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Modeling and Designing a Genetically Optimized PID Controller for Separately Excited DC Motor

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***Abstract*—This paper presents an intelligent method to design a proportional-integral-derivative (PID) controller to control the speed of a separately excited DC motor (SEDCM). There are various artificial intelligent (AI) based proposed methods for tuning the parameters of a PID controller. Genetic Algorithm is a powerful optimization tool used to optimize several parameters from the given population based on natural evolution. The purpose of this paper is to obtain the suitable speed characteristics of a SEDCM by optimizing the transient response i.e. by minimizing the settling time, overshoot and the rise time using genetic algorithm (GA). In this method, integral of absolute error (IAE) is taken as the cost function. The GA optimized PID controller shows better performance with respect to settling time, rise time and percentage of overshoot than other conventional methods and adaptive fuzzy PID controller.**

Keywords—Intelligent, PID controller, SEDCM, Transient response, Object function

I. Introduction

DC motors have wide spread applications due to its simple torque-speed characteristics and speed controlling methods [1]. It becomes an indispensable part for modern industries [2] though its maintenance cost is more than the induction motor [3]. Its control mechanism is still developing day by day. Besides DC motor can provide high starting torque [4] which makes it suitable for some special applications like actuators in trains and automotive traction applications. DC motor drives are needed for precise speed control of the motors [5]. Developing a highly perform motor drive is an important field of interest for the researchers because it is an indispensable part of today's industries. A drive system should have good command tracking capability as well as load regulating response [6]. There are various advantages of DC drives over AC drives such as speed controlling and regulation, frequent breaking, revering and starting etc [7].

DC motors are of different kinds based on the purpose of usage, connection type, and winding. [8]. DC motor stator is either permanent magnet type or wound type. Also, there are four types of DC motor based on field connections. These are shunt DC motor, series DC motor, compound DC motor, and SEDCM. In series DC motor, the field and the armature coils are series connected, for the shunt DC motor, they are parallel connected and compound DC motor uses both the connections type. In SEDCM, armature winding and excitation winding are independent of each other and they are excited separately [8]. The speed of the SEDCM can be control by changing the field current or armature voltage or armature resistance. Each of the methods has their own advantages and disadvantages. SEDCM is a special type of DC motor where the field is excited separately. Due to separate excitation, its speed is independent of torque i.e. it is possible to achieve full torque at all speed. Besides, it is easier to rotate the motor in reverse direction simply by reversing the polarity of the field supply. These advantages make SEDCM suitable for wide range of applications [9].

There are various control approaches for controlling the speed of a DC motor. But 90% of the industries use PID type controller due to its clear functionality, simplicity as well as applicability [10]. Traditional controllers have drawbacks like unnecessary overshoot and sensitivity to controller gains [11]. Besides, it is difficult to choose PID controller's gain parameters for optimum response. The famous conventional method to tune the PID controller is Ziegler-Nichols tuning formula but it does not provide fruitful result always [12]. On the other hand, intelligent and adaptive PID type controllers can overcome the limitations of the conventional controllers. Some intelligent computing methods like GA, Neural Network (NN), Adaptive Neuro-Fuzzy Interface System (ANFIS), Fuzzy logic could a better solution for it.

The Neural Network (NN) can be trained by previous data just like human being which results in self-learning and self-improvement [13]. Fuzzy PID controllers are suitable for systems where there are uncertainties in their mathematical models though it is simple to realize as well as it is sensitive to process parameters change [14]. But it requires expert's knowledge and experience to established fuzzy rules. ANFIS is an effective method to predict functionality [15]. An ANFIS PID controller possesses both the advantages of Neural Network and Fuzzy logic [16]. Genetic Algorithm (GA) was first introduced by John Holland in1975 [17]. It is an optimization technique that optimized the object function to obtain a suitable result. It randomly searches for the optimum solution from the given set of population. It involves three fundamental process selection, crossover and mutation to obtain the new and best solution.

Sadiq and Bakare design a fuzzy base controller using both the armature voltage and field current [18]. In paper [19] they design an ANFIS based controller using PSO. The authors Meena and Sunita in paper [20] proposed a position and speed controlling by DC servo motor using the genetic

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algorithm. In paper [21], the authors verified the effectiveness of the RLS method based PID controller experimentally. The paper [22] made an improvement of the dynamic response of the electric machine using fuzzy logic controller (FLC). The authors Yaote Chang and Sun-Li Wu design a non-linear controller for SEDCM based on lyapounov stability and backstepping control theorems [23]. In paper [24] and [25] the authors' design an ANFIS based controller for SEDCM. The authors Nivedita Pati and Nibedita Swain [26] studied the controlling of speed of DC motor by youla parameterization and PID controller.

The subsequent sections of the paper include the mathematical model of the SEDCM, PID controller, Genetic Algorithm, Proposed PID controller, result and analysis and conclusion.

II. Literature Review

A. PID Controller

The PID controller is frequently used in today's industries where 90% of the controllers are PID type [16]. It is used for a long time due to its simplicity, satisfactory performance, and flexibility [27]. To design a PID controller the challenging task is choosing the value of the PID gain parameters K_i, K_d, and K_p. If the PID parameters are not finely tuned, the settling time, overshoot and rise time would be high for which the precise and fast control would be impossible. Fig. 1 shows the PID type controller. The output equation of a PID type controller is given by [12], [28]:

$$Q(t) = k_p e(t) + k_i \int e(t) + k_d \frac{de(t)}{dt} \qquad (1)$$

Taking laplace transform:

$$Q(s) = k_p E(s) + k_i \frac{E(s)}{s} + sk_d E(s) \qquad (2)$$

$$\frac{Q(s)}{E(s)} = k_p + \frac{k_i}{s} + sk_d$$

$$U(s) = k_p + \frac{k_i}{s} + sk_d \qquad (3)$$

Here e(t) = error function. The output of PID controller acts in such a way that it tries to minimize the error signal i.e. the output speed tries to align with the set speed. Though the simple structure and robustness of the methodology of the PID controller, optimum tuning of the PID parameters is not an easy task [29]. If the k_p increases, the rise time as well as steady-state error decreases. If the k_i increases, the rise time decreases but the settling time and overshoot increases which can be overcome by the increase of the k_d.

So, to obtain the optimum value of these characteristics parameter, we need to find the suitable value of the gain parameters. So, we applied GA for optimal tuning of the PID controller.

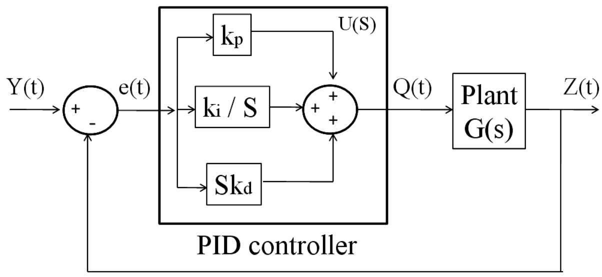

Fig. 1. Conventional PID controller

B. Genetic Algorithm

With the advances in simulation methodologies, it opens the door of development and implementation of complex algorithm like fuzzy logic, genetic algorithm [30]. Genetic Algorithm (GA) is an optimization technique that follows the natural evaluation process [28]. GA search for the optimum (minimum) value of a function called cost function or object function from a given set of values known as population. The value of each population is called chromosome. There are three basic processes of GA namely selection, crossover and mutation. The GA uses these operations to find the fittest value based on the fitness value of each chromosome. The fig. 2 [31] shows flow chart of the genetic algorithm.

III. Mathematical Model

In recent years, DC motors have wide spread use [3] in industries because of its simple characteristics and stability. Fig. 3 represents the diagram of a voltage controlled SEDCM. In SEDCM the field is excited from a separate source voltage. The equation that describes the dynamic behavior of a SEDCM is given by [6], [26], [27]:

$$v = i_a R_a + L_a \frac{di_a}{dt} + e_b \qquad (4)$$

Here, V_a = applied armature voltage
i_a = armature current
L_a = armature inductance
e_b = back emf
T_m = motor torque
K_t = torque constant
K_b = back emf constant
J = inertia of the rotor
ω = velocity of the rotor (rad/sec)

Again, the back emf is directly proportional to the rotor speed. So,

$$e_b = k_b \omega \qquad (5)$$

So, replacing the e_b in (4) we get,

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + k_b \omega \qquad (6)$$

Taking Laplace transformation of (3),

$$V_a(s) = I_a(s)R_a + L_a s I_a(s) + k_b \omega(s) \quad (7)$$

$$\therefore I_a(s) = \frac{1}{R_a + L_a s}\left(V_a(s) - k_b \omega(s)\right) \quad (8)$$

Now, torque T_m is proportional to armature current. So,

$$T_m = k_t i_a \quad (9)$$

$$\therefore T_m(s) = k_t I_a(s) = \frac{k_t}{R_a + L_a s}\left(V_a(s) - k_b \omega(s)\right) \quad (10)$$

Again, according to the Newton's law the torque is:

$$T_m = J\frac{d\omega}{dt} + B\omega \quad (11)$$

Taking Laplace transformation,

$$T_m(s) = Js\omega(s) + B\omega(s) \quad (12)$$

$$\therefore \frac{\omega(s)}{T_m(s)} = \frac{1}{Js + B} \quad (13)$$

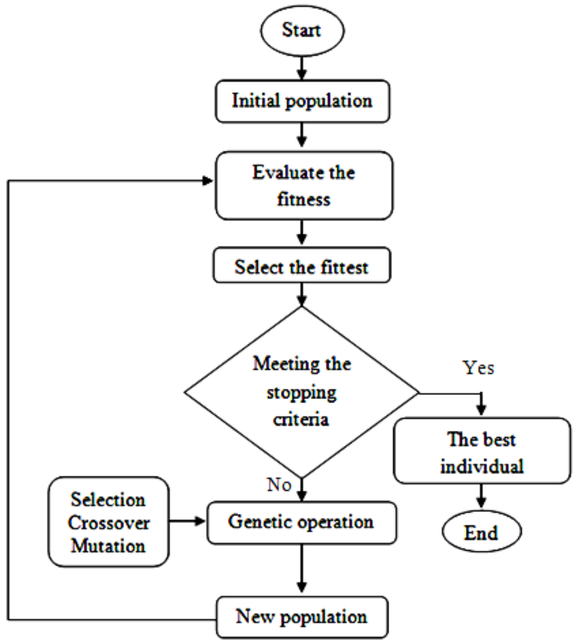

Fig. 2. Flow chart of the Genetic Algorithm [31].

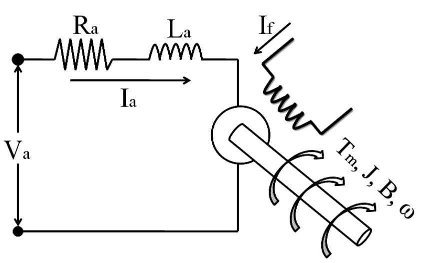

Fig. 3. Schematic diagram of SEDCM

From (8), (10) and (13), we find the relation between the motor speed and armature voltage. Fig. 4 shows the complete diagram of the SEDCM.

Reducing the above block,

$$\frac{\omega(s)}{V_a(s)} = \frac{k_t}{(R_a + sL_a)(Js + B) + k_t k_b} \quad (14)$$

The value of the equivalent circuit parameters [11] is represented in table I.

TABLE I. EQUIVALENT CIRCUIT PARAMETERS

Parameter	Value
Moment of Inertia (J)	0.093 Kg.m^2
Friction Coefficient (B)	0.008 N.ms
Back emf constant (k_b)	0.6 V/rad.s^{-1}
Torque constant (k_t)	0.7274 Nm/A
Armature resistance (R_a)	0.6 ohm
Armature Inductance (L_a)	0.006 H

Putting these values in 11, we find the overall transfer function of the SEDCM given by:

$$G(s) = \frac{727.40}{0.558s^2 + 55.85s + 441.2} \quad (15)$$

IV. Proposed Control Approach

Fig. 5 represents the proposed control methodology for controlling the speed of the SEDCM. Here the output speed is feedback to the input where the output speed is subtracted from the set point. This resultant (error) signal governs the PID controller. On the other hand, GA used this signal as the object function for optimum tuning of the PID type controller.

A. PID Parameters

The characteristics parameters like settling time, overshoot and rise time vary with the change of PID parameters (K_i, K_p and k_d). If the k_p increases, the rise time as well as steady-state error decreases. If the k_i increases, the rise time decreases but the settling time and overshoot increases which can be overcome by the increase of the k_d. To obtain the suitable value of these characteristics parameter, we need to find the suitable value of the PID parameters (K_i, K_p and k_d). So, to obtain the optimum value of the PID/gain parameters we applied genetic algorithm.

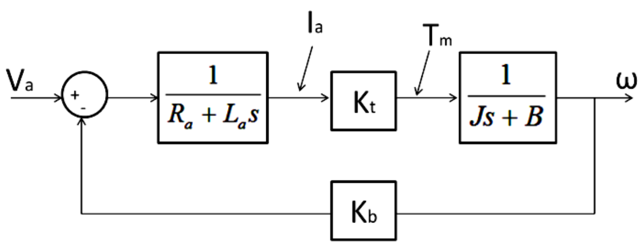

Fig. 4. Block diagram of SEDCM

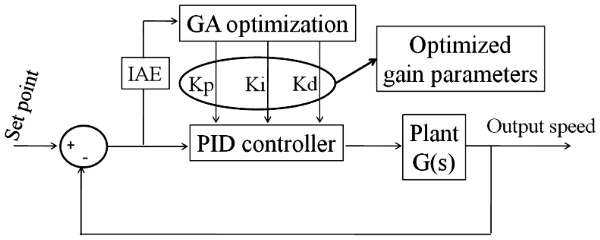

Fig. 5. Proposed control methodology

B. Object Function

Object function is the crucial part of the genetic algorithm. Here the integral of the absolute error is taken as the object function which given by:

$$IAE = \int_0^{\infty} |e(t)| dt \tag{16}$$

C. GA Parameters

Table II shows the different GA parameters and table III shows the range of the gain parameters (K_i, K_p, and k_d). There is no hard and fast rule to select the ranges of these gain parameters and the range is selected by trial and error basis for which the controller shows better result [31].

TABLE II. VALUES OF THE PARAMETERS FOR GA

Parameter	Value
Crossover	Single point
Selection	Roulette
Mutation	Uniform
Population size	20
Population type	Double vector
Fitness scaling (scaling function)	Rank
Creation function	Constraint dependent

TABLE III. RANGE OF K_p, K_i and K_d

Parameters	Minimum value	Maximum value
K_p	30	40
K_i	0	1
K_d	0	1

V. Result and Analysis

The above simulation work is carried out in MATLAB. The result is tested in different methods. To evaluate the performance of the proposed method, the simulink model of fig. 6 is considered.

A. Performance of the proposed methodology

The performance of the proposed method as well as others methods is measured based on settling time, percentage of overshoot and rise time. Fig. 7 shows the response of the motor with conventional PID controller and adaptive fuzzy controller [11]. Here in adaptive fuzzy controller the transient response (settling time 0.0978 sec, rise time 0.079674 sec, overshoot 0.465 %) is improved compared to conventional PID controller (settling time 0.353 sec, rise time 0.094621 sec, overshoot 8.152 %). Fig. 8 represents the step response of the system (motor) without controller and with proposed GA-PID controller. From the fig. 7 it is apparent that without controller the response has high rise time (0.256 sec.) and settling time (0.464 sec.) which can create problem in controlling DC motors in industries. So, we used genetic algorithm to properly select

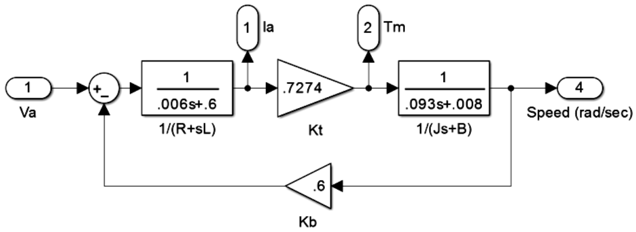

Fig. 6. Simulink model of the SEDCM

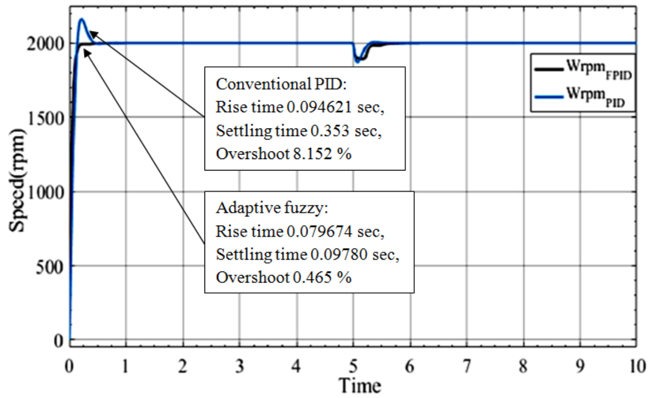

Fig. 7. Response of the conventional PID and adaptive fuzzy controller [11].

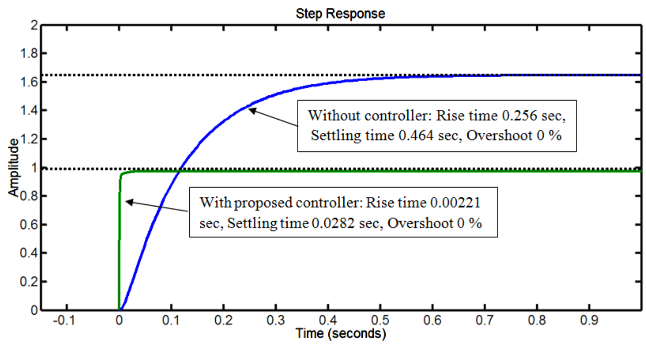

Fig. 8. Step response without controller and with proposed GA-PID controller

the value of the gain parameters for improving control characteristics.

In table IV the value of the optimized gain parameters that is obtained using the GA is listed.

TABLE IV. OPTIMISED GAIN PARAMETERS

Gain Parameters	Value
K_p	35.4700
K_i	0.7160
k_d	0.2830

From the response with proposed GA-PID controller (using the optimized gain parameters), it is clear that the settling time and the rise time is substantially reduced and also there is no overshoot compared to the above mentioned methods. Here the rise time is 0.00221 second and settling time 0.0282 second.

B. Performance Comparision

Table V represents the comparative data of step response in different methods such as without controller, with conventional PID controller [11], with adaptive fuzzy PID type Controller [11] and with proposed GA-PID controller.

The results are compared based on settling time, rise time and percentage of overshoot. And fig. 9, fig. 10 and fig. 11 show the pictorial view of the comparative data of different methods for settling time, rise time and overshoot.

TABLE V. COMPARISSION OF DIFFERENT METHODS

Characteristics	Rise time (Sec.)	Settling time (Sec.)	Overshoot (%)
Without Controller	0.256000	0.46400	0
Conventional PID [11]	0.094621	0.35300	8.152
Adaptive Fuzzy PID [11]	0.079674	0.09780	0.465
Proposed GA-PID	0.002210	0.02820 sec	0

From the above data and analysis, it is apparent that the proposed method has least settling time (0.0282 sec), rise time (0.00221 sec) and no overshoot.

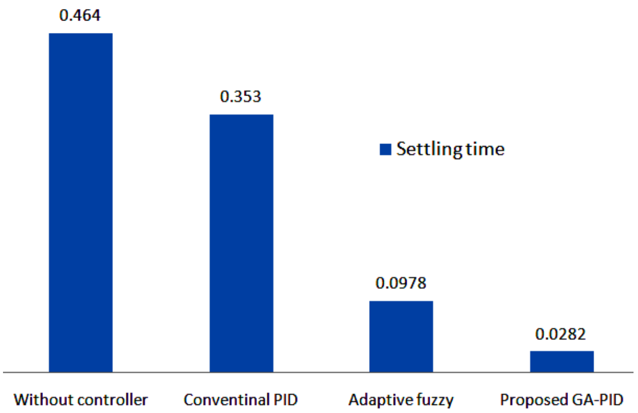

Fig. 10. Comparison of settling time

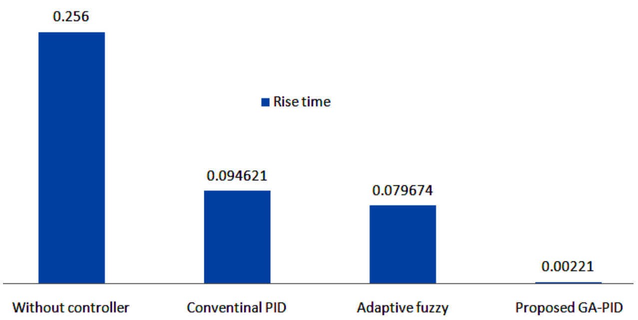

Fig. 9. Comparison of rise time

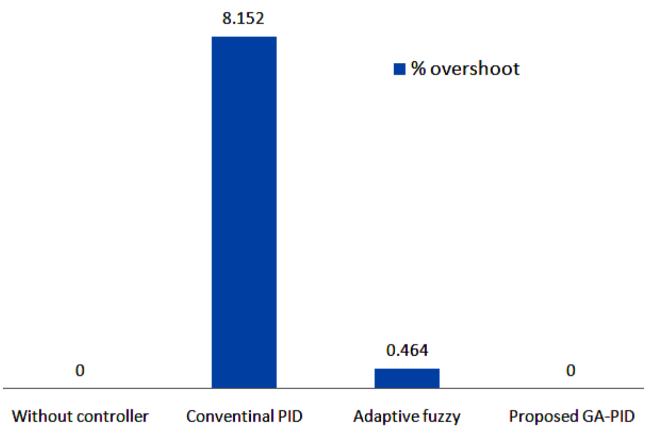

Fig. 11. Comparison of percentage of overshoot

VI. CONCLUSION

In this work a developed genetically optimized PID controller is designed and simulated in MATLAB. This proposed method/controller shows better performance than the conventional controller as well as adaptive fuzzy PID controller. Here for the obtain gain parameter $k_p = 35.4700$, $k_i = 0.7160$ and $k_d = 0.2830$ the settling time is 0.0282 second, the rise time is 0.00221 second and no overshoot which enables precise and fast control of separately excited DC motor (SEDCM). Due to this prompt and precise control of the speed, it opens the doors of sophisticated applications of SEDCM as well as it accelerates the industrial production and quality control.

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