



Optimization of Proportional Integral Derivative Parameters of Brushless Direct Current Motor Using Genetic Algorithm

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Authors' contributions

This work was carried out in collaboration among all authors. Author OA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors DA and IA managed the analyses of the study. Authors DA and IA also managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2020/v16i317170

Editor(s):

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- Complete Peer review History: <http://www.sdiarticle4.com/review-history/57806>

Original Research Article

Received 10 May 2020
Accepted 15 July 2020
Published 01 September 2020

ABSTRACT

Optimal performance of the Brushless Direct Current (BLDC) motor is to be realized using an efficient Proportional Integral Derivative (PID) controller. However, conventional tuning technique fails to perform satisfactorily under parameter variations, nonlinear conditions and time delay. Also using conventional technique to tune the parameters gain of the PID controller is a difficult task. To overcome these difficulties, modern heuristic optimization technique are required to optimally tune the Proportional, Integral, Derivative of the controller for optimal speed control of three phase BLDC motor. Thus, genetic algorithm (GA) based PID controller was used to achieve a high dynamic control performance. The Brushless DC Motor mathematical equation which describes the

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voltage and corresponding rotational angular speed and torque of the brushless DC motor was employed using electrical DC Machines theorem. The Genetic algorithm was further analyzed by adopting the three common performance indices i.e. Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Absolute Error (IAE) in order to capture and compare the most suitable BLDC Motor speed and torque control characteristics. All simulations were done using MATLAB (R2018a). The simulation result showed that the system with GA-PID controller had the better system response when compared with the existing technique of ZN-PID controller.

Keywords: GA- PID controller; ziegler nichols; optimization technique; BLDC motor; ITAE; ISE; IAE.

1. INTRODUCTION

The BLDC motors, also called Permanent Magnet DC Synchronous motors, are one of the motor types that have more rapidly gained popularity, mainly because of their better characteristics and performance. These motors are used in many industrial applications because their architecture is suitable for any critical safety application [1]. The term speed control stands for intentional speed variation carried out either automatically or manually. DC motor are most suitable for wide range speed control and are therefore used in many adjustable speed drive [2]. Since speed is directly proportional to armature voltage and inversely proportional to magnetic flux produced by the poles, adjusting the armature voltage and the field current will change the rotor speed. The brushless DC motor is a synchronous electric motor that, from a modeling perspective, looks exactly like a DC motor, having a linear relationship between current, torque, voltage and speed. It is an electronically controlled commutated system, instead of having a mechanical commutation, which is typical of brushed motors. Additionally, the electromagnets do not move, the permanent magnets rotate and the armature remains static [3]. In BLDC motor power losses are practically all in the stator where heat can be easily transferred through the frame or cooling systems can be used especially in large machine [4].

The PID controller is widely used in industrial control system because of its simple structure and easy implementation [5]. The proportional integral derivatives controller is a generic control loop feedback mechanism. It is the most commonly used feedback controller, when the PID controller is used for controlling the BLDC motor, tuning is important [6]. Many methods are available for tuning the PID controller, but the conventionally tuned PID controller does not provide optimum performance under nonlinear

conditions and parameter variations [7]. In this work GA was suggested to find suitable PID gains for Control of BLDC motor. The remainders of this work are arranged as follows: Section II gives a brief structure and mathematical formulation of the conventional PID controller while section III presents the suggested structure and problem formulations of the GA-PID controller. Results obtained are presented in section IV. Section V concludes the work.

2. STRUCTURE AND PROBLEM FORMULATION OF THE CONVENTIONAL PID CONTROLLER

PID controller parameters consist of three separate terms: Proportional, Integral and Derivative values are denoted by K_p, K_i, K_d , respectively. The fundamental structure of a PID Control system is shown in Equation 1. Appropriate setting of these parameters will improve the dynamic response of a system, reduce overshoot, eliminate steady state error and increase stability of the system [8].

$$C(s) = U(s)/E(s) = K_p + (K_i/S) + K_dS \quad (1)$$

where:

- error, $e(s)$ is the set point – plant output
- K_p represents proportional gain
- K_i represents integral gain
- K_d represents derivative gain

The Block diagram of a conventional PID is shown in Fig.1. Once the set point has changed, and the error determined as the difference between the set point and the actual output $E(s)$, was used to generate the Proportional, Integral, Derivative actions, with the resulting signals weighted and summed to form the control signal, $U(s)$, applied to the model [9]. The new output signal obtained sent to

the controller resulted in another error signal. This process run continuously until steady- state.

3. MATERIALS AND METHODS

Mathematical model of brushless DC motor has been considered, the commutation of the BLDC can only be done by electronic control [10]. The operation of BLDC motor can be realized in many modes (phases), generally 3 phases. The main advantage of 3-Phase was better efficiency and quiet low torque and has best precision in control. The use of Maxon EC flat ϕ 45 mm, brushless, 30 Watt motor with Hall Sensors has been used. The schematic illustration of the considered system is shown in Fig. 2.

Using Kirchoff's Voltage Law (KVL), the following equation was obtained:

$$E_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + E_b(t) \quad (2)$$

where:

$$R_a i_a(t) = \text{Voltage across } R_a$$

$$L_a \frac{di_a(t)}{dt} = \text{Voltage across } L_a$$

Similarly while considering the Mechanical properties, Newton's second law of motion gives

$$\omega = \frac{d\omega}{dt} + b\omega(t) = T_m(t) \quad (3)$$

Thus, the transfer function was obtained by using the ratio of the angular velocity to the source voltage as:

$$P(s) = \frac{\frac{1}{K_b}}{T_m \cdot T_s \cdot s^2 + T_m \cdot s} \quad (4)$$

Therefore, since there is a symmetrical arrangement and a three phase, the Mechanical and Electrical constants become Mechanical constant,

$$T_m = \frac{J \cdot 3R}{K_b K_t} \quad (5)$$

Electrical constant,

$$T_m = \frac{L}{3R} \quad (6)$$

Where

k_e is the Back emf and k_t represents the Torque Constant.

The Mathematical model of the Maxon BLDC motor was modeled based on parameter listed in Table 1.

Therefore, the $P(s)$ becomes

$$P(s) = \frac{13.11}{2.66 e^{-3} s^2 + 0.017 1s + 1} \quad (7)$$

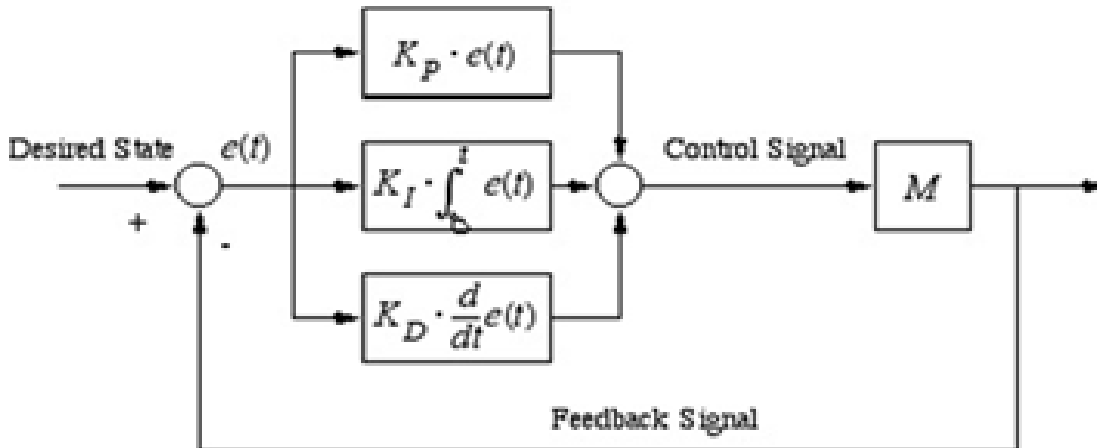


Fig. 1. Block diagram of a conventional PID controller [10]

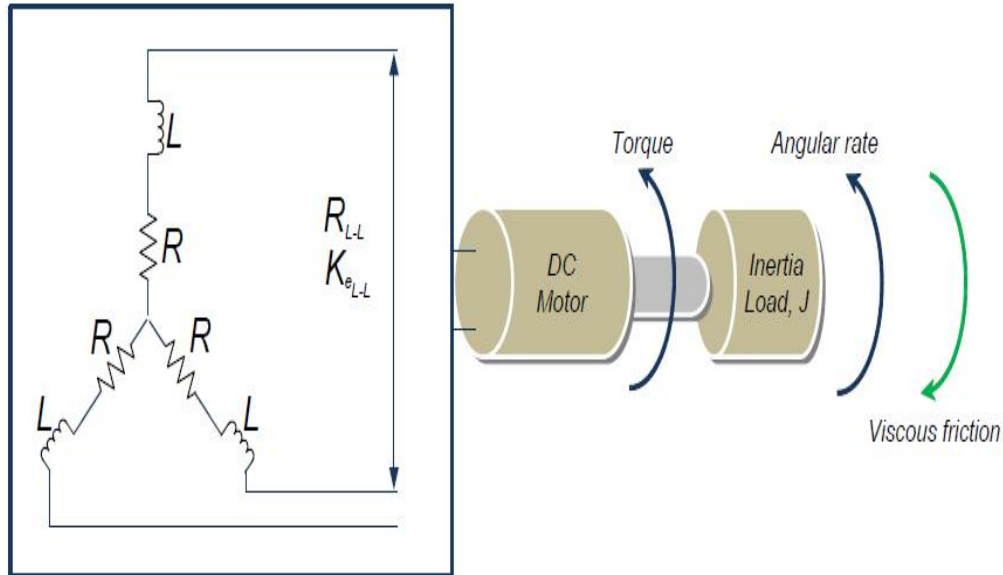


Fig. 2. Schematic diagram of BLDC Motor [21]

Table 1. Parameter of BLDCM

Maxon motor data	Unit	Value
Value of nominal voltage		
Nominal voltage	V	12.00
No load speed	Rpm	4370
No load current	mA	151
Nominal speed	Rpm	2860
Nominal torque	mNm	58
Nominal current	A	2.14
Stall torque	mNm	255
Starting current	A	10
Maximum frequency	%	77
Characteristics		
Terminal resistance phases to phase	Ω	1.2
Terminal inductance	mH	0.560
Torque constant	mNm/A	25.5
Speed constant	rpm/V	37.4
Speed / torque gradient	rpm/mNm	17.6
Mechanical time constant	Ms	17.1
Rotor inertia	gcm ²	92.5
Number of phase		3

4. GENETIC ALGORITHM FOR PID TUNING

Genetic algorithm is a robust technique for optimization based on natural selection. The main objective of using genetic algorithm is to optimize a function fitness called fitness function [11]. A possible solution of a problem is seen as

an individual. The collection of number of individual is called as population. The current population produces new generation, the new generation and new individuals are supposed to be better than the previous one. A basic structure of GA-PID controller consists of a conventional controller, whose gain coefficients are auto tuned by the GA technique for a given plant. Hence a

GA algorithm consists of three basic things, reproduction, crossover and mutation [12]

4.1 Objective Function Value

The most crucial step in applying GA is to choose the objective functions that are used to evaluate fitness of each chromosome. Some works use performance indices as the objective functions [13]. Other Author uses Mean Squared Error(MSE), Integral of Time multiplied by Absolute Error (ITAE), Integral of Absolute Error (IAE) and Integral of the Squared Error (ISE) [14]. Performance indices were used to minimize error signal $E(s)$ and compare them to find the most suitable one the performance indices are defined as follow [15]

$$MSE = \frac{1}{t} \int_0^T e(t)^2 dt \tag{9}$$

$$ITAE = \int_0^T te(t)dt \tag{10}$$

$$IAE = \int_0^T e(t)dt \tag{11}$$

$$ISE = \int_0^T e(t)^2 dt \tag{12}$$

$$ITSE = \int_0^T te(t)^2 dt \tag{13}$$

4.2 Implementing GA-PID for Speed Control

Since the speed control transfer function has been developed, the control codes are configured on MATLAB software using the C++ code. Fig. 2 is the genetic algorithm tuned PID controller which will iterate the solver to achieve the best possible chromosome that will give the best K_p , K_i and K_d values [16,17]. This is aimed at improving the system dynamic response

characteristics. The voltage input for the system which is converted into speed as output is adjusted by limiting the errors for the desired output speed values. Fig. 3 show the speed control program on MATLAB with GA-PID implemented using the ITAE solver method. The number of variables are entered as three for K_p , K_i and K_d . The upper bounds and lower bounds are set from -50 to 250 for the three variables. Other parameters used for the GA solver are shown in Table 2.

Table 2. Parameter for genetic algorithm function variables

Parameter	Value
Generation numbers	50
Selection method	Roulette
Cross over possibility	Constraints Dependent
Mutation possibility	0.002

4.3 GA Controlled Speed and Torque System Model on MATLAB-Simulink

A PID controller tuned with the aid of PID tuners that automatically linearize models in Simulink. These designs was tuned interactively and tested in non-linear simulation. Interactive techniques such as root locus and bode was employed for complex systems. Dynamic characteristics and the stability of the control system was linearized around operating points. Linear models can be examined in time and frequency domains and imported to MATLAB environment for simulation. Simulations based frequency responses was used for models that cannot be easily linearized [18-20]. The common three genetic algorithm objective functions employed for tuning and optimization were Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Absolute Error (IAE).

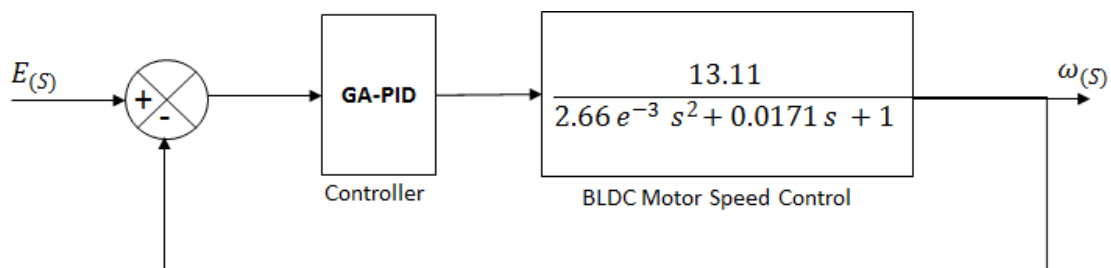


Fig. 3. GA-PID controller application for BLDC motor speed control

5. RESULTS AND DISCUSSION

Implementing genetic algorithm for tuning the Proportional Integral and Derivative gains involves running the optimization tool on MATLAB as shown in Fig. 4. The iterative solver continuously selects at random (k_p , k_i and k_D) values based on the reproduction, mutation and crossover function variables. The genetic algorithm solver was also used to determine the best Fitness and best Mean values for the optimal solution of the solver as shown in Fig. 5. The best Mean was 1.068×10^{-4} and best Fitness value gotten as 1.068×10^{-4} which showed convergence of the genetic algorithm iterative solver process.

The Genetic algorithm was further analyzed by adopting the three common performance indices

that is, Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Absolute Error (IAE) in order to capture and compare the most suitable BLDC Motor speed and torque control characteristics. This analysis can be seen on Fig. 6 for the BLDC Motor system control plots .Table 2 is the extracted values for system response parameters for all the adopted control methods, the GA-PID (ITAE) had the optimal control characteristics for the BLDC speed control followed by the GA-PID (ISE) and lastly GA-PID (IAE).

The k_p , k_i and k_D values extracted from the PID controllers are compared on Table 3 with GA-PID (ITAE) having the highest value for k_p while ZN-PID has the highest value of k_i and k_D . The derivative values for genetic algorithm

```

1  function [J] = pid_optim(x)
2
3  s = tf('s');
4
5  plant = 13.11/(2.66*10e-3*s^2 + 0.0171*s + 1);
6
7  Kp = x(1);
8  Ki = x(2);
9  Kd = x(3);
10
11 cont = Kp + Ki/s + Kd*s;
12
13 step(feedback(plant*cont,1));
14
15 dt = 0.01;
16 t = 0:dt:1;
17
18 e = 1 - step(feedback(plant*cont,1),t);
19
20 J = sum(t'.*abs(e)*dt); %ITAE GA
21 grid on
22 title('Step Response for GA-PID BLDCM Speed Control')
23

```

Fig. 4. Configuration of BLDC motor speed control on MATLAB

```

Kd =
    170.9944

Kp =
    103.1740

Ki =
    225.1002

Kd =
    40.1068

```

Fig. 5. Genetic algorithm PID iterations on MATLAB (NB: PID variables not final values)

optimization were minimal as that for Integral Time Absolute Error (ITAE) deflected negative. An interesting observation on Fig. 7 was the close margin between the integral and derivative values for ITAE solver. Thus, in this solution, the best control error limiting algorithm had a proportional gain lower to the derivative gain or to have them both in equal values. This situation

makes the derivative value of no effect which occurred with classical control technique. Small perturbations are considerably eliminated when the system's tolerance to external disturbances are constrained. Classical control systems design allows more estimations when compared to robust control designs with state-space models.

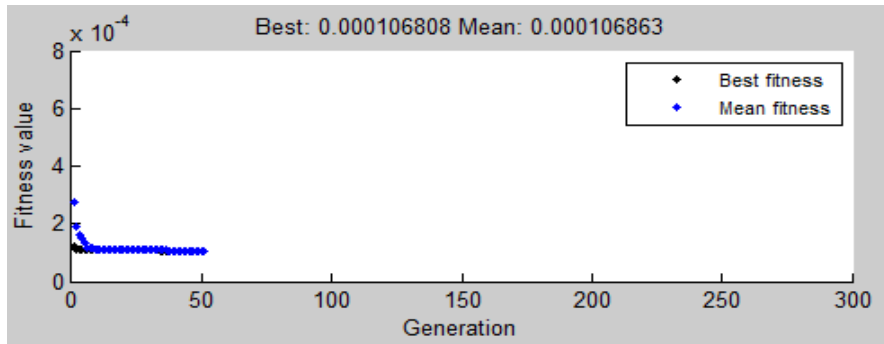


Fig. 6. Genetic algorithm iterative solve process indicating convergence of optimal solution

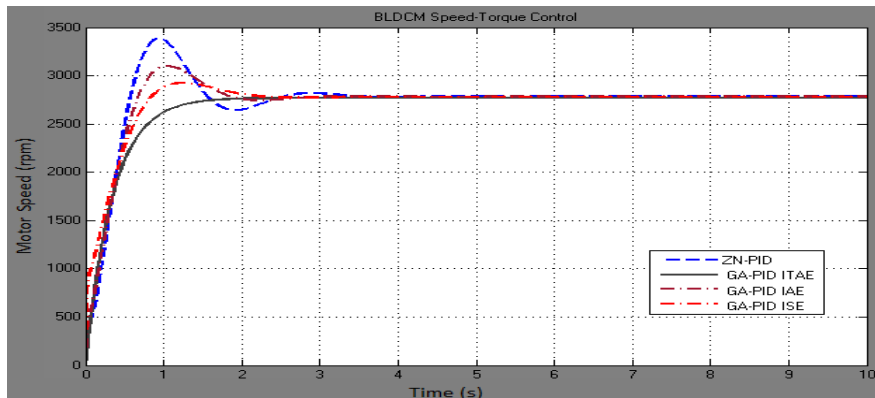


Fig. 7. Comparison plots for ZN-PID, GA-PID (ITAE), GA-PID (IAE) and GA-PID (ISE)

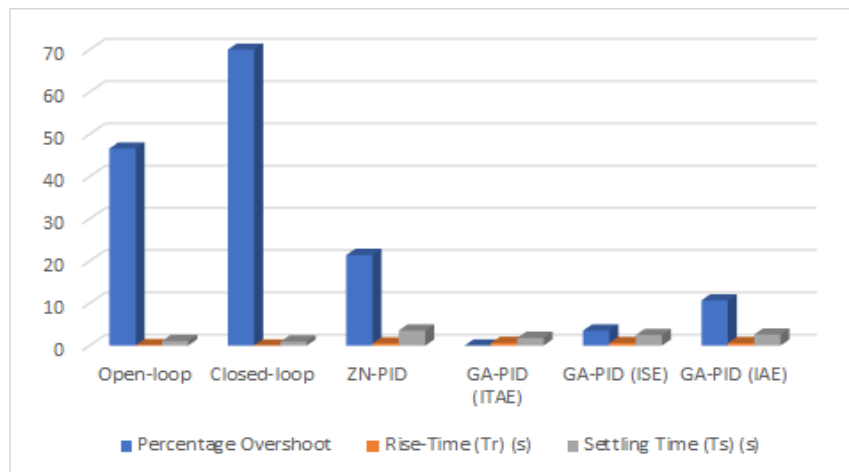


Fig. 8. Comparison plots for K_p , K_i and K_d values for BLDC motor system

Table 3. Controlled system response characteristics for BLDC motor control

Tuning technique	Percentage Overshoot	Rise-Time (T_r) (s)	Settling Time (T_s) (s)
ZN-PID	21.44	0.51	3.56
GA-PID (ITAE)	0.00	0.65	1.82
GA-PID (ISE)	3.57	0.61	2.51
GA-PID (IAE)	10.71	0.59	2.62

Table 4. Corresponding k_p, k_I and k_D values for BLDC motor

Tuning technique	k_p	k_I	k_D
ZN-PID	107.45	238.37	14.94
GA-PID (ITAE)	204.62	189.23	-1.12
GA-PID (ISE)	196.44	232.33	3.43
GA-PID (IAE)	182.74	212.65	5.91

6. CONCLUSION

It can be deduced that genetic algorithm solver dwell on optimizing the cross-over function for new offspring using the mutation algorithm to select the best fitness function as it iterates the solver. In control objective using genetic algorithm, the fitness scaling and performance of systems dynamic responses as simulation result show that GA offers less overshoot, rise time and settling time. Genetic Algorithms have proved better in achieving the transient and steady-state response parameter. The GA-PID (ITAE) had the optimal control characteristics for the BLDC speed control followed by the GA-PID (ISE) and lastly GA-PID (IAE).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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