f(x) + g(x)u \tag{6}$$

B. Linear Model

Nonlinear model was linearized around a point $x = x_{01}$, with vector as under;

$$X_0 = [x_{01} \quad x_{02} \quad x_{03}]^T \tag{7}$$

At equilibrium, rate of x with respect to time must be equal to zero i.e. $x_{02} = 0$. Also, Equation (3) provides the equilibrium current which must satisfy the following condition;

$$x_{03} = x_{01}\sqrt{\frac{gm}{C}} \tag{8}$$

Using equations (1)-(8), the linearized model in state space form can be given as;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ Cx_{03}^2 & 0 & -2\frac{Cx_{03}}{mx_{01}^2} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^2} & -\frac{R}{L}\end{bmatrix} \quad B = \begin{bmatrix}0\\0\\\frac{1}{L}\end{bmatrix} \tag{9}$$

$$C = [1 \quad 0 \quad 0] \tag{10}$$

IV. PID Control Design

Physical parameters of MLS are presented in Table 1 [16].

TABLE I
Parameters of Magnetic Levitation System

Parameter	Unit	Value
Mass of ball, m	kg	0.5
Gravitational acceleration, g	m/s^2	9.8
Inductance of coil, L	H	0.01
Resistance of coil, R	Ohms	1
Constant, C		0.0001
Ball position, X_{01}	m	0.012
Velocity, X_{02}	m/s	0
Current, X_{03}	A	0.84

On the basis of parameter values presented in table 1, state space model of the system is given as;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1633.33 & 0 & -23.33 \\ 0 & 116.66 & -100\end{bmatrix} \quad B = \begin{bmatrix}0\\0\\100\end{bmatrix} \tag{11}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (12)$$

Poles of the system matrix "A" appear at +31.3616, –65.6808 + 29.9013i, – 6 5.6808 – 29.9013i which indicate that system is unstable in open loop.

The Transfer function obtained from state space model is given by:

$$T(s) = \frac{-2333}{s^3+100s^2+1088s-1.633exp5} \quad (13)$$

Transfer function of PID controller, in s domain, can be written in general form as;

$$T_{PID}(s) = \frac{K_D s^2+K_P s+K_I}{s} \quad (14)$$

Where, K_D, K_P and K_I are the gains of Derivative, Proportional and Integral part of PID controller.

The job of the PID controller is to produce the system response within the user's specifications. Obviously, the parameters (gains) of PID controller should be fine-tuned so as to meet required performance indices i.e. settling time, rise time, overshoot etc. Mostly used conventional tuning method, Z-N rule, often leads to a rather oscillatory response to set-point changes as in the following systems [17]

- Plants in which the system has nonlinearities.
- Systems having uncertainties such as modeling error and external disturbances etc.

Above mentioned difficulties results in an unacceptable controller response of the system with traditional tuning methods, hence a lot of random search techniques are widely in use for tuning PID controllers optimally. GA, being one of them, has already been proved better for improving the response as compared to conventional methods [18, 19]. This paper presents tuning of PID controller parameters using GA for MLS, which is a nonlinear and unstable open loop system.

V. Overview of Genetic Algorithm

GA is a nature inspired optimization technique. It is considered as effective optimization tool as it has successfully applied for solving complex optimization problems in many different fields. Basing on the processes of natural selection of the fittest and evolution, GA has proved extremely robust technique in finding the global optimum point.

GA is not is not a single step technique, in fact it consists of number of steps or methods which take the names from genetics but are based on stochastic optimization principles [20]. These steps are random selection of probable solutions, called generation, followed by checking their feasibility to be used as population member and if they succeed in doing so, their crossing over is done for getting the next generation. Before the new generation can start the process again, few important tests are performed. The individuals/chromosomes which have least likeliness for being the final solution must be kicked out in new generation. To make the process more robust and help it in searching the whole search space for getting the "best" solution, the process of mutation is also used [21].

Main theme, which is related to the genetics, is the idea of survival of the fittest. This, in turn, results into the evolution of better and better solutions then the previous generations. This process continues till it could find the nearest optimal solution. The convergence in the start is extremely fast and once the nearest optimum is found, further convergence slows down, which can be made fast by somehow altering the intermediate processes. Flow chart in Fig. 2 explains the implementation of GA with respect to the problem under study.

Applying GA for solving an optimization problem requires addressing the following important issues.

a) Representation

b) Formulation of the fitness function

c) Genetic operators

A. *Representation*

As mention earlier, initial population for solving an optimization problem with GA contains the candidate solutions. In case of PID controller tuning, K_D, K_P and K_I are the elements of the solution. Due to the reasons of better accuracy and lesser memory usage, the real (floating point) numbers are used in this study for encoding. Binary encoding takes longer to evaluate due to extra computation for converting to/from binary. Another drawback is that binary string loses the precision during conversion.

B. *Formulation of the fitness function*

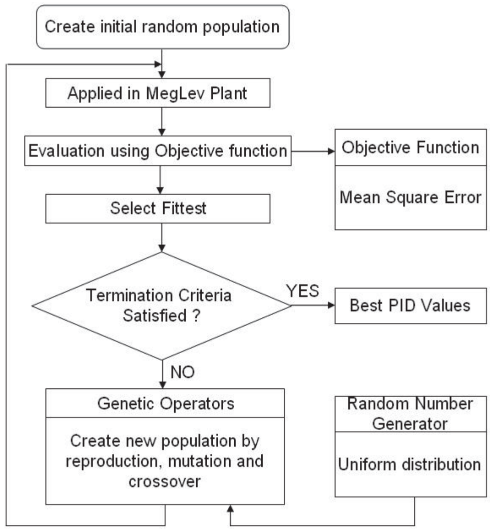

Fig. 2. Flow chart of Genetic Algorithm

Fitness of individuals in the population is checked base on the fitness function hence it must be carefully formulated. In this study, 'Fitness' of each individual is evaluated using the objective function. Fitness function of the individuals is calculated by using Mean Square Error (MSE).

C. *Genetic Operators*

The three genetic operators are;

- Selection
- Crossover
- Mutation

The selection of individuals i.e., contestant for the final optimum solution to produce generation plays an important role in GA. Following some specific strategy, new population of same population size is made by selecting from the existing population. This is called Reproduction. Once this process is over, the fitness i.e., likelihood of members of new population (also called offspring) for being the final solution is checked and highest in fitness are selected for proceeding while the others are rejected. Roulette-wheel selection, ranking methods, tournament selection, and normalized geometric selection are few among the methods for selecting the fittest offspring.

As the overall run time of GA is usual issue, the normalized geometric selection was chosen as selection process in this paper due to longer compilation time for tournament selection than the rest. Ref [22] states the roulette wheel option as inappropriate.

Like normal genetics, in crossover some portions from each of the parents' chromosomes are interchanged to produce offspring. By extracting the common features from different chromosomes, this operator tries to achieve even better solutions. In this study, being simplistic for working with chromosomes, arithmetic crossover procedure was preferred over single point crossover. At the cost of increased compilation time, which is highly undesirable, heuristic crossover performs the crossover procedure a number of times to finally picks the best one.

To ensure that the entire search space is being explored and reducing the chances for missing the best solution, mutation is a key operator. In this study, mutation process is used occasionally with the small probability to introduce variations into the chromosome.

To avoid losing the best offspring in any population, these are saved before crossover and mutation operators. This is often called as preserving the elitist models. After saving, the operators are applied and new population is examined if the previous best structure has been regained. If it does not happen, the saved copy is reinserted into the population and GA continues to work as normal [23].

VI. Simulation Results

Objective functions were developed to find PID controller parameter that results in reasonably small overshoot, fastest rise time or quickest settling time. For this purpose four objective functions were tested and these are Mean Square Error (MSE), Integral of Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time Absolute Error (ITAE).

$$\left.\begin{array}{ll} MSE = \frac{1}{t}\int_0^t (e(t))^2 dt & ITAE = \int_0^t t|e(t)| \; dt \\ ISE = \int_0^t (e(t))^2 dt & IAE = \int_0^t |e(t)| \; dt \end{array}\right\} \quad (15)$$

In the end an objective function was chosen with which the error of the controlled system would be minimized and MSE was used.

Overall objective of PID controller was to minimize the error signals, thus fitness value of corresponding chromosomes was measured using the error. Fitness value was defined as

$$Fitness\ value = \frac{1}{MSE} \quad (16)$$

Fig. 3 illustrates the convergence of Genetic algorithm through generations.

System was simulated using MATLAB and step response was observed. Various settings of GA parameters were tested and final values used are presented in Table II. Comparisons of PID tuned using ZN Rule and PID tuned using GA is made in Fig. 4. It was observed that settling time of system tuned with GA was 1.257 s and settling time with ZN Rule tuned PID is 4.1237 s and is given in Table III. However there was not much difference between rise time, overshoot and peak response.

TABLE II
Parameters of Genetic Algorithm

Parameter	Value
Selection Method	Normalized Geometric Selection
Population size	120
Generation Size	40
Cross Over Method	Arithmetic Crossover
Mutation Method	Uniform Mutation
Selection Probability	0.08
Number of Crossover points	4

TABLE III
Performance Comparison

Item	GA Tuned	ZN
Rise Time (sec)	0.0065	0.0028
Settling Time (sec)	1.25	4.12
Overshoot (%)	78.69	72.06
Peak Amplitude	1.78	1.72
Final Value	1	1

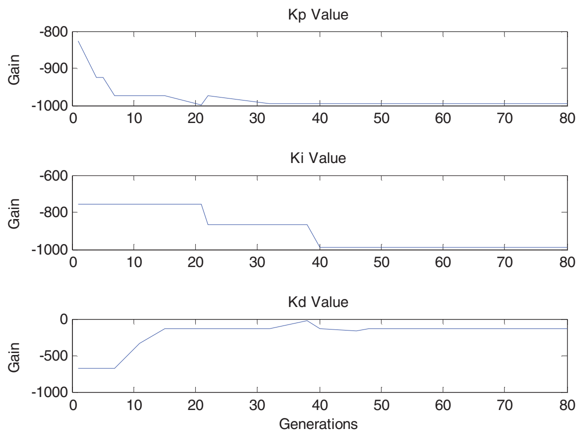

Fig. 3. Genetic Algorithms converging through generations

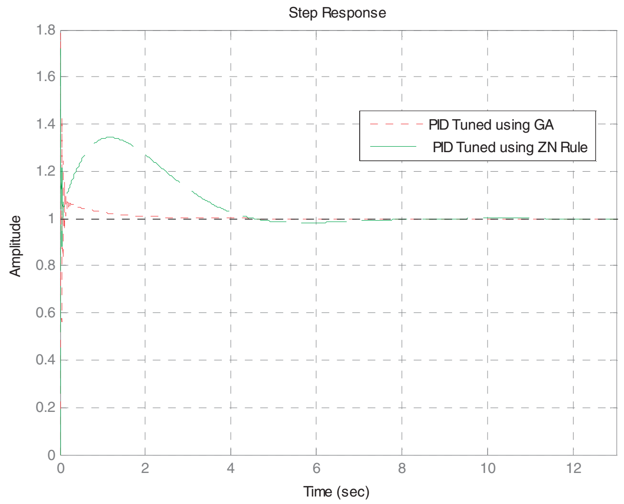

Fig. 4. Unit step response of the system using GA tuned PID Vs Z-N tuned PID

VII. CONCLUSION

On the basis of results obtained from simulation following can be concluded;

- Selection of objective function that is used for fitness value is very critical while applying GA and should be chosen according to the desired performance.
- As it was simple to find PID controller parameters using GA, the other soft computing techniques should also be considered while optimally tuning the controller parameters.
- Settings of GA parameters play an important role in finding the gain values, and selection of parameters should be made carefully.
- Thus GA with some modifications can speed up the process of optimization and should be studied

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