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Speed Control of DC Motor using FOPID Controller based on Ant Colony Optimization

Jatin Yadav[1], Prashant Kumar[2], Neeraj Gupta[3], Manjeet Kaur[4]
j7yadav0@gmail.com[1], prashant.pratap3698@gmail.com[2], neerajsingla007@gmail.com[3], activesweety@gmail.com[4]
Amity School of Engineering and Technology, Gurugram, India

Abstract

Direct current (DC) motors are widely used because of their easily controllable and reliable access. DC motors have many salient features that include a wide range of torque speed control, reliable operation with greater efficiency and a greater starting torque and many more. A nonlinear model for a DC motor can be represented for considering all uncertainties and non-linearties. In this paper, DC motor is studied which is having a third order system. Many controllers are being used for controlling speed of DC motor. An analysis is carried out on mathematical model of DC motor whose field is excited by an external or separate supply. Tuning method of DC Motor i.e. Ziegler Nichols Method is also discussed along with intelligence technique-Ant Colony Optimization (ACO).

Keywords: Location-based services, Advanced Public Transport System, Digital geographic database, management, security

1. Introduction

The speed control as well as the starting torque is high for DC motors. The high transient response and compactness makes DC motor popular in most of the industries. Mostly used motors for industrial purposes are PMBLDCM i.e. permanent magnet brushless DC Motors in which the necessary flux is given by the permanent magnets but not by the field coils and DC motor in which the flux is given by the current through shunt or field coils. Most widely used controller for DC motors is conventional Proportional-Integral-Derivative (PID) controller. But due to drive inertia, load changes and limitation of the armature current, there is non-linearity in DC motor which causes problems to these controllers. Overshoot and control gains sensitivity are some disadvantages of the PID controller. Ziegler-Nichols method, Cohen-coon rule, Astrom- Hagguland methods are some of the approaches or techniques that can be implemented and are impactful in the parameters tuning of PID controller [1]. Smith predictor PID controller, PID dead time controller are some of the variant PID controllers proposed [2]. The PID controllers with λ (order of the integrator) and μ (order of the differentiator) is known as Fractional Order PID controllers which is the recently proposed generalization of the PID controller [3].

One of the popular and mostly used heuristic tuning methods for a PID controller was proposed by John G. Ziegler and Nathaniel B. Nichols called Ziegler-Nichols tuning method [4,5]. Yet these methods have their own limitations such as the instability of the loop due to a little robustness left behind by the loop and also for a dead-time dominant process, the response is quite poor. Evolutionary techniques like PSO (Particle Swarm Optimization) or particle swarm intelligence, combination of genetic algorithm and artificial neural network and fuzzy system are more popular as these approaches are almost able to find an appropriate and ideal solution for designing and optimization process for PID controllers [6]. ACO method is a known modern heuristic optimization technique. This technique is a part of SI (Swarm Intelligence). In Swarm Intelligence, certain behavior and characteristics of various species are taken and study of some of their specific properties help in realizing the tasks e.g. optimization.

2. Controllers

2.1 PID Controllers

Apart from the significant development in the advanced control theory, for over 50 years, the most common and popular controller in process industries is the PID i.e. Proportional-Integral-Derivative controller. In 1989, a survey was conducted by the Japanese association called Japan Electric Measuring Instrument Manufacturers Association whose results concluded that approx. 90% of the industries are considering PID type control loops [7,1]. The required set point is different from the measured process variable and this difference is calculated as an 'error' by the PID. The control inputs are processed and adjusted by the controller to minimize this error.

This standard three-term controller is made up of the following individual terms

- P term (representing the proportional part)
- I term (representing the integral part)
- D term (representing the derivative part)

and thus, mnemonic PID is referring the first letters of these terms.

The PID controller can be represented as:

$$u(t) = K_p e\,(t) + K_d \frac{de\,(t)}{dt} + K_i \int_0^t e\,(t) \qquad (1)$$

PID controller experiences various limitations such as, noise in derivative, feedback controller, etc. Fig. 1 depicts the block diagram of PID controller. The steady-state error as well as the rise time can be decreased by the proportional controller i.e. (K_p) while the transient response is degraded by the integral controller (K_i) even though the steady state error is eliminated with its help. Reduction in overshoot, improved transient response and a stable system can be achieved with the help of derivative control (K_d) [8].

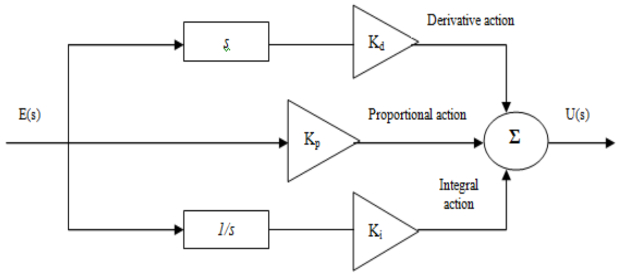

Fig. 1 PID Controller

2.2 Ziegler-Nichols Tuning(ZNT) Method

One of the heuristic and conventional methods, that is considered for PID controller tuning process, is called ZNT. D i.e. Derivative and I i.e. Integral are settled in this method and after that there is an increment rise in the proportional gain (K_p) from zero to largest ultimate gain (K_u). At this ultimate gain (K_u), the control loop output oscillations become stable. However, the oscillations will diverge if the gains further exceed the ultimate gain. Depending upon the controller type used and the desired behavior, the gains of P, I and D are set by using K_u and T_u i.e. oscillation period [9].

Table 1 Ziegler-Nichols Method [4]

Control Type	K_p	T_i	T_d	K_i	K_d
P	$0.5\,K_u$	-	-	-	-
PI	$0.45\,K_u$	$T_u / 1.2$	-	$0.54\,K_u / K_d$	-
PD	$0.8\,K_u$	-	$T_u / 8$	-	$K_u\,T_u / 10$
Classic PID	$0.6\,K_u$	$T_u / 2$	$T_u / 8$	$1.2\,K_u / K_d$	$3\,K_u\,T_u / 10$
Pessen Integer Rule	$7\,K_u / 10$	$2\,T_u / 5$	$3T_u / 20$	$1.75\,K_u / K_d$	$21\,K_u\,T_u / 200$
some overshoot	$K_u / 3$	$T_u / 2$	$T_u / 3$	$0.666\,K_u / K_d$	$K_u\,T_u / 9$
no overshoot	$K_u / 5$	$T_u / 2$	$T_u / 3$	$(2/5)\,K_u / K_d$	$K_u\,T_u / 15$

$$K_u = 1 / M \qquad (2)$$

Here, M represents the amplitude ratio.

$$K_i = K_p / T_i \qquad (3)$$

$$K_d = K_p / T_d \qquad (4)$$

With the help of these three parameters, via an eq^n., error e(t) is corrected

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e\,(\tau)\,d\tau + T_d\frac{de(t)}{dt}]$$

Thus, the controller output is having a transfer function relationship given by:-

$$u(s) = K_p[1 + \frac{1}{T_i s} + T_d s]e(s) \qquad (5)$$

2.3 FOPID – Fractional Order PID Controller

Fractional calculus based conventional PID controller is further expanded into FOPID ($PI^{\lambda}D^{\mu}$).

In case of, conventional PID controller, the transfer function would be

$G_{PID}(s) = \frac{u(s)}{e(s)} = K_c[1 + \frac{1}{\tau_I s} + \tau_d s]$ (6)

Similarly, for a FOPID, it would be

$G_{FOPID}(s) = \frac{u(s)}{e(s)} = K_c[1 + \frac{1}{\tau_I s^{\lambda}} + \tau_d s^{\mu}]$ (7)

Here, the arbitrary real numbers, λ and μ can attain any value

K_c = amplification gain

τ_i= integration constant

τ_d = differentiation constant

The control system dynamics can be better adjusted by a $PI^{\lambda}D^{\mu}$ controller as it has more flexibility as compared to conventional PID controller. The fractional order system has a difficult analog realization apart from its simplicity. Intuitively, on comparison with conventional PID controller, $PI^{\lambda}D^{\mu}$ is having greater degree of freedom and thus a better performance is expected from $PI^{\lambda}D^{\mu}$ with appropriate control parameters.

3. Mathematical modeling of DC Motor

The two different control modes of using a dc motor in control systems are:-

- Armature-Control mode (with its field current fixed)
- Field-Control mode (with its armature current fixed)

Here, the Armature-Control mode (with fixed field current is considered because of its ability to maintain constant torque levels as well as the field current throughout the application. Fig. 2 illustrates the separately excited DC motor.

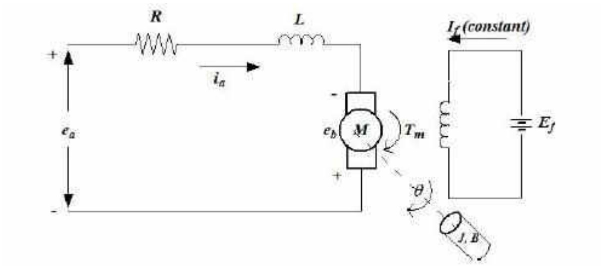

Fig. 2 separately excited constant field current DC motor.

R = Armature resistance

L = inductance of the Armature winding (H)

e_a= Applied Armature Voltage (V)

e_b = back e.m.f. (V)

i_a= Armature current (A)

i_f= field current (A)

The developed Torque by the motor is T_m (Nm) and the motor shaft's angular displacement is θ (rad. / sec.). When referring to motor shaft, the motor's equivalent moment of inertia is J (kg-m^2) while the coefficient of the motor's equivalent friction is denoted by B (Nm*s / rad.).

Generally, for the applications having linear range of magnetization curve, the DC motors are preferably used. The flux is directly proportional to the field current, i.e.

$\phi = K_f i_f$ (8)

Where, K_f is a constant of proportionality.

The torque developed is also directly proportional to the air gap flux and the armature current product,

$T_m = K_l K_f i_a i_f$ (9)

Where, K_l is proportionality constant.

In this type of DC motor, the field current must be const., so that,

$T_m = K_T i_a$ (10)

where, K_T is known as motor torque constant which is a constant of proportionality. The back e.m.f. and the speed are also directly proportional to each other.

Therefore, $e_b = K_b \frac{d\theta}{dt}$ (11)

For an armature circuit, the differential equation would be

$L \frac{di_a}{dt} + R\, i_a + e_b - e_a = 0$ (12)

and thus, the equation for the torque would be would be

$J \frac{e^2\theta}{dt^2} + B\frac{d\theta}{dt} - T_m = K_t i_a$ (13)

With the initial conditions as zero, we will take the Laplace transform of the equations and thus,

$$E_b(s) = K_b s\, \theta(s)$$

$$(Ls + R)\, I_a(s) = E_a(s) - E_b(s)$$

$$(Js^2 + Bs)\, \theta(s) = T_m(s) = K_T\, I_a(s)$$

Thus the Final Transfer Function would be,

$$\frac{\theta(s)}{E_a(s)} = \frac{K_T}{s\ [(R + s\,L)(J\,s + B) + K_T K_b]}$$

(14)

Or

$$G(s) = \frac{\omega(s)}{E_a(s)} = \frac{K_T}{(R + s\,L)(J\,s + B) + K_T K_b}$$

(15)

4. Swarm Intelligence

In 1989, Beni and Wang were the first one to include this expression "swarm intelligence" in the cellular robotic systems context. This artificial intelligence technique is basically the collective study of the behaviors of self-organized and decentralized systems. A group of simple agents interacting with each other locally as well as with the environment make up a typical SI (swarm intelligence) system. Usually the behavior of the individual agents is not dedicated by any centralized control structure. But such agents interacting locally are often leading to the global behavior emergence. Bee swarming, animal herding, ant colonies and bacteria molding are some of the examples of systems found in nature.

Depending on the evolutionary computation, the artificial intelligence is succeeded by the computational intelligence (CI). This technique i.e. CI is one of the famous optimization technique. The learning elements i.e. evolution and adaption is combined by CI to create some sensible and intelligent programs. The complementary view is often given by CI research but the statistical methods are not rejected. Multimodal optimization techniques, parameter control methods and the fitness function design are the areas where the fundamental application of the computational intelligence is found. The computational intelligence is imperative because, when compared with the methods of traditional optimization, the optima are more quickly found for more complicated and difficult optimization problems [10, 11]. The further classification of SI is as follows:-

- PSO (Particle Swarm Intelligence)
- ACO (Ant Colony Optimization)
- Bees Search
- Cuckoo Search

5. Ant Colony Optimization

The real ants, without using any visual cues find the shortest route between their source and their destination e.g. food. Pheromone is a chemical that is deposited by these ants along their path during their movement from source to the destination and then the chemical deposited is used by the ants to follow the path (the path which is rich in pheromone). This behavior of real ants is used to relate the meta heuristic algorithm i.e. ACO as the definition of the methods used to solve wide range of problems. ACO is a part of SI or ant algorithms. Swarm intelligence deals with the algorithmic approaches inspired by many insects' behaviors such as ant colonies. There are artificial ants that solve the optimization problems in consideration and the information is exchanged via a communication method similar to the one used by the real ants [11].

ACO is a probabilistic one that is used to solve various computational problems which find appropriate and suitable paths through graphs. The multi-agent methods i.e. artificial 'ants' are inspired by the real ant's behavior. The predominant paradigm being used is the biological ant's communication particularly based on pheromone. These artificial ants are combined with local search algorithms to make a suitable method for various optimizing tasks that involves graphs for example, routing of vehicles or the internet routing.

This ACO, for example can be considered as a class of optimizing algorithms modeled on the action and behavior of ant colony. The simulating agents i.e. artificial 'ants' find the optimal and appropriate solutions of the problems moving through a parameter space with all kind of feasible solutions. In the real world, the real ants direct each other to the resources while they explore their environment by laying down the chemical pheromone. Similarly, the artificial 'ants' have the records of their positions and their solutions quality so that more and more ants are able to locate the better solutions during the later simulation iterations. The main benefit of using ACO is the confirmation of convergence, adaptive to various changes like distance, speed, position, and providing rapid and appropriate solutions. Although ACO offers splendid benefit but suffers from uncertainty in convergence time and difficulty in theoretical analysis [12,13,14].

6. Result and Discussion

In these results, we have compared FOPID i.e. fractional order PID controller with a conventional PID controller.

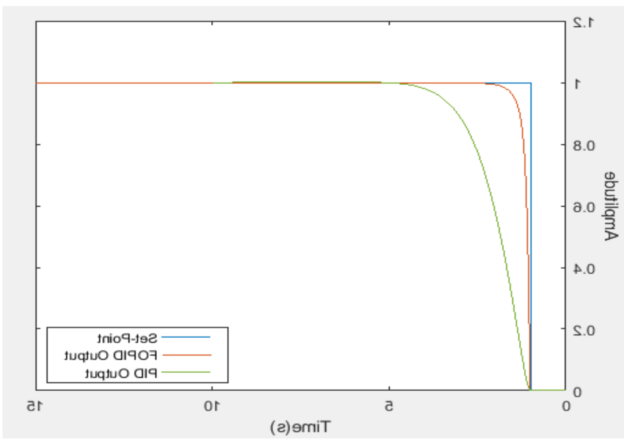

Fig. 3 Comparison of FOPID and PID controller

The above figures show the dynamic responses of both the controllers i.e. Fractional as well as the conventional PID controller. From these graphs, it can be clearly observed that in case of a FOPID controller system, the rise time is shorter in comparison to that of a traditional PID controller.

7. Conclusion

In this paper FOPID controller is used to optimize the speed control of DC motor. The requirements for speed control process of a DC motor with the help of FOPID and with the use of optimization technique is discussed in this paper. The parameters of FOPID and conventional PID controller are optimally tuned by ACO. Both of the controllers are compared in simulation. The results of FOPID controller can reduce settling time, overshoot and steady state error. Advantages of using FOPID over PID, Ziegler-Nichols tuning method and Ant Colony Optimization technique is briefly discussed here. Also, conventional PID controller is slower than FOPID controller while stopping the motor. With this we have shown that FOPID has more flexibility and capability.

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