Research Article

Optimization of PID Controller for Brushless DC Motor by using Bio-inspired Algorithms

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Abstract: This study presents the use and comparison of various bio-inspired algorithms for optimizing the response of a PID controller for a Brushless DC Motor in contrast to the conventional methods of tuning. For the optimization of the PID controllers Genetic Algorithm, Multi-objective Genetic Algorithm and Simulated Annealing have been used. PID controller tuning with soft-computing algorithms comprises of obtaining the best possible outcome for the three PID parameters for improving the steady state characteristics and performance indices like overshoot percentage, rise time and settling time. For the calculation and simulation of the results the Brushless DC Motor model, Maxon EC 45 flat ф45 mm with Hall Sensors Motor has been used. The results obtained the optimization using Genetic Algorithms, Multi-objective Genetic Algorithm and Simulated Annealing is compared with the ones derived from the Ziegler-Nichols method and the MATLAB SISO Tool. And it is observed that comparatively better results are obtained by optimization using Simulated Annealing offering better steady state response.

Keywords: Brushless DC motor, controller tuning, genetic algorithm, PID controllers, PID optimization, simulated annealing, ziegler nichols

INTRODUCTION

The generic dc motors have high efficiency and have a high starting torque versus falling speed characteristics, which helps to counter the sudden rise in load and thus find their application in industries since ages (Katal et al., 2012). Since dc motors suffer from the deficiencies like:

- The lack of periodic maintenance
- Mechanical wear-outs
- Acoustic noise
- Sparkling
- Brushes effect, etc., so, the current focus has adapted the development of brushless direct current models

The Brushless Direct Current (BLDC) motors are typically dc voltage driven permanent synchronous motors and are gaining grounds in aeronautics, medicine, consumer and industrial automation applications. The BLDC motors have better:

- Speed versus torque characteristics
- High efficiency
- High dynamic response
- Noiseless operation
- Low maintenance and many more (Padmaraja, 2003; Krause et al., 2002) and the best advantage in terms of higher ratio of torque obtained to the size of motor

Proportional, Integral and Derivative-PID controllers are playing an imperative role in the industrial control applications. Because of their simplicity and wide acceptability, they are still the best solutions for the industrial control processes (Åström et al., 2001). Modern industrial controls are often required to regulate the closed-loop response of a system and PID controllers account for the 90% of the total controllers used in the industrial automation. The simple block level representation of the PID controller based system can be obtained as in Fig. 1.

The general equation for a PID controller for the above figure can be given as Norman (2003):

\[ C(s) = K_p e(s) + K_i \int e(s)dt + K_d \frac{de(s)}{dt} \]

where,

\[ K_p, K_i \] and \( K_d \) = The controller gains
\[ C(s) \] = Output signal

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In this study, the optimization of the PID controller gains has been carried out using Genetic Algorithms (GA), Multi-Objective Genetic Algorithm (MOGA) and Simulated Annealing (SA) in contrast to the Ziegler-Nichols (ZN) method and the automated tuning provided in MATLAB viz. SISO Tool. Then, these gain parameters can be optimally tuned with respect to the objective function, stated as “Sum of the integral of the squared error and the squared controller output deviated from its steady-state” (Goodwin et al., 2001).

According to the results obtained in this paper, considerably better results have been obtained in the case of the Simulated Annealing (SA) when compared to those obtained by Genetic Algorithm, Multi-objective Genetic Algorithm, Ziegler-Nichols method and the MATLAB SISO Tool in respective the step response of the system.

**MATERIALS AND METHODS**

**Mathematical model of brushless DC motor:** In this study the model of a BLDC motor has been considered, unlike the dc motor, the commutation of the BLDC can only be done by electronic control (Padmaraja, 2003). The operation of BLDC motor can be realized in many modes (phases), generally 3 phases. The main advantage of 3-Phase is better efficiency and quiet low torque and has best precision in control (Texas Instruments).

In this study, 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 Kirchhoff’s Voltage Law (KVL), the following equation is obtained:

\[ V_s = R_i + L \frac{di}{dt} + e \]

where,

- \( V_s \) = The DC Source voltage
- \( i \) = Armature current

Similarly while considering the mechanical properties, Newton’s second law of motion gives the relative dependence of torque of the system as the product of the inertial load, \( J \) and the rate of angular velocity, \( \omega_m \), as:

\[ J \frac{d\omega_m}{dt} = \sum T_i \]

\[ T_e = k_f \omega_n + J \frac{d\omega_m}{dt} + T_L \]

where,

- \( T_e \) = Electric torque
- \( k_f \) = Friction constant
- \( J \) = Rotor inertia
- \( \omega_n \) = The angular velocity
- \( T_L \) = The supposed mechanical load
### Table 1: Parameters and units of maxon motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value at nominal voltage</td>
<td>V</td>
<td>12.000</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No load speed</td>
<td>Rpm</td>
<td>4370</td>
</tr>
<tr>
<td>No load current</td>
<td>mA</td>
<td>151</td>
</tr>
<tr>
<td>Nominal speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal torque</td>
<td>mNm</td>
<td>2860</td>
</tr>
<tr>
<td>Nominal current (max. continuous)</td>
<td>A</td>
<td>58.000</td>
</tr>
<tr>
<td>Nominal current (max. continuous)</td>
<td>mNm</td>
<td>2.140</td>
</tr>
<tr>
<td>Stall torque</td>
<td>mNm</td>
<td>255</td>
</tr>
<tr>
<td>Starting current</td>
<td>A</td>
<td>10.000</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>%</td>
<td>77.000</td>
</tr>
<tr>
<td>Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terminal resistance phase to phase</td>
<td>Ω</td>
<td>1.200</td>
</tr>
<tr>
<td>Terminal inductance phase to phase</td>
<td>mH</td>
<td>0.560</td>
</tr>
<tr>
<td>Torque constant</td>
<td>mNm/A</td>
<td>25.500</td>
</tr>
<tr>
<td>Speed constant</td>
<td>rpm/V</td>
<td>37.400</td>
</tr>
<tr>
<td>Speed/torque gradient</td>
<td>rpm/mNm</td>
<td>17.600</td>
</tr>
<tr>
<td>Mechanical time constant</td>
<td>Ms</td>
<td>17.100</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>gcm²</td>
<td>92.500</td>
</tr>
<tr>
<td>Number of phases</td>
<td>-</td>
<td>3.000</td>
</tr>
</tbody>
</table>

### Table 2: Parameters of the PID controller calculated by ziegler-nichols method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ziegler nichols PID parameters</td>
<td></td>
</tr>
<tr>
<td>$K_p$</td>
<td>0.3160</td>
</tr>
<tr>
<td>$K_i$</td>
<td>31.3000</td>
</tr>
<tr>
<td>$K_d$</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

### Table 3: Parameters of the PID controller calculated by SISO based automated designing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SISO tuned parameters</td>
<td></td>
</tr>
<tr>
<td>$K_p$</td>
<td>0.265000</td>
</tr>
<tr>
<td>$K_i$</td>
<td>17.867000</td>
</tr>
<tr>
<td>$K_d$</td>
<td>-0.000586</td>
</tr>
</tbody>
</table>

The electrical torque and the back emf can be obtained as:

$$e = k_e \sigma_m \quad \text{and} \quad T_e = k_e \sigma_m$$  \hspace{1cm} (4)

where, $k_e$ = The back emf
$\sigma_m$ = Torque constant

Thus the transfer function can be obtained by using the ratio of the angular velocity, $\omega_m$ to source voltage, $V_s$, as:

$$G(s) = \frac{k_e}{\tau_m \omega_m s^2 + \tau_m s + 1}$$  \hspace{1cm} (5)

Since the system is symmetrical and a three phase, thus constants used above in Eq. (5) can be given as:

$\tau_m$ = Time Constant and $\omega_m$ = (Time Constant):

$$\tau_m = \frac{R.3J}{k_e k_i} \quad \text{and} \quad \omega_m = \frac{L}{3.R}$$

The mathematical model of the Maxon BLDC motor (Sabudin, 2012) can be modelled on the parameters listed in Table 1.

Thus by using the above listed parameters, the value for $K_p$, $\tau_m$ and $\omega_m$ can be obtained as:

$\tau_m = 155.56 \times 10 - 6 \quad \text{Kgm}^2$; $\omega_m = 0.0171 \quad \text{and} \quad K_e = 0.763 \quad \text{v-sec/rad}$

Therefore, the transfer function $G(s)$ becomes:

$$G(s) = \frac{13.11}{2.66 \times 10^{3} s^2 + 0.0171 s + 1}$$  \hspace{1cm} (6)

Equation (6) gives us the open-loop transfer function for the Brushless DC Maxon Motor.

### Design of the PID controllers:

#### Tuning of PID gains using ziegler nichols:
One of the most widely used method for the tuning of the PID controller gains is to use the open loop response as inferred by Ziegler-Nichols (ZN), yet this method finds its in application till the ratio of 4:1 for the first two peaks in the closed loop response (Goodwin et al., 2001), which leads to a oscillatory response of the system.

Initially, the unit step function (Fig. 3 and 4) is derived and hence as suggested by the Ziegler-Nichols, the parameters required can easily be estimated as given in Table 2.

#### MATLAB SISO automated designing:
The SISO tool accelerates the PID controller design by its GUI based interactive compensator tuning. The tuning can be done interactively by balancing the poles and zeros on Bode or root-locus plots, or can be optimized by meeting the pre-defined time and frequency domain requirements by the system. The SISO tuned PID controllers for the BLDC Motor can be seen in the Fig. 5 (Table 3).
The steps involved in the implementation of the Genetic Algorithms for a control system are as follows:

- Generating the initial, random population of the fixed numbered individuals for the declaration of the initial ranges for $K_p$, $K_i$, and $K_d$
- For the evaluation of the fitness integral it minimizes the integral square error, followed by the selection of the fittest individuals of the population
- Reproduction among members of population
- Crossover of the reproduced chromosome followed by the mutation operations and the selection of the best individuals i.e., Survival of the Fittest
- Looping the step 2 till the pre-defined convergence is obtained

The optimization of the system has been designed and simulated in MATLAB and Genetic Algorithm toolbox, with population size of 100, scattered crossover and migration direction in both sides. Table 4 shows the GA optimized PID parameters and Fig. 6 shows the GA-PID step response of the system.

**PID controller optimization using multi-objective genetic algorithm:** Optimization of PID’s using multi-objective genetic algorithm aims at using the controlled elitist genetic algorithm which boosts obtaining the better fitness value of the individuals and if the fitness value is less, it still favors increasing the diversity of the population (Deb, 2001). Diversity is controlled by the elite members of the population; elitism is controlled by Pareto fraction and at Pareto Front also bound the number of individuals. Optimization of the PID controllers using Multi-Objective Genetic Algorithm aims at improving the objective function of the both the objectives used by obtaining an optimal Pareto solution. In this study, two objective functions have been used F1 (ITSE) and F2 (OS %):

$$\text{ITSE} = \alpha \int_0^t |e(t)|^2 \, dt \quad \text{and}$$

$$\text{Overshoot \%age} = 100 \times e^{\left(\frac{\pi}{\sqrt{1-\zeta^2}}\right)}$$

where,

$\zeta = \text{The Damping ratio}$

First objective function ITSE i.e., Integral Time Square Error tries to minimize the larger amplitudes by suppressing the persistent larger errors (Jean-Pierre, 2004) while second objective function overshoot percentage; thus forcing the solution towards the global best solution.

The system implementation and optimization has been carried out in MATLAB and SIMULINK.
PID controller optimization using simulated annealing: Simulated annealing is a global optimization algorithm, as the name suggests, the muse comes from metallurgic annealing, which involves relation between the relation between the statical mechanics and multivariate optimization (Berrsimas, 1993). It follows the technique involving heating the material followed by controlled cooling, fetching increased crystal size and reduced deformities.

The population size of 45 has been considered, with adaptive feasible mutation function, heuristic crossover and the selection of individuals on the basis of tournament with a tournament size of 2. A hybrid function of Fitness Goal Attain ($f_{goalattain}$) is used which further minimizes the function after GA terminates. After the optimization the PID parameters are shown in Table 5 along with the controller response in Fig. 7 and 8.

In Simulated Annealing (SA), at each iteration, a new point is randomly generated and its distance from the current point is the function of probability distribution with a scale proportional to temperature. The randomly generated points are accepted if they lower the objective but in order to help the algorithm to search for global solution and to omit the trapping of the algorithm in local minima, some points are so chosen that they raise the objective. With the advent of algorithm, the temperature is decreased leading in reduction of the extent of search to converge the minima.

The optimization has been carried out in MATLAB environment using Global Optimization Toolbox. The population size of 45 has been considered, with adaptive feasible mutation function, heuristic crossover and the selection of individuals on the basis of tournament with a tournament size of 2. A hybrid function of Fitness Goal Attain ($f_{goalattain}$) is used which further minimizes the function after GA terminates. After the optimization the PID parameters are shown in Table 5 along with the controller response in Fig. 7 and 8.

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RESULTS AND DISCUSSION

In this study, a dynamic model of a Maxon BLDC Motor has been designed and implemented in

Table 7: Comparison of the results

<table>
<thead>
<tr>
<th>Methods of design</th>
<th>Overshoot (%)</th>
<th>Tr (sec)</th>
<th>Ts (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ziegler-nichols method</td>
<td>11.50</td>
<td>0.008690</td>
<td>0.011400</td>
</tr>
<tr>
<td>MATLAB SISO tool</td>
<td>5.88</td>
<td>0.006230</td>
<td>0.018900</td>
</tr>
<tr>
<td>Genetic algorithm</td>
<td>0.00</td>
<td>0.000643</td>
<td>0.001319</td>
</tr>
<tr>
<td>Multi-objective genetic</td>
<td>0.00</td>
<td>0.000560</td>
<td>0.001040</td>
</tr>
<tr>
<td>algorithm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated annealing</td>
<td>0.00</td>
<td>0.000542</td>
<td>0.000888</td>
</tr>
</tbody>
</table>
MATLAB along with the optimization using the various bio-inspired algorithms like Genetic Algorithm, Multi-objective Genetic Algorithm and Simulated Annealing. The value of parameters obtained using Ziegler-Nichols rules (Ziegler and Nichols, 1942) were used in the formation of the boundary limits for the intervals for the design parameters in soft-computing algorithms, to control the controller by minimizing the error and hence the determination of the optimum parameters for the plant.

The computation of the PID parameters is done by the Ziegler-Nichols rules, SISO Design Tool, Genetic Algorithms, Multi-objective Genetic Algorithm and Simulated Annealing and their closed loop step responses are shown in Fig. 4 to 9. Figure 11 shows the comparative response of all the controllers over a single plot and Fig. 12 shows the comparative values of the various steady-state parameters. Table 7 shows the numeric comparison of the results of various steady-state parameters. From Table 7 and Fig. 11 and 12, it’s clearly evident that Simulated Annealing solutions present zero oscillatory response and reduced rise and settling times in contrast to the Ziegler-Nichols, SISO, Genetic Algorithm and Multi-objective Genetic Algorithm. Concluding, Simulated Annealing offers superior results in terms of system performance and controller output for the tuning of PID controllers.

CONCLUSION

The use of Simulated Annealing for optimizing the PID controller parameters as presented in this study offers advantages of decreased overshoot percentage, rise and settling times for the Maxon EC flat φ45 mm, brushless, 30 Watt motor. Results when compared with the other tuning mythologies as presented in this study, the Simulated Annealing has proved superior in achieving the steady-state response and performance indices.

REFERENCES