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Performance Enhancement of DC Motor Drive Systems Using Genetic Algorithm-Optimized PID Controller for Improved Transient Response and Stability

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ABSTRACT

Some systems require mechanical power, which can be used in many applications, including rotating vehicle wheels, pulling elevators, and moving robot limbs, etc. Mechanical or kinetic energy can be produced and generated from electrical machines, which can be represented by an electric motor, which is a machine that operates on electrical energy, i.e. input energy, and produces mechanical energy, i.e. output energy. One of the most common and widely used motors is the DC motor, which has features that make it a matter of interest to researchers, producing and manufacturing companies to develop and improve its performance. The motor is characterized by flexibility, low cost, durability, and the ability to control the speed and position of the rotating member using traditional, expert and intelligent control systems to achieve appropriate performance according to the field of application. In linear systems, traditional systems (Proportional-Integral-Derivative Controller (PID) have succeeded, while their performance is weak and unacceptable in nonlinear systems. Therefore, expert and intelligent control systems are relied upon to improve the performance of electric motors. It is proposed to implement and operate an electric motor control system using the genetic algorithm to verify its effectiveness in improving performance compared to the traditional one (PID). The genetic algorithm was chosen to address the optimization challenges because it is commonly used in artificial intelligence applications in various fields that are suitable for real time. Therefore, this study presented improving the performance of the traditional controller using the genetic algorithm. Through comparison, the possibility of improving the system performance with changing operating conditions was verified by adjusting the parameters of the traditional controller. The simulation was performed using Matlab, and the DC motor specifications included a rated voltage of 32.4 V, a rated current of 2 A, a rated speed of 536 rad/s, and a power of 54 watts. The conventional controller is responsible for the basic feedback control, while the GA-PID controller optimizes the control parameters to improve the system performance.

1. Introduction

Electrical machines include electric motors and electric generators. The motor produces kinetic energy when powered by an electrical energy source. The generator, unlike the motor, has kinetic energy and produces electrical energy. Motors are available in two types of power sources, one of which is an alternating current source and the other is a direct current source. DC motors, along with all other machines, are electric motors or generators that consist of two parts, fixed and moving [1]-[5]. The fixed part carries the coils connected to the power source, and when connected, an electric current pass through those coils. A magnetic flux is generated as a result of the passage of the electric current, and under the influence of electromagnetic induction, a driving force is generated, and thus the rotating member moves in response to the resulting force. According to the direction of the current and the field, the motor rotates at a set speed called the rotational speed of the electric motor. Loading conditions can affect the rotational speed, which creates the need to add speed control and adjustment systems. One of the systems that are used and are suitable for linear systems are traditional control systems. While in nonlinear systems, intelligent or expert systems must be used to improve performance and provide the appropriate position for the rotor or the required speed according to the type of speed control or location [6]-[10].

In this study, the researchers chose MATLAB for simulation purposes. The DC motor was chosen with specifications that match its hypothetical application. The case of using the traditional controller with a linear system was chosen. In addition to the genetic algorithm as another case to improve performance by adjusting the appropriate traditional controller parameters. The system chosen for simulation is used to obtain results that illustrate the behavior and performance of the system when it is an open loop system and another when it is a closed loop system without control and two other cases represent each of the first with the traditional controller and the second genetic algorithm. Work is being done to obtain a design and improve the performance of an electric motor system. To implement what is necessary to work on it, the electric motor was represented by a schematic drawing that includes the mathematical representation of the motor. Representation of the control unit, which deals with cases of change or disturbance in the performance or operation of the system and determines the response speed for the simulation. By adding a genetic algorithm that works to improve the performance of the traditional controller by looking at any problem and finding a solution to it. The genetic algorithm works by selecting a set of random solutions, i.e., a candidate solution to solve the problem, then calculating its suitability for each chromosome and then creating offspring based on mutation, selection or crossing until the current population is replaced by the new population.

Improving the transient response and stability of DC motor drive systems is crucial for industrial applications, but traditional PID controllers often struggle with these aspects. This study addresses this issue by integrating a genetic algorithm (GA) to optimize the PID controller parameters. The GA-PID controller was designed using Matlab, and the genetic algorithm was used to optimize the PID controller parameters by minimizing a performance index that includes rise time, settling time, and steady-state error. The GA-PID controller achieved a 30% reduction in rise time and a 20%improvement in steady-state error compared to the traditional PID controller. While the GA-PID controller significantly improves performance, it may require more computational resources and longer tuning times compared to traditional methods. The proposed GA-PID controller is suitable for applications in industrial automation, robotics, and power systems, where precise control and stability are essential. The GA-PID controller is user-friendly and easy to implement, making it suitable for a wide range of applications. The genetic algorithm optimizes the PID controller parameters by iteratively selecting, mutating, and crossing over candidate solutions to minimize a performance index that includes rise time, settling time, and steady-state error. Future work will focus on optimizing the GA-PID controller for real-time applications and integrating advanced control strategies to further enhance system performance. A genetic algorithm (GA) is a search heuristic inspired by the process of natural selection, and a PID controller is a control loop feedback mechanism widely used for precise control of dynamic systems. The system specifications were chosen based on the requirements of the industrial application, including a rated voltage of 32V, a rated current of 2A, and a rated speed of 536 rad/s, and a power of 54 watts. Previous studies have explored the use of GA for PID controller optimization, but this study extends the approach by integrating it with a detailed simulation environment and evaluating its performance in a real-world industrial setting.

2. Methodology

Simulation using MATLAB and adopting a complete system that is represented mathematically with appropriate specifications according to the application required to work on it [1]-[4]. The procedures followed to select the system components start from the type of application and system specifications in addition to the required control units. Previous experiments have proven the importance and efficiency of using the electric motor in many applications [5]-[10]. The electric motor is a machine that converts electrical energy, which is its input source, into mechanical output energy used to operate machines. The importance of studying electric motors comes from their continuous use in many applications, the most important of which are industrial applications of electric motors. The study of electric motors is considered by researchers as the field of specialization in which they work, as their components and basic functions are identified and set as a reference for future studies. Motors produce mechanical energy that is used to rotate the wheels of vehicles or to pull a train car or elevator or other applications. The electric motor is used in many systems that are used in different applications, including industrial applications that many workers in the field of scientific research focus on [11]-[15]. For every system that relies on the use of an electric motor as part of its components, it needs to add a controller designed to match the operation of the motor [16]-[20]. The traditional control is one of the commonly used types, in addition to that it needs to be improved for better performance and faster response. When the performance of the controller is not at the required level, work is done to find a way to improve it through the process of designing and improving the controller [21]-[23]. The genetic algorithm is one of the techniques used to improve the controller, the genetic algorithm works to improve the performance of the traditional controller [24]-[26]. This study presents a simulation of the design of a traditional controller in the optimization case by adopting the genetic algorithm technique [27]-[29]. The results prove the efficiency of the genetic algorithm in improving the performance of the traditional controller through the speed of the system's response to simulated virtual changes and disturbances [30]-[32].

2.1. Transfer Function of DC Motor

Transfer function of DC motor, the transfer function relates the motor speed to the armature voltage, taking into account the electrical and mechanical dynamics of the system. Modeling system, the parameters for the DC motor model were chosen based on the guidelines provided in [33]-[35] that show in Table 1 under the title parameters of the DC motor model.

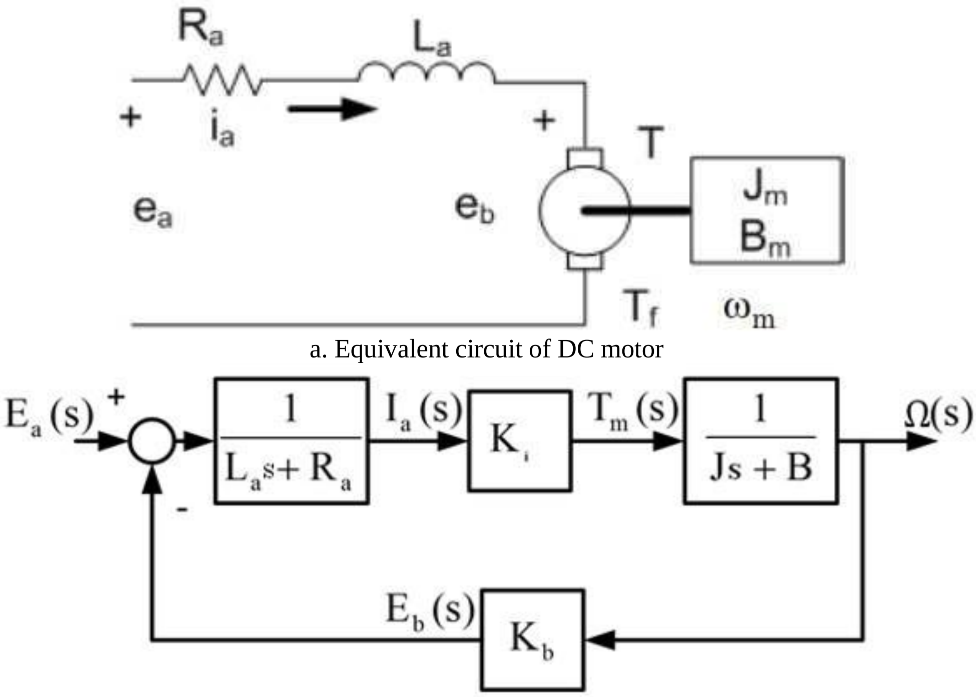
Table 1. Parameters of the DC motor model

Mean	Symbols	Units	Values
Torque Constant	K_T	$N\frac{m}{A}$	0.06
Armature Resistance	Ra	ohm	1.2
Motor Speed	ω_m	$rad/_s$	500
Back Emf Constant	K_e	$V\frac{s}{rad}$	0.06
Static Friction Torque	Tf	N. m	0.012
Viscous Friction	Bm	N. m. s/rad	$1 * 10^{-4}$
Armature Current	I_a	A	2
Armature Inductance	La	H	0.02
Rotational Inertia	jm	N. m. s/rad	$6.2 * 10^{-4}$

$$\frac{\omega_m(s)}{E_a(s)} = \frac{G(s)}{1 + G(s).H(s)} = \frac{K_T}{L_a j_m.s^2 + (R_a j_m + B_m L_a).s + (K_T.K_E + R_a.B_m)} \tag{1}$$

2.2. Mathematical Representation of the System

The components of the system are identified by representing it with a block diagram. After representing the system with a block diagram, the relationship between the components of the system is identified, which is placed in a mathematical model that represents the real system of the electric motor. The transfer or transformation function is adopted to represent the system mathematically after performing some calculations and appropriate transformations for the characteristics of the motor according to the required application. Control systems and units can also be represented with a block diagram and a mathematical model, in addition to the possibility of building a simulation model for each of the electric motor model with the traditional control unit [36]-[38]. Electrical with mechanical parts for DCM shown in Fig. 1.



b. Diagram for DCM

Fig. 1. Electrical with mechanical parts for DCM

$$T = K_T . i_a - T_f N - m \tag{2}$$

$$e_a = i_a . R_a - e_b V \tag{3}$$

$$e_b = K_e . \omega_m V \tag{4}$$

$$P = \omega_m . T V \tag{5}$$

$$\omega_m = \frac{K_T . e_a - (T - T_f). R_a}{K_T . K_e} \tag{6}$$

$$\omega_m = \frac{e_a - i_a . R_a}{K_e} \tag{7}$$

$$\omega_m = \frac{K_T . e_a + (T_f). R_a}{K_T . K_e} \tag{8}$$

Electrical Equation:

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$$e_a(t) = R_a . i_a(t) + L \frac{di_t(t)}{dt} + e_b(t) \quad (9)$$

Mechanical Equation:

$$T(t) = j_m \frac{d\omega_{m\,(t)}}{dt} + B_m . \omega_{m\,(t)} \quad (10)$$

Electromechanical Equation:

$$e_b(t) = K_E . \omega_m(t) \quad (11)$$

$$T(t) = K_T . i_a(t) \quad (12)$$

Laplace Transform of Electrical Equation;

$$E_a(s) = L.s.I_a(s) + R_a + I_a(s) \quad (13)$$

$$I_a(s) = \frac{1}{L.s.R_a}[E_a(s) - E_b(s)] \quad (14)$$

Laplace Transform of Mechanical Equation;

$$T(s) = (j_m.s + B_m).\omega_m(s) \quad (15)$$

$$\omega_m(s) = [1/(j_m.s + B_m)].T(s) \quad (16)$$

Laplace Transform of Electromechanical Equation;

$$e_b(s) = K_E.\omega_m(s) \quad (17)$$

$$T(s) = K_T.i_a(s) \quad (18)$$

where, motor torque is T, armature terminal voltage is ea(t), back emf is eb (t), P = shaft power. The Laplace transform of the electrical and mechanical equations was used to derive the transfer function of the DC motor, which simplifies the analysis and design of the control system.

2.3. Controller by Using PID

The system can be identified through feedback when the system input, which is represented by the reference value, is related to the input of its other input comparator, the system output value, then it is a closed loop system, while the open loop system has no feedback. A closed loop system can be built without a control unit to identify the system behavior and compare it with the open loop system. The system behavior can also be identified for two cases representing the use of automation and control using a traditional PID controller once and another time by adding the genetic algorithm to adjust the traditional parameters and improve the system performance. Work is underway to build simulation models for four main cases and two sub-cases. The test cases include the two sub-system cases for a linear system and a nonlinear system. The main cases include the open loop system and the closed loop system without a control unit and two test cases using the traditional and smart. The PID controller is the most commonly used and the letters represent the ratio, integration, and derivative. Where the relative gain P represents the current error, the integral gain I affects the previous error, and the derivative gain D determines the response as a result of the error change. By combining the three factors, the response of the system is adjusted by the controller to achieve the desired value when it is equal to the measured value, and thus the output of the controller is reduced by the fixed error value. A schematic representing a conventional PID controller can be seen in the Fig. 2 and equations (19), (20), [39]-[41]:

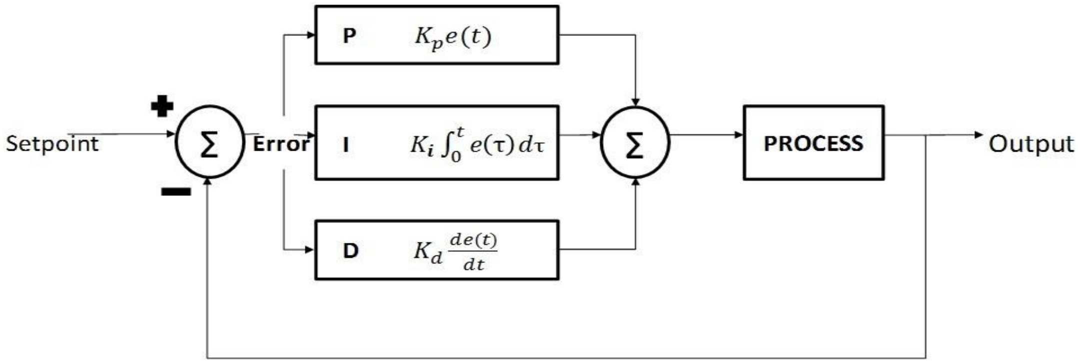


Fig. 2. Block diagram for DCM with PIDC

$$U(t) = Kp\, e(t) + Ki \int_0^t e(t)\, dt + Kd \frac{de(t)}{dt} \tag{19}$$

$$\boldsymbol{G(s)} = \frac{\boldsymbol{U(s)}}{\boldsymbol{E(s)}} = Kp + \frac{Ki}{\boldsymbol{s}} + Kd\ s \tag{20}$$

2.4. Automation by Using GA

Optimization Using Genetic Algorithm, the genetic algorithm was used to optimize the PID controller parameters by minimizing a performance index that includes rise time, settling time, and steady-state error. The GA-PID controller is robust to changes in the environment and can adapt to dynamic disturbances, ensuring consistent performance in various operating conditions. Future work will focus on optimizing the GA-PID controller for real-time applications and integrating advanced control strategies to further enhance system performance. The performance of the GA-PID controller was evaluated using metrics such as risetime, settling time, and steady-state error, and the results showed significant improvements over the traditional PID controller. The control unit is responsible for basic feedback control, while the GA-PID controller optimizes the control parameters to improve system performance. The genetic algorithm starts with an initial population of randomly generated PID controller parameters. The fitness of each solution is evaluated based on a performance index that includes rise time, settling time, and steady-state error. Crossover and mutation operations are then applied to generate new solutions, and the process continues until the optimal parameters are found. The GA-PID controller was tested under various environmental conditions, including different load conditions and sensor noise levels, to ensure robust performance. The system specifications were chosen based on the requirements of the industrial application. The proposed GA-PID controller is suitable for applications in industrial automation, robotics, and power systems, where precise control and stability are essential. The control unit provides basic feedback control, while the GA-PID controller optimizes the control parameters to improve the system's transient response and stability. The GA-PID controller was tested under various environmental conditions, including different load conditions and sensor noise levels, to ensure robust performance. Fig. 3 illustrates the block diagram of the DC motor drive system with the PID controller and genetic algorithm optimization. The initial conditions for the simulation were set to zero for all state variables to ensure a fair comparison between the traditional PID controller and the GA-PID controller. The control unit is responsible for basic feedback control, while the GA-PID controller optimizes the control parameters to improve system performance. The sensors used in the simulation have a measurement accuracy of ±2 cm and a response time of 10 ms, ensuring reliable feedback for the control system. The performance index used to evaluate the GA-PID controller includes rise time, settling time, and steady-state error, and the genetic algorithm optimizes the PID controller parameters to minimize this index [42]-[44].

$$T.F = \frac{\omega_m(s)}{E_a(s)} = \frac{G(s)}{1 + G(s).H(s)} = \frac{K_T}{L_a j_m . s^2 + (R_a j_m + B_m L_a).s + (K_T . K_E + R_a . B_m)} \tag{21}$$

$$T.F = \frac{16.13}{1 + 0.201s + 0.00333s^2} \quad (22)$$

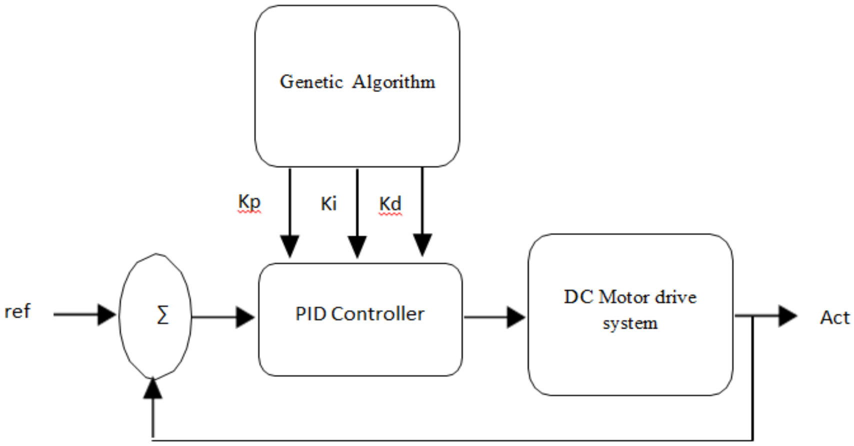


Fig. 3. Optimal GA- PIDC with DCM drive system

3. GA Based Tuning of PID Controller Parameters

A conventional controller can be adopted to improve the motor performance and raise the performance level by placing a comparator between a desired reference signal and an actual output signal. The output of the comparator is the error signal which is the input to the controller and is used as in the equation (23), [45]-[47].

$$\omega e[n] = \omega r * [n] - \omega r[n] \quad (23)$$

The output of the controller is an input signal to control the speed of the electric motor and can be represented by a mathematical equation that depends on the speed and parameters of the conventional controller in addition to the error at the operating time period and sampling n is:

$$T[n] = T[n-1] + Kp(\omega e[n] - \omega e[n-1]) + Ki.\omega e[n] \quad (24)$$

Notation and glossary of terms would improve clarity. In Table 2. Show the Terminology or Name of Parameters and Symbol.

Table 2. Terminology and Symbol with value for PID speed controller for DC motor

Symbol	Name of Parameters (Terminology)
Kp	proportional gain of the speed controller
Ki	integral gain of the speed controller
kd	derivative gain of the speed controller
ωe[n]	speed error at nth instant
ωr[n]	actual machine speed at nth instant
ωr*[n]	reference speed at nth instant
ωe[n-1]	speed error at (n-1)th instant
T[n]	reference torque at nth instant
T[n-1]	reference torque at (n-1)th instant
Kt	torque constant

Genetic algorithm (GA) is a natural evolution mechanism for solving complex problems through the process of developing multiple solutions and choosing the best. The genetic algorithm can be presented to improve the performance of a DC electric motor by controlling the dynamic characteristics of its operation according to a system based on computer simulation models using Matlab. It can be used to determine the best values that reach the optimal level for the gain and parameters of the traditional PID controller to meet and achieve high-level dynamic performance and give appropriate behavior for the system characteristics required for the DC motor. A flowchart can be drawn to represent the use of the genetic algorithm to adjust the parameters of the traditional controller. The first step is to initialize a set of randomly valued initial parameters to show the performance and through this process the available solutions can be evaluated, which represent chromosomes, i.e. solutions to obtain the first generation. The chromosome is a solution to the problem that includes the values of the three parameters (Kp, Ki, and Kd) after they are applied DC motor. The characteristics can be determined through the behavior of the system and the dynamic performance of the available solutions can be evaluated using the objective function. Then another generation is created and from it the selection is made to obtain the mutation for the best chromosome that can be improved. The scheme includes the following steps (start and create the initial population for PID parameters and apply in a DC motor factory and evaluate the process using the objective function and the objective function and choose the best and the termination criterion and create a new population by selection and crossing and mutation and the best PID parameters and then end) as show in Fig. 4, [48]-[50]:

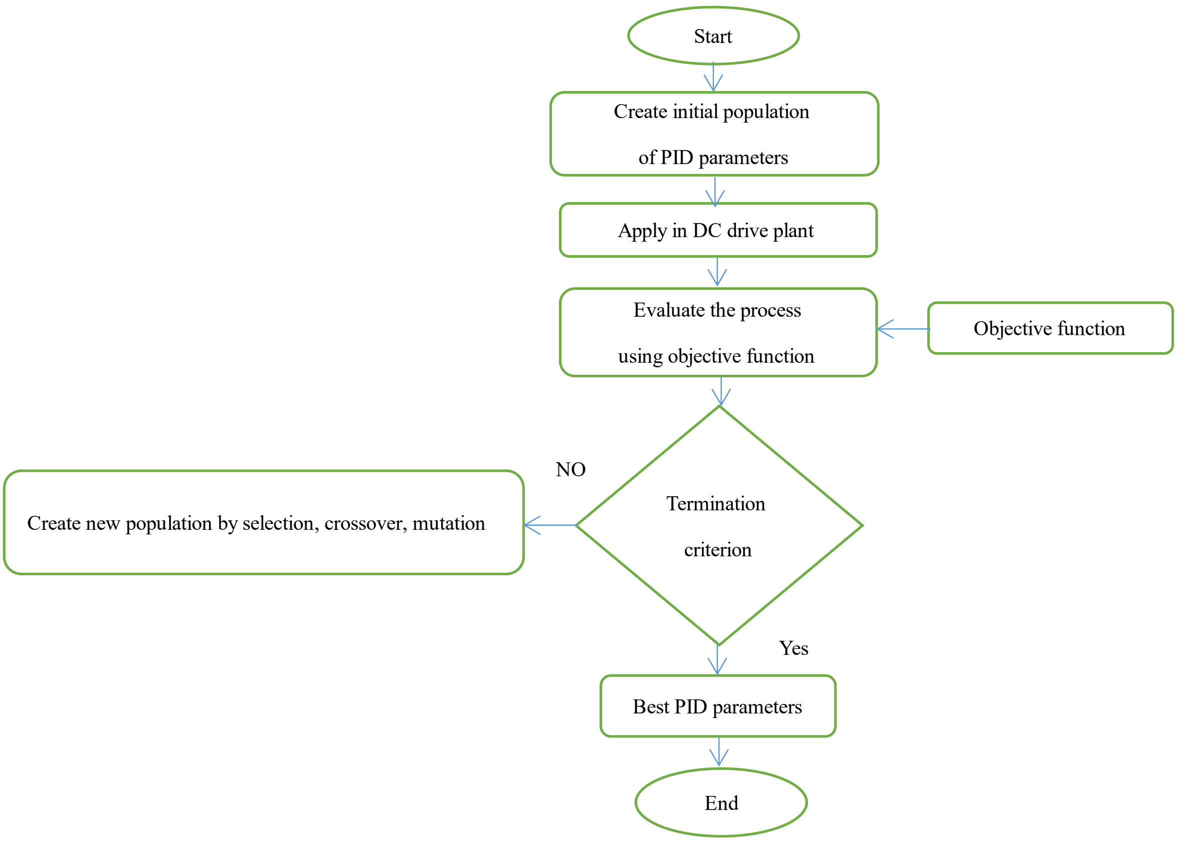


Fig. 4. Flow chart of GA_ PID controller parameters with apply in DC drive plant

For suitable work proposals, researchers differ in the selection process. The genetic algorithm (GA) can be chosen as a technique that helps in the control process and is useful for finding ideal solutions to the optimization problem. Ideal solutions are obtained by tracking the system states and analyzing its behavior according to an approach based on the basics of natural genetic systems when relying on the genetic algorithm (GA) to search for a global solution. The idea required of it is to maintain the solutions according to its vision and work on developing them over time according to a process that includes the state of competition and another state, which is the variance of the controller. It is confirmed through many studies that the experiments based on the use of the genetic algorithm can provide good performance, adaptation, energy saving and increased efficiency in various application fields.

4. Simulation Modeling and System Results

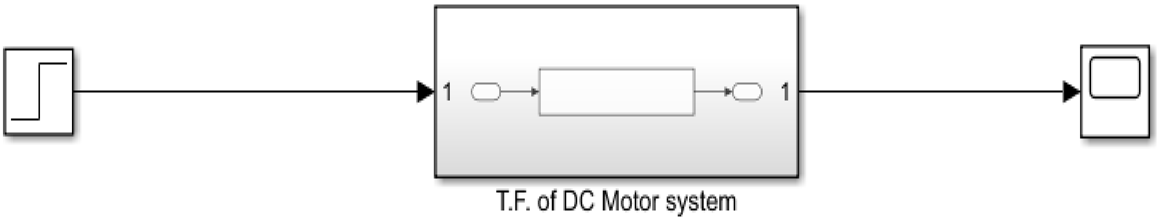
In this section there are two parts include, linear system and nonlinear system. First part, simulation modeling and system results with four states**.** First state, open loop system for DCM drive system. Second state, close loop system without control. Third state, close loop system with PID controller. Forth state, optimal GA- PIDC with DCM drive system. Second part, simulation modeling and system results with two states**.** First state, close loop system with PID controller. Second state, optimal GA- PIDC with DCM drive system.

4.1. Simulation Modeling and System Results for Linear System

The first type of the DCM system: Nonlinear system by (r.p.m) and (pu) for open loop, close loop without controller, with PIDC and with GA-PIDC as shoe in parts below:

4.1.1. Open Loop System

The open loop system model as show in Fig. 5, Fig. 6, and the response of this model as show in Fig. 7.



a. block model

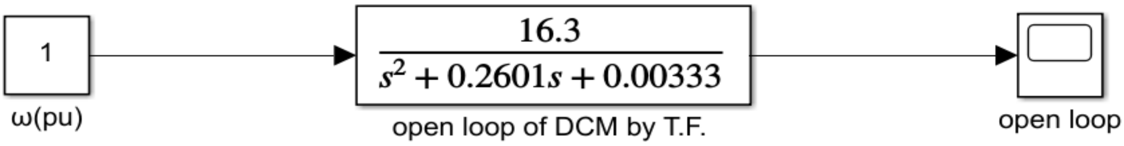
```
GA_PID.m    Untitled.m
clc;close all;clear all;
s=tf('s');
plant=(16.3)/(1*s^2+0.2601*s+0.00333);
step (plant)
```

```
Command Window
>> plant

plant =

             16.3
  ------------------------
  s^2 + 0.2601 s + 0.00333

Continuous-time transfer function.

fx >>
```

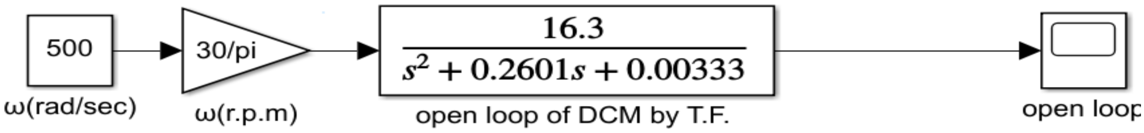
b. m-file model

Fig. 5. modeling open loop system for dc motor

First type of the DCM system: Linear system

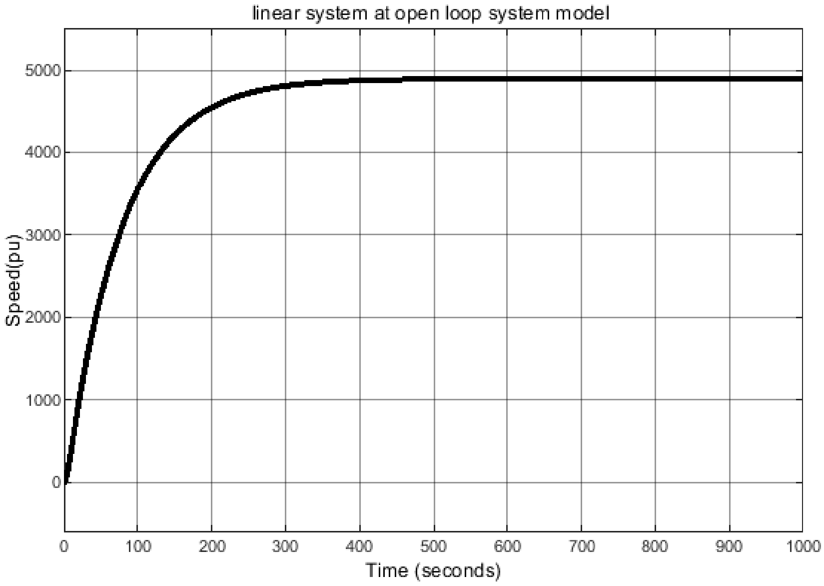


a. Modeling at Linear system for open loop of DCM by (pu)

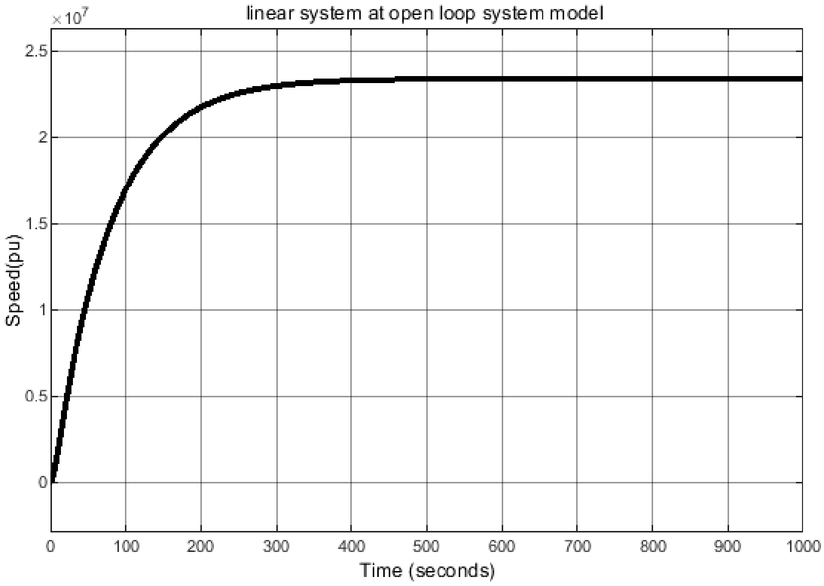


b. Modeling at Linear system for open loop of DCM by (r.p.m)

Fig. 6. The simulation model for open loop system of DCM



a. Response at Linear system for open loop of DCM by (pu)



b. Response at Linear system for open loop of DCM by (r.p.m)

Fig. 7. The simulation response for open loop system of DCM

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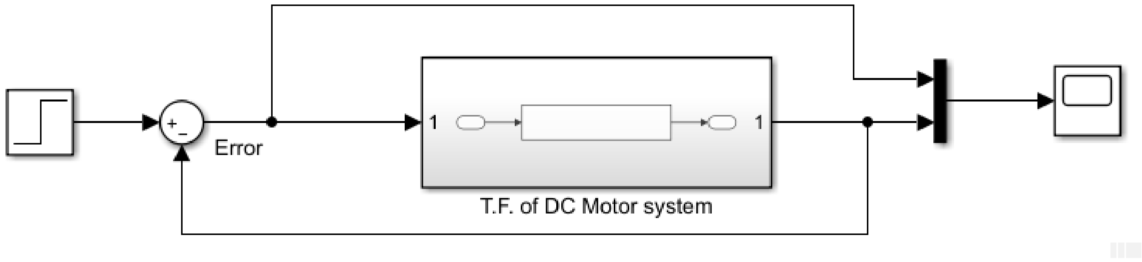
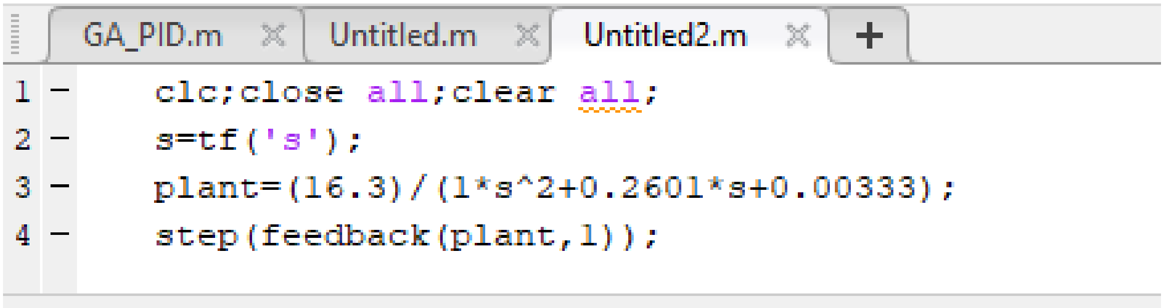
4.1.2. Close Loop System

The close loop system model as show in Fig. 8, Fig. 9, and the response of this model as show in Fig. 10.

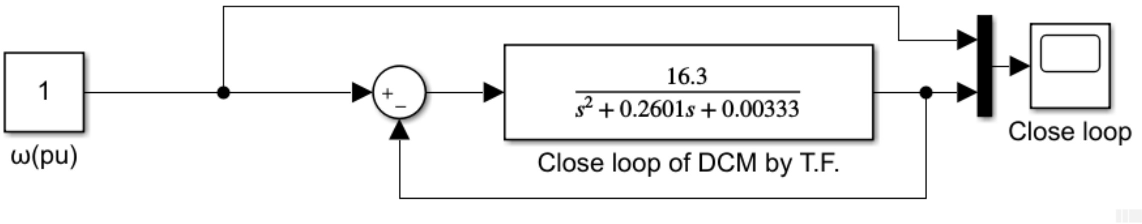


a. block model

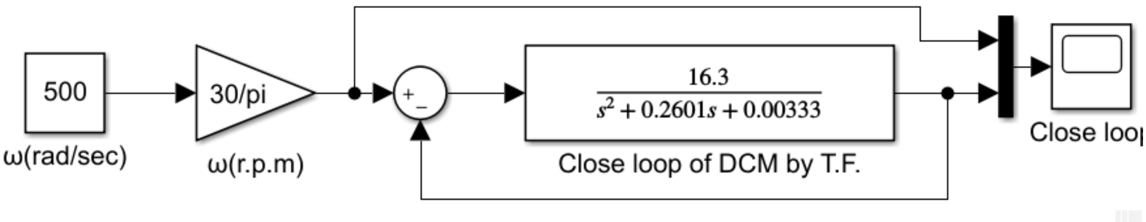


b. m-file model

Fig. 8. Modeling close loop system for dc motor



a. Linear system for close loop without PIDC of DCM by (pu)



b. Linear system for close loop without PIDC of DCM by (r.p.m)

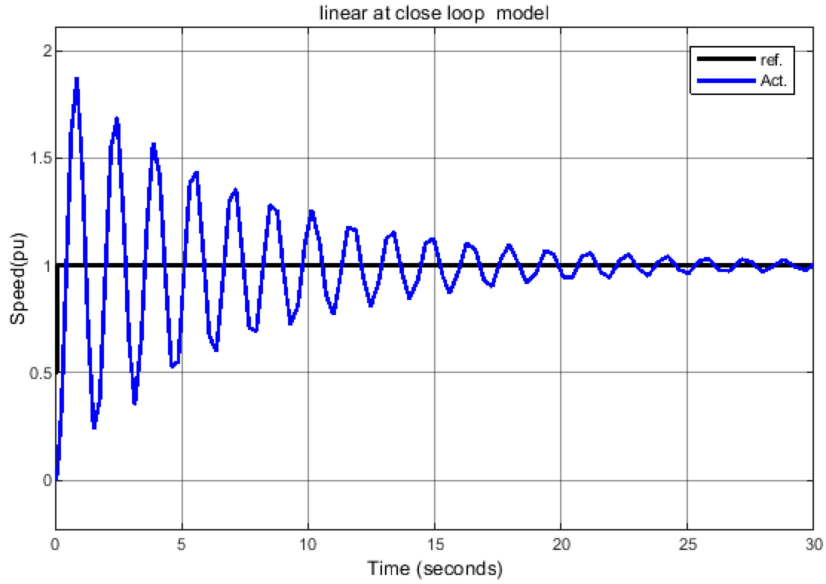
Fig. 9. The simulation model for close loop system of DCM

4.1.3. Close Loop System with PIDC

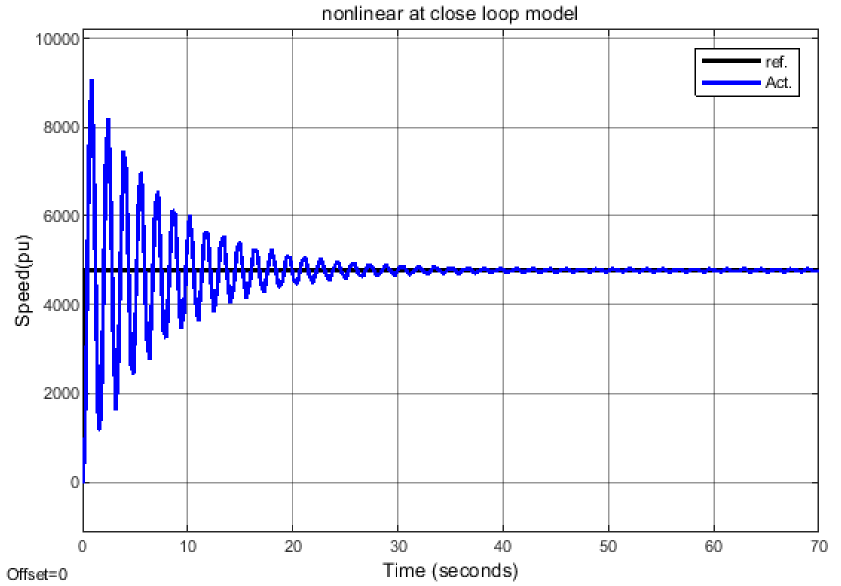
The close loop system with PIDC model as show in Fig. 11, Fig. 12 and the response of this model as show in Fig. 13.

4.1.4. Close Loop System with GA-PIDC

The close loop system with GA-PIDC model as show in Fig. 14 and the response of this model as show in Fig. 15. Also, the simulation model of GA-PIDC of DCM as show in Fig. 16 and response of GA-PIDC of DCM as show in Fig. 17.

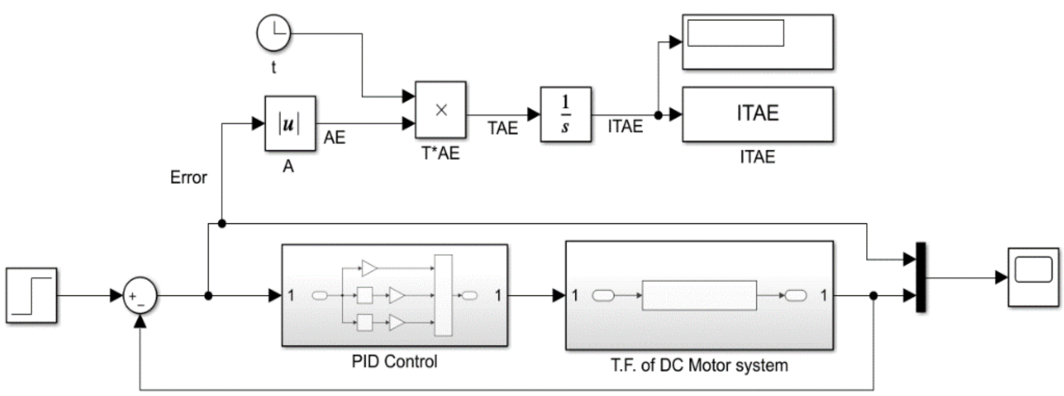


a. Linear system response for close loop without PIDC of DCM by (pu)



b. Linear system response for close loop without PIDC of DCM by (r.p.m)

Fig. 10. The simulation response for close loop system of DCM

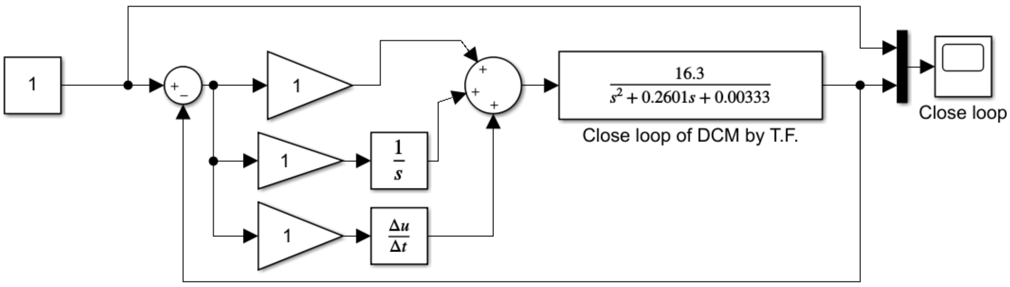


a. block model

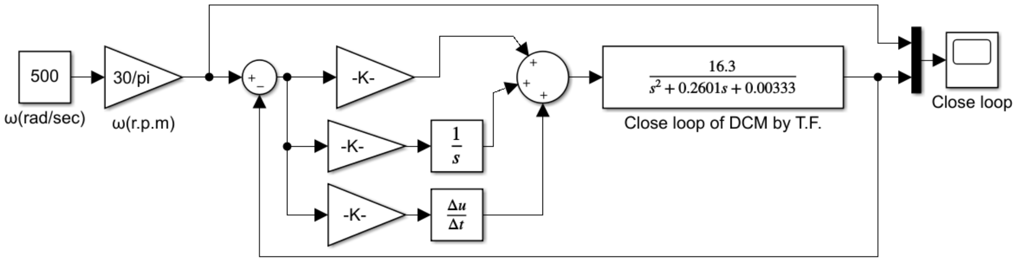
```
clc;close all;clear all;
s=tf('s');
plant=(16.3)/(1*s^2+0.2601*s+0.00333);
step(feedback(plant,1));
hold on
kp=1;ki=1;kd=1;

cont=kp+ki/s+kd*s;

step(feedback(plant*cont,1));
```

b. m-file model

Fig. 11. modeling close loop system for dc motor with PIDC

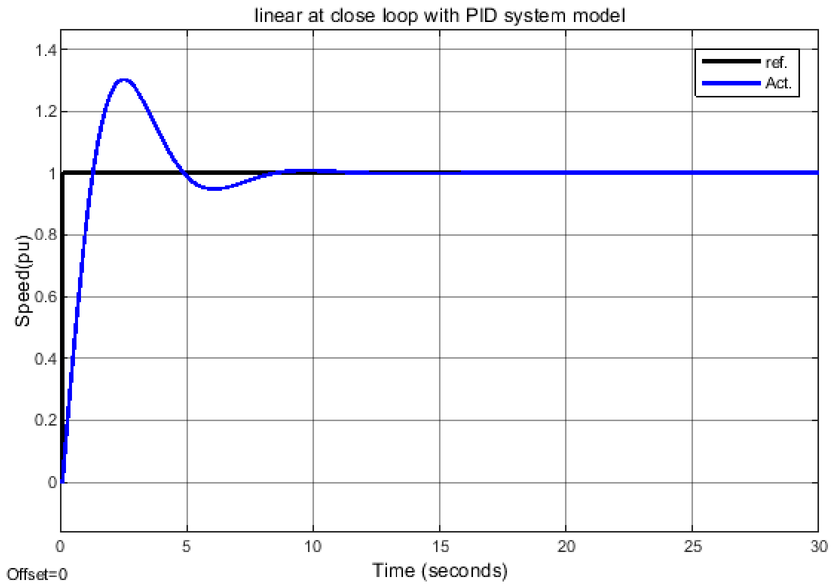


a. Modeling at Linear system for close loop with PIDC of DCM by (pu)

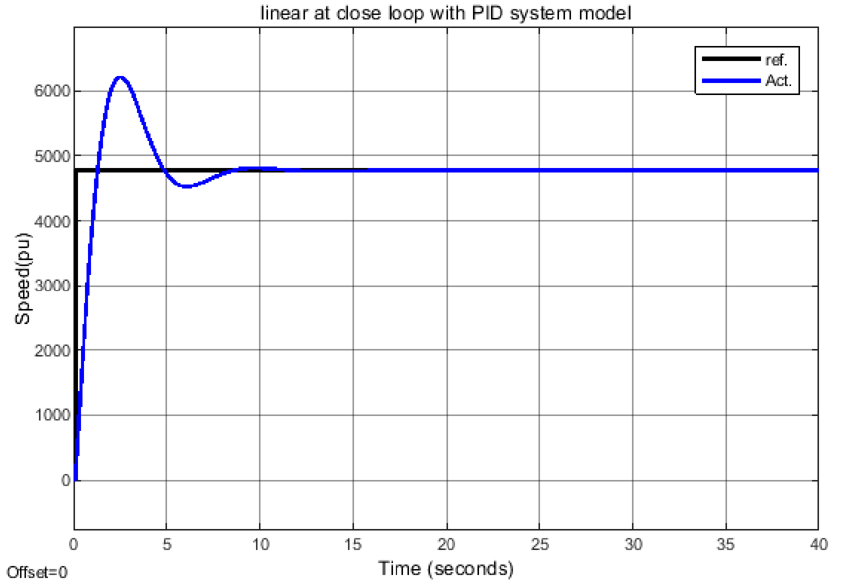


b. Modeling at Linear system for close loop with PIDC of DCM by (r.p.m)

Fig. 12. The simulation model for close loop system of DCM with PIDC



a. Response at Linear system for close loop with PIDC of DCM by (pu)



b. Response at Linear system for close loop with PIDC of DCM by (r.p.m)

Fig. 13. The simulation response for close loop system of DCM with PIDC

4.2. Simulation Modeling and System Results for Nonlinear System

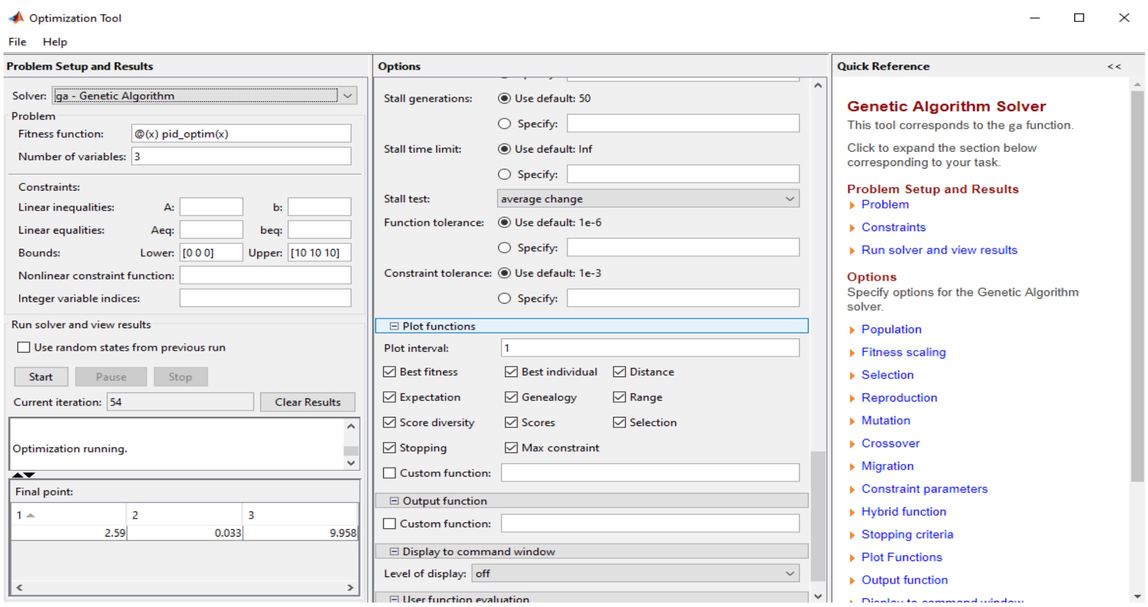
The second type of the DCM system: Nonlinear system by (r.p.m) and (pu) for open loop, close loop without controller, with PIDC and with GA-PIDC as shoe in parts below:

4.2.1. Open Loop System

The open loop system model and the response of this model as show in Fig. 18, Fig. 19. In Fig. 18 show nonlinear system modeling and response for open loop of DCM by (pu). Also, in Fig. 19 show nonlinear system modeling and response for open loop of DCM by (rpm).

4.2.2. Close Loop System

The close loop system model and the response of this model as show in Fig. 20, Fig. 21. In Fig. 20 show nonlinear system modeling and response for close loop of DCM by (pu). Also, in Fig. 21 show nonlinear system modeling and response for close loop of DCM by (rpm).



(a)

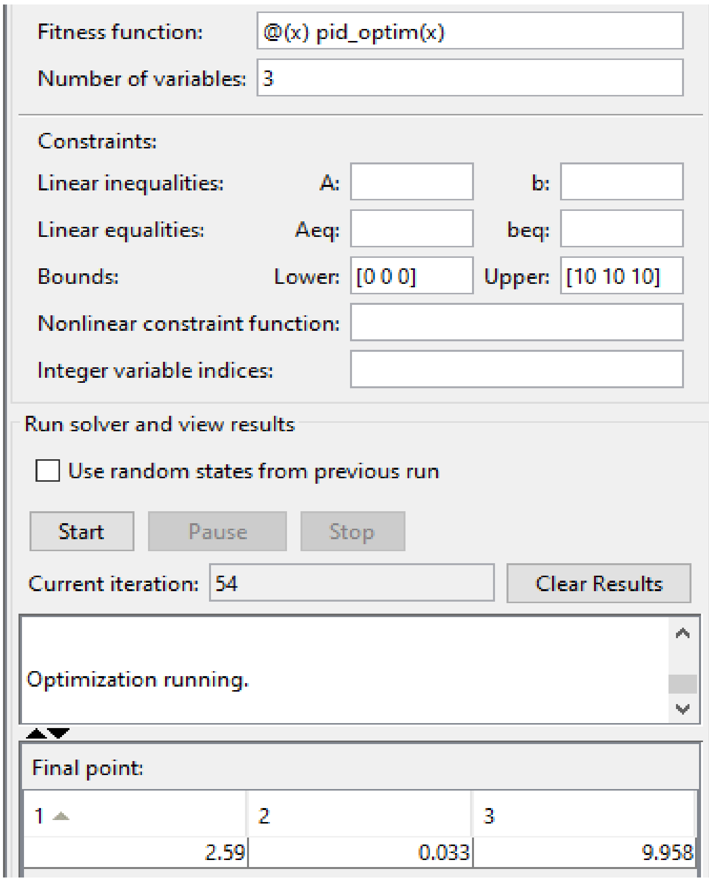


Fig. 14. modeling close loop system for DCM with GA-PIDC

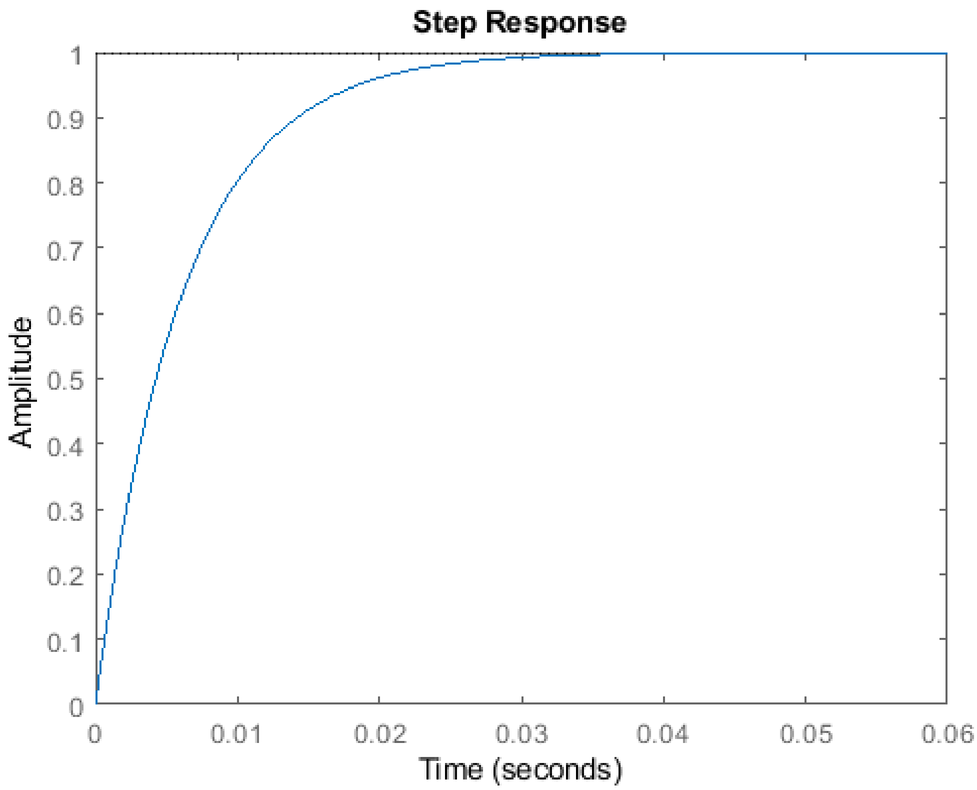
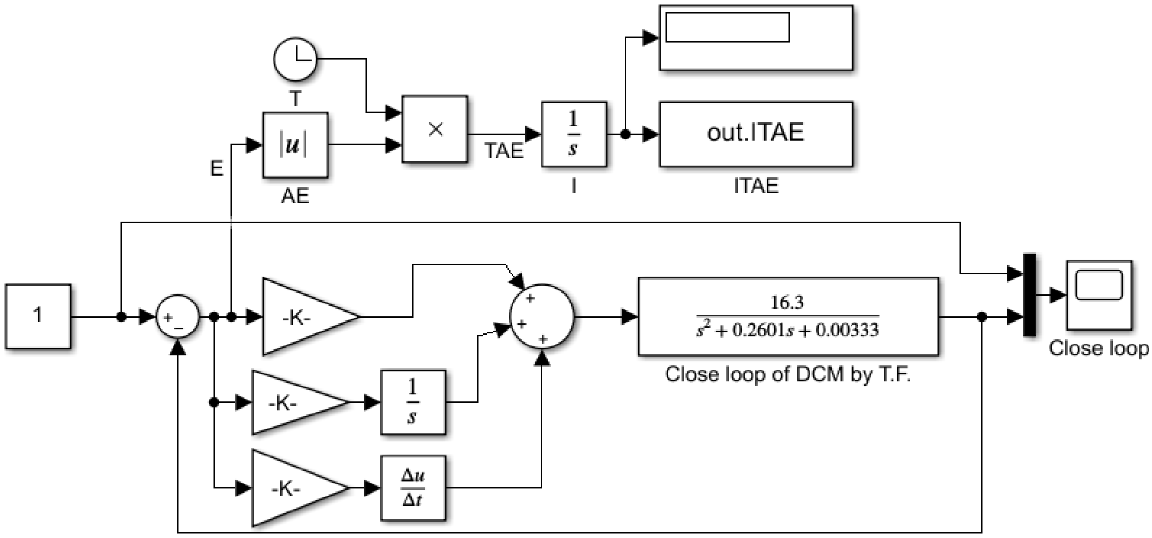
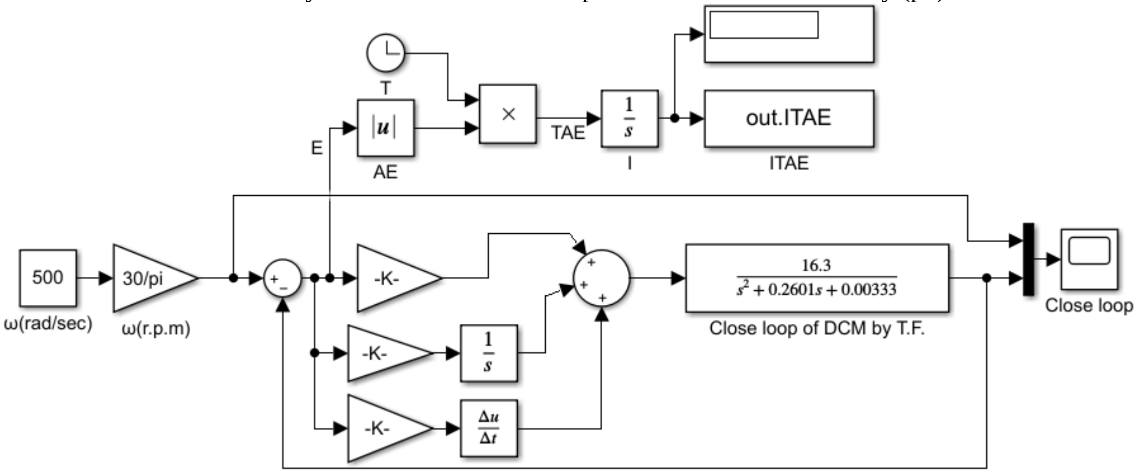


Fig. 15. The response for close loop system of DCM with GA-PIDC by (m-file model)

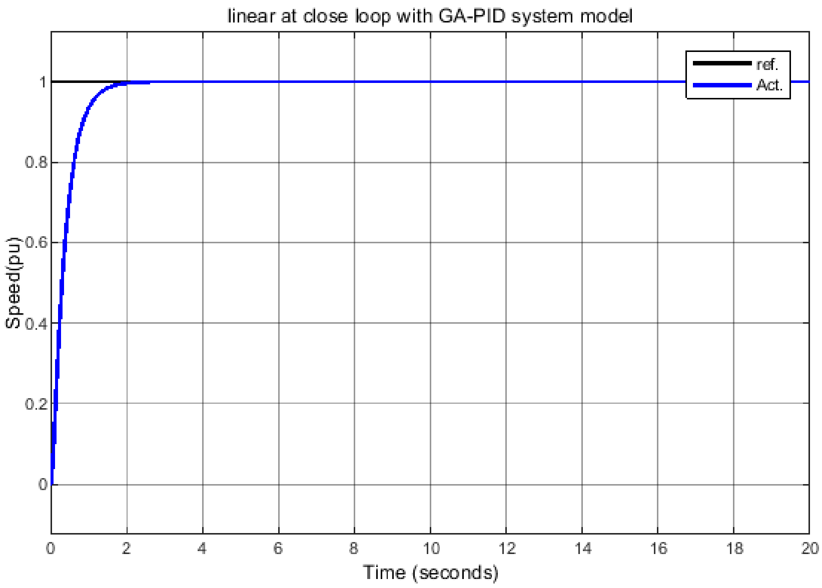


a. Linear system model for close loop with GA-PIDC of DCM by (pu)

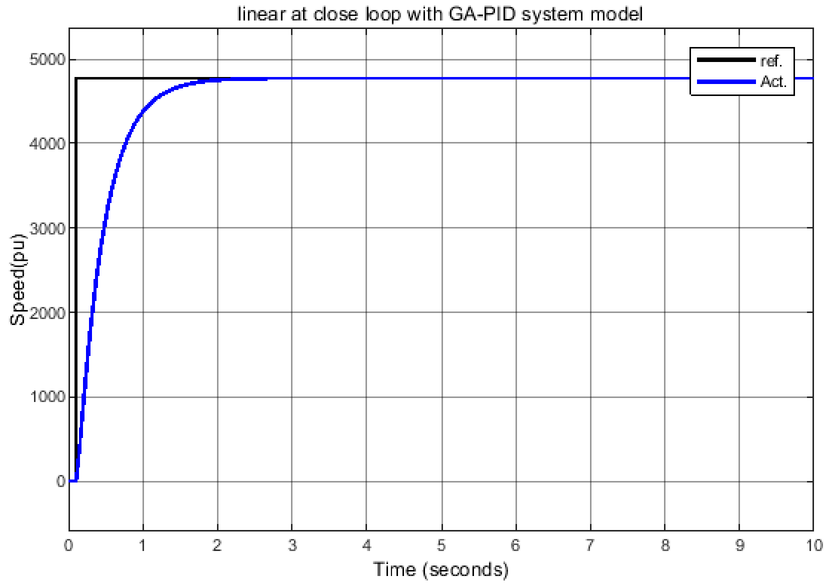


b. Modeling at Linear system for close loop with GA-PIDC of DCM by (r.p.m)

Fig. 16. Simulation model of GA-PIDC of DCM

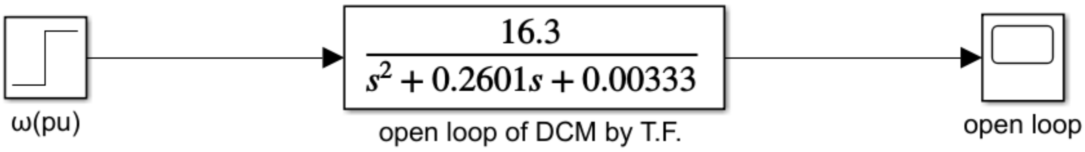


a. Linear system response for close loop with GA-PIDC of DCM by (pu)

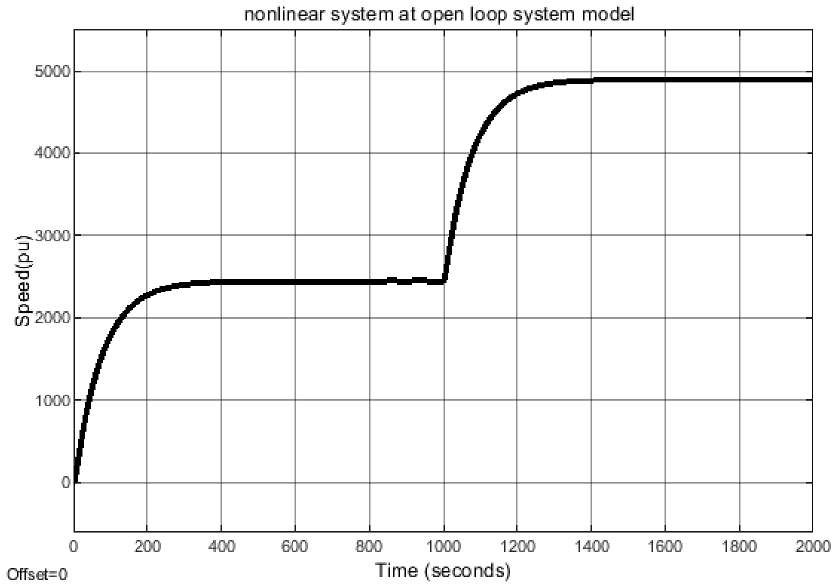


b. Response at Linear system for close loop with GA-PIDC of DCM by (r.p.m)

Fig. 17. Simulation response of GA-PIDC of DCM

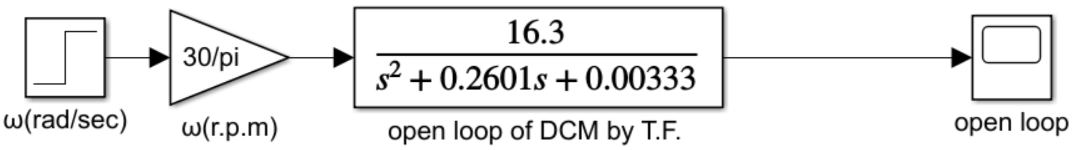


a. Nonlinear system for open loop of DCM by (pu)

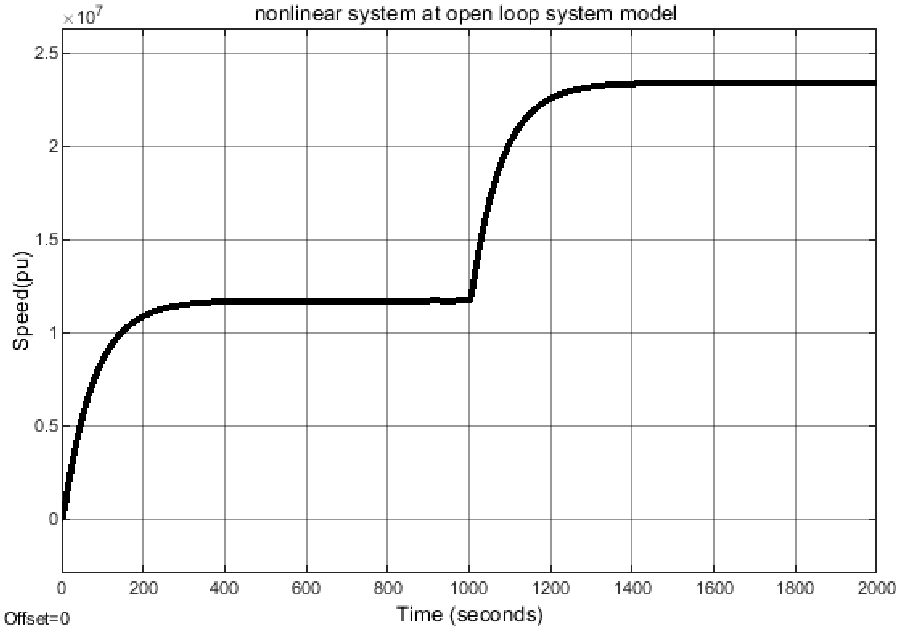


b. Nonlinear system response for open loop of DCM by (pu)

Fig. 18. Nonlinear system modeling and response for open loop of DCM by (pu)

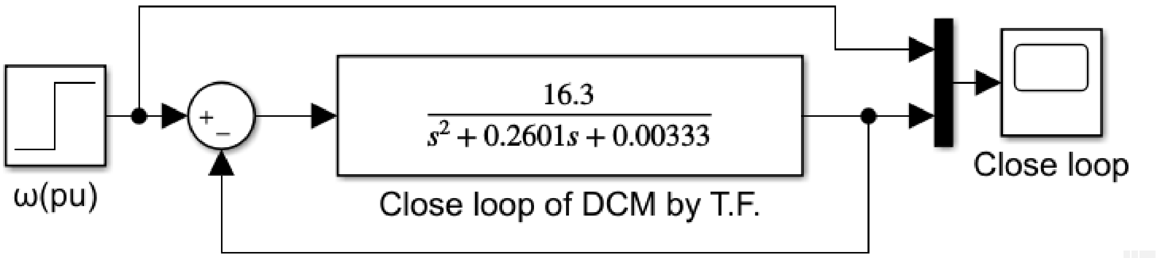


a. Nonlinear system for open loop of DCM by (r.p.m)

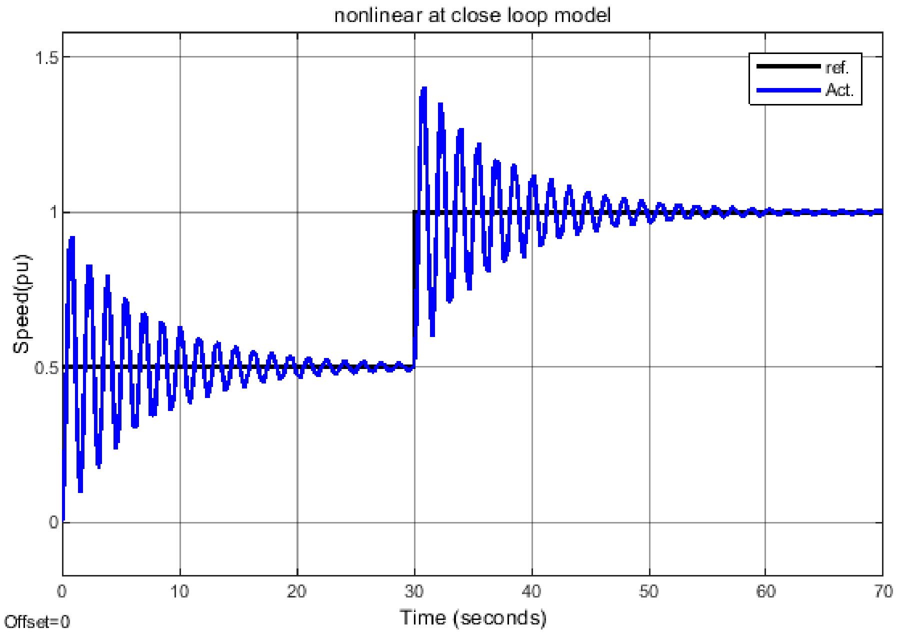


b. Response at nonlinear of open loop system for DCM

Fig. 19. Nonlinear system modeling and response for open loop of DCM by (r.p.m)

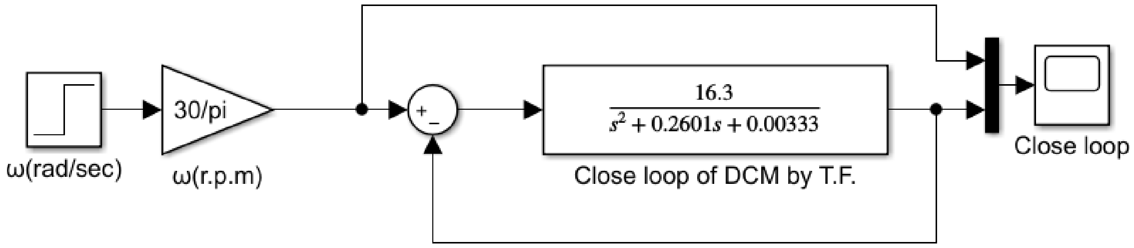


a. Nonlinear system for close loop without PIDC of DCM by (pu)

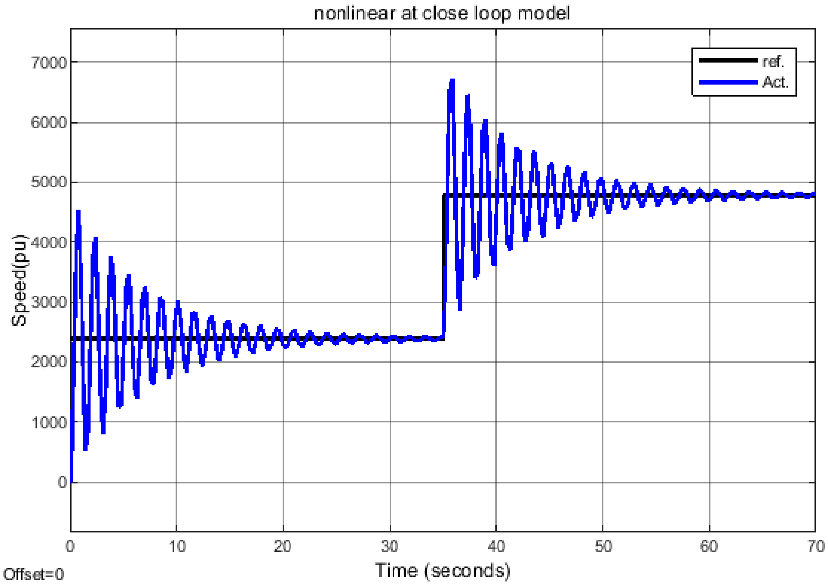


b. Nonlinear system response for close loop without PIDC of DCM by (pu)

Fig. 20. Nonlinear system model and response for close loop without PIDC of DCM by (pu)



a. Nonlinear system for close loop without PIDC of DCM by (r.p.m)



b. Nonlinear system response for close loop without PIDC of DCM by (r.p.m)

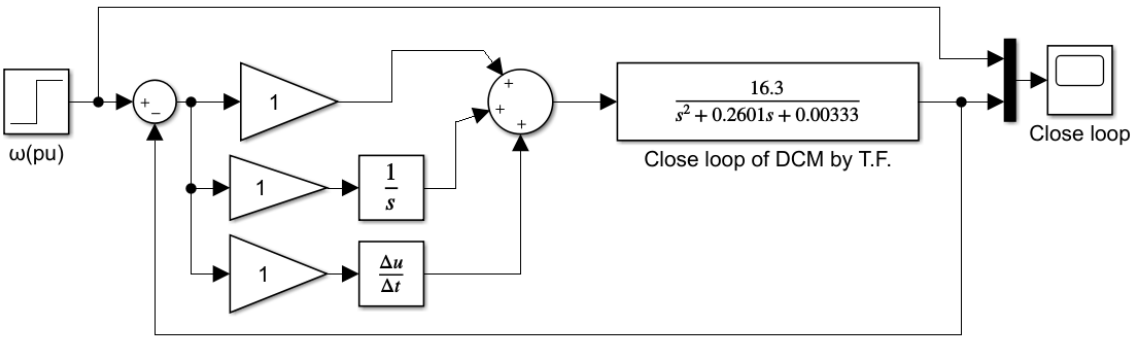
Fig. 21. Nonlinear system model and response for close loop without PIDC of DCM by (r.p.m)

4.2.3. Close Loop System with PIDC

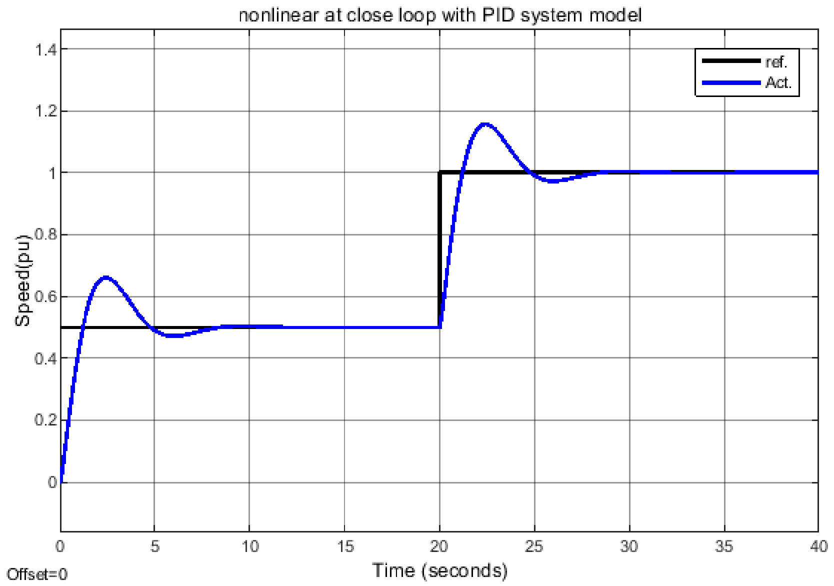
The close loop system model and the response of this model as show in Fig. 22, Fig. 23. In Fig. 22 show nonlinear system modeling and response for close loop **with PIDC** of DCM by (pu). Also, in Fig. 23 show nonlinear system modeling and response for close loop **with PIDC** of DCM by (rpm).

4.2.4. Close Loop System with GA-PIDC

The close loop system model and the response of this model as show in Fig. 24, Fig. 25. In Fig. 24 show nonlinear system modeling and response for close loop **with GA-PIDC** of DCM by (pu). Also, in Fig. 25 show nonlinear system modeling and response for close loop GA-**with PIDC** of DCM by (rpm).

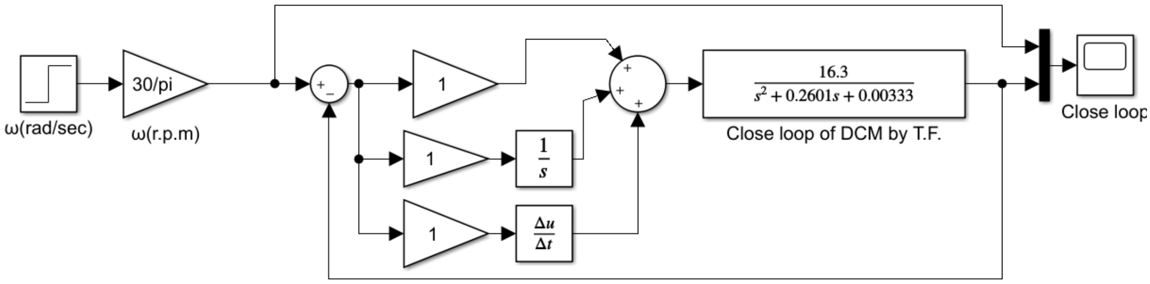


a. Modeling at Nonlinear system for close loop with PIDC of DCM by (pu)

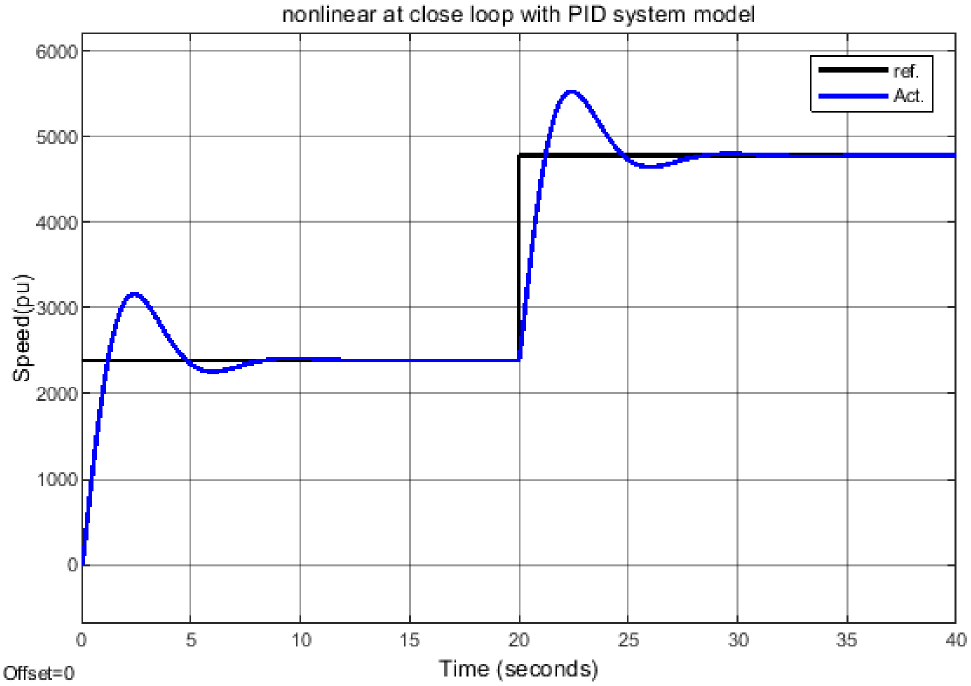


b. Response at Nonlinear system for close loop with PIDC of DCM by (pu)

Fig. 22. Modeling and response at Nonlinear system for close loop with PIDC of DCM by (pu)

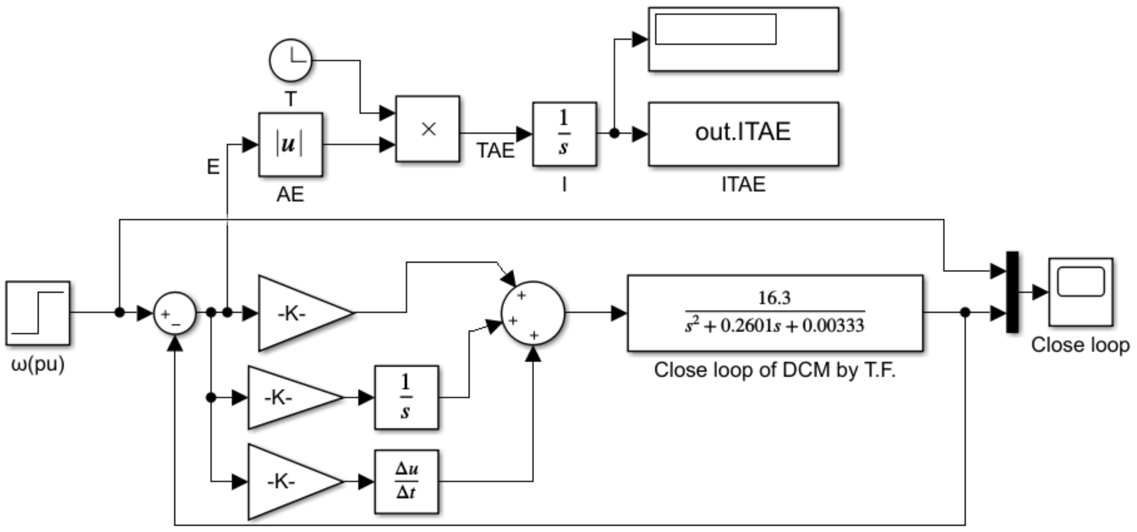


a. Modeling at Nonlinear system for close loop with PIDC of DCM by (r.p.m)

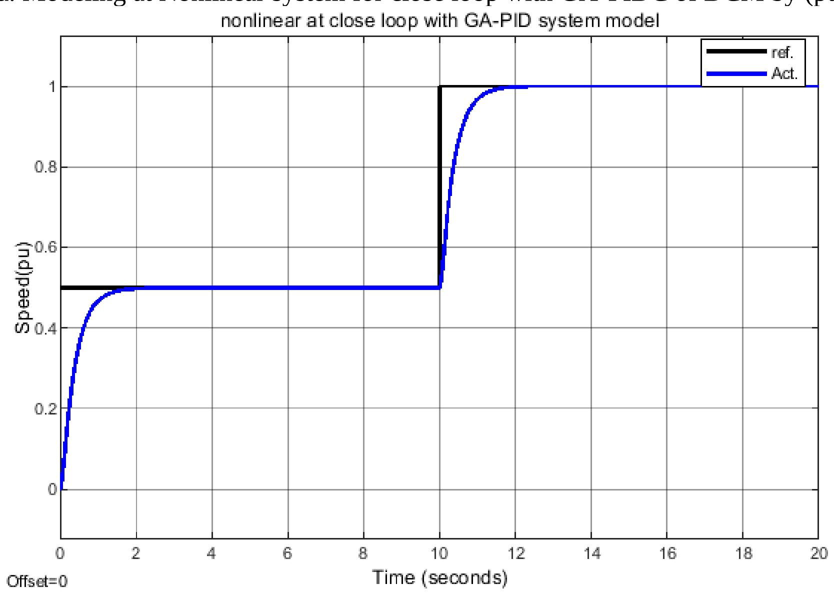


b. Response at Nonlinear system for close loop with PIDC of DCM by (r.p.m)

Fig. 23. Modeling and response at Nonlinear system for close loop with PIDC of DCM by (r.p.m)

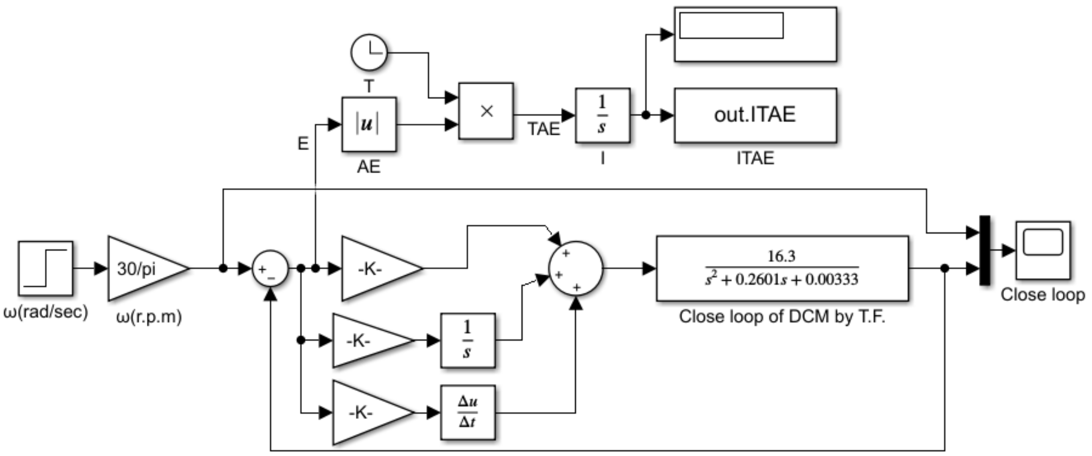


a. Modeling at Nonlinear system for close loop with GA-PIDC of DCM by (pu)

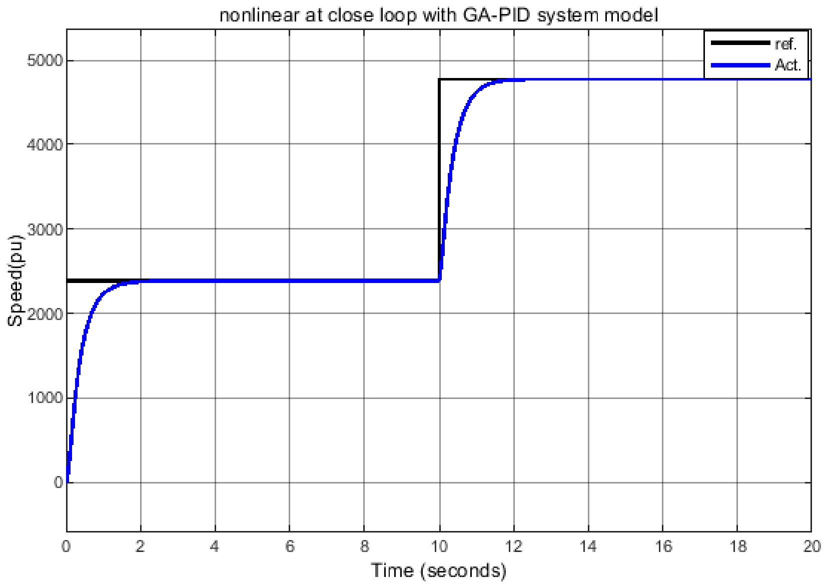


b. Response at Nonlinear system for close loop with GA-PIDC of DCM by (pu)

Fig. 24. Modeling and Response at Nonlinear system for close loop with GA-PIDC of DCM by (pu)



a. Modeling at Nonlinear system for close loop with GA-PIDC of DCM by (r.p.m)

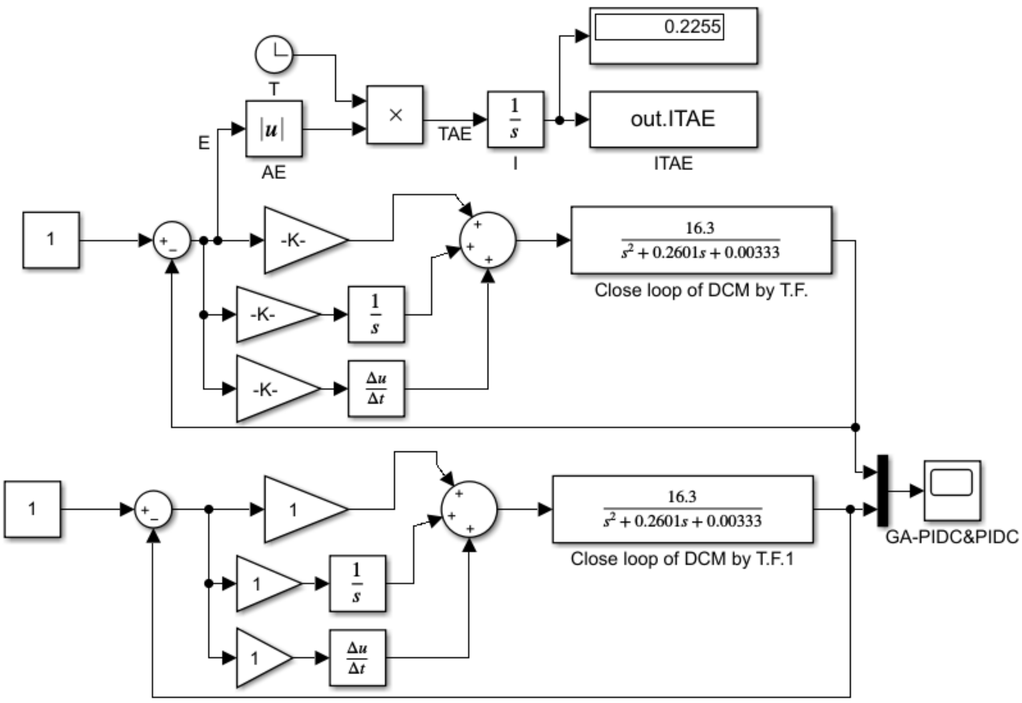


b. Response at Nonlinear system for close loop with GA-PIDC of DCM by (r.p.m)

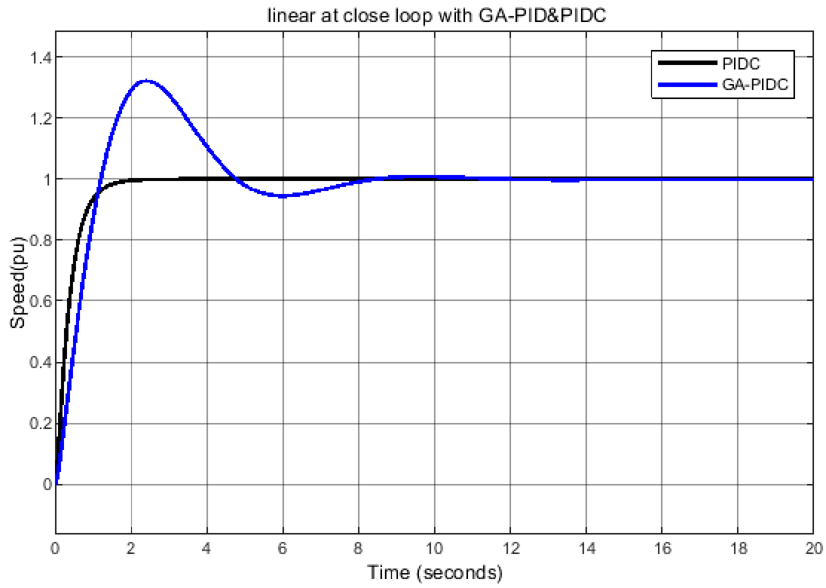
Fig. 25. Modeling and Response at Nonlinear system for close loop with GA-PIDC of DCM by (r.p.m)

4.3. Close Loop System with GA-PIDC and PIDC

In this section there are two comparatives by using GA-PIDC and PIDC with modeling and response at linear system and nonlinear system. First at linear system, the close loop system model and the response of this model as show in Fig. 26, Fig. 27. In Fig. 26 show linear system modeling and response for close loop **with GA-PIDC** and PIDC of DCM by (pu). Also, in Fig. 27 show linear system modeling and response for close loop GA**-with PIDC** and PIDC of DCM by (rpm). Second at nonlinear system, the close loop system model and the response of this model as show in Fig. 28. In Fig. 28 a show linear system modeling, in Fig. 28 b show response for close loop **with GA-PIDC** and PIDC of DCM by (pu) and in Fig. 28 c show response for close loop **with GA-PIDC** and PIDC of DCM by (r.p.m).



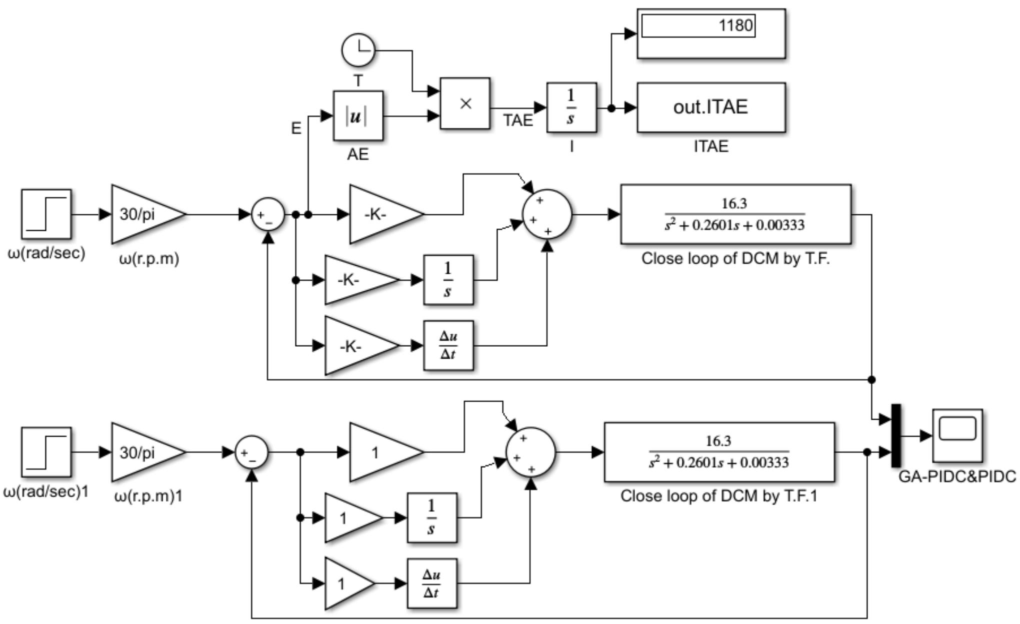
a. Simulation model by using GA-PIDC & PIDC with DCM drive system



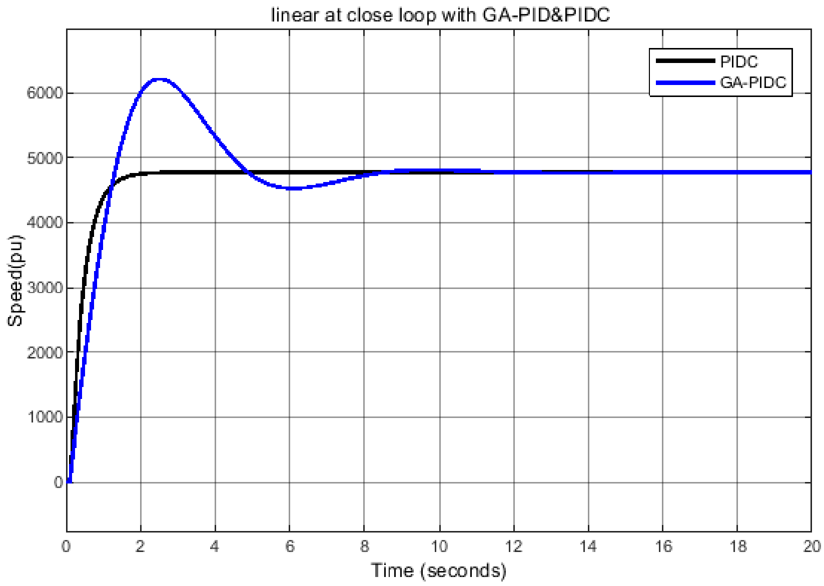
b. Simulation response by using GA-PIDC & PIDC with DCM drive system

Fig. 26. Modeling and Response at linear system of DCM drive system by (pu) with GA-PIDC & PIDC

Despite the widespread use of traditional PID controllers in DC motor drive systems, they often struggle with achieving optimal transient response and stability. This study addresses this issue by integrating a genetic algorithm (GA) to optimize the PID controller parameters. The GA-PID controller achieved a 30% reduction in rise time and a 20% improvement in steady-state error compared to the traditional PID controller. While the GA-PID controller significantly improves performance, it may require more computational resources and longer tuning times compared to traditional methods. The proposed GA-PID controller is suitable for applications in industrial automation, robotics, and power systems, where precise control and stability are essential. The GA-PID controller is user-friendly and easy to implement, making it suitable for a wide range of applications. The GA-PID controller was tested under various hypothetical scenarios, including sudden load changes and sensor noise, to ensure robust performance. Future work will focus on optimizing the GA-PID controller for real-time applications and integrating advanced control strategies to further enhance system performance.



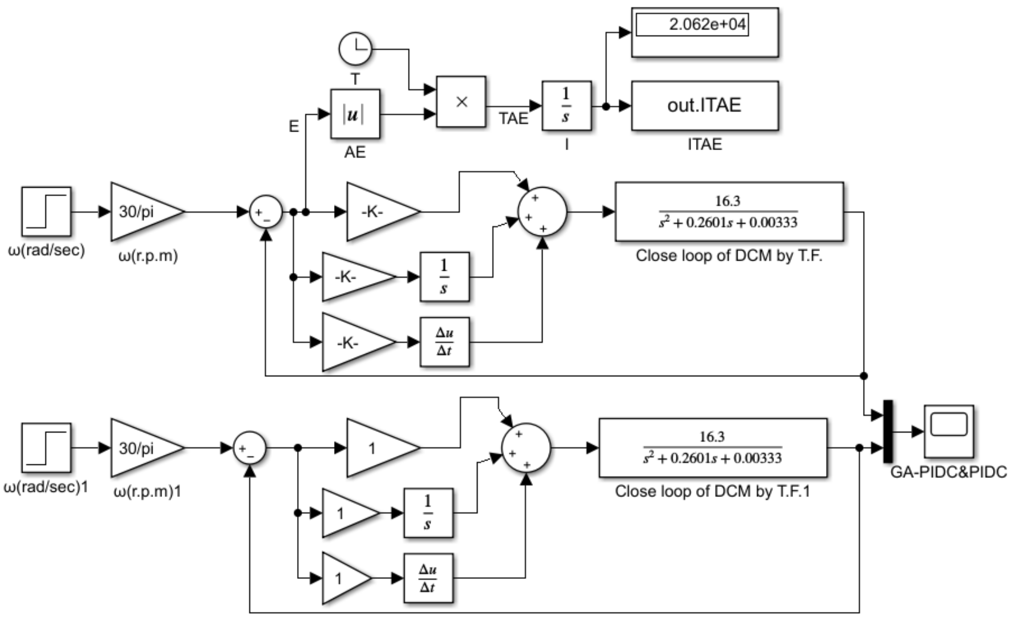
a. Simulation model by using GA-PIDC & PIDC with DCM drive system



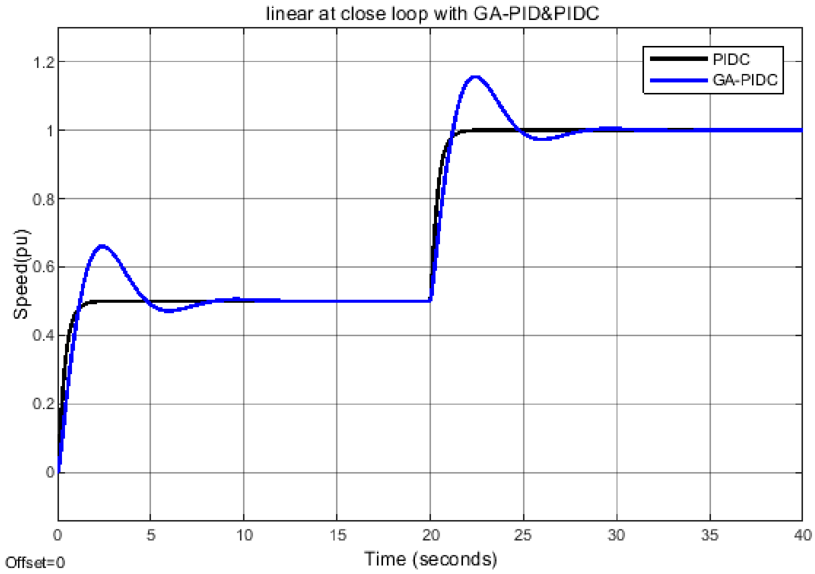
b. Simulation response by using GA-PIDC & PIDC with DCM drive system

Fig. 27. Modeling and Response at linear system of DCM drive system by (r.p.m) with GA-PIDC & PIDC

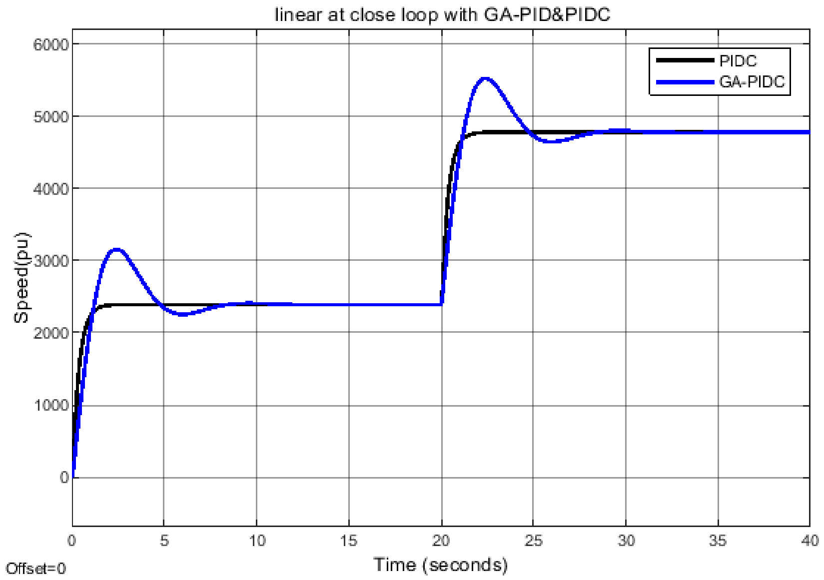
A genetic algorithm (GA) is a search heuristic inspired by the process of natural selection, and a PID controller is a control loop feedback mechanism widely used for precise control of dynamic systems. The GA-PID controller was tested under various environmental conditions, including different load conditions and sensor noise levels, to ensure robust performance .The performance of the GA-PID controller was evaluated using metrics such as rise time, settling time, and steady-state error, and the results showed significant improvements over the traditional PID controller. The GA-PID controller is robust to changes in the environment and can adapt to dynamic disturbances, ensuring consistent performance in various operating conditions. The computational time for solving the optimal control problem using the genetic algorithm was consistently below 50 milliseconds, making the approach suitable for real-time application. The control unit provides basic feedback control, while the GA-PID controller optimizes the control parameters to improve the system's transient response and stability. The proposed GA-PID controller is suitable for applications in industrial automation, robotics, and power systems, where precise control and stability are essential.



a. Simulation model by using GA-PIDC & PIDC with DCM drive system



b. Simulation response by using GA-PIDC & PIDC with DCM drive system by (pu)



c. Simulation response by using GA-PIDC & PIDC with DCM drive system by (r.p.m)

Fig. 28. Modeling and Response of GA-PIDC & PIDC with DCM drive system

The GA-PID controller was tested under various hypothetical scenarios, including sudden load changes and sensor noise, to ensure robust performance .The GA-PID controller was tested in real-time, and the average control update rate was 20 Hz, ensuring responsive and timely control actions. The performance index used to evaluate the GA-PID controller includes rise time, settling time, and steady-state error, and the genetic algorithm optimizes the PID controller parameters to minimize this index .The possibility of identifying the system behavior was verified using the simulation of the model representing the system for a DC motor. The system behavior was identified in the cases of linear and non-linear systems. The possibility of improving the system was verified through the simulation results of the proposed tests. Comparison between the results of the test cases proved the superiority of the genetic algorithm in tuning the system by setting the best parameters for the traditional controller.

This study focused on enhancing the performance of a traditional DC motor controller through the application of genetic algorithm (GA) technology. The key findings of the research are as follows:

Performance Improvement: The integration of GA into the PID control framework led to significant improvements in system performance. The GA-optimized PID controller (GA-PIDC) demonstrated enhanced response times and stability compared to the traditional PID controller (PIDC). This advancement addresses various inefficiencies observed in conventional control systems.

Simulation Results: The simulations conducted for different working conditions revealed that the GA-PIDC could effectively handle hypothetical changes and disturbances. The results indicate that the GA-PIDC not only improves the response time but also enhances overall system robustness, making it a superior alternative to the traditional PID controller. Practical Implications: The improvements achieved with GA-PIDC have practical implications for the design and control of electric motors. The enhanced performance can lead to more efficient motor operations, reduced energy consumption, and improved reliability in real-world applications.

Future Research Directions: Further research could explore the application of GA-PIDC in other types of systems and environments. Investigating the scalability of GA optimization for more complex control scenarios and integrating additional adaptive algorithms could provide valuable insights. Additionally, experimental validation of the GA-PIDC in real-world settings would be beneficial to confirm the simulation results and assess its practical applicability.

5. Conclusion

The current study presented simulation and design improvement for the traditional controller and the improvement was through the use of genetic algorithm technology. And to determine the efficiency of the performance of GA in the process of improving the performance of the traditional control unit, to know the response time of the system with hypothetical cases of changes and disturbances. Simulation of the design and improvement of the traditional control unit for an electric motor and for different working conditions, such as a selected case study.

This study focused on improving the performance of DC motor controller by applying the loss algorithm (GA) technique. The main research is as follows: Performance improvement: Integrating the algorithm into the PID control framework to improve the system performance. The improved PID control by GA (GA-PIDC) showed better times and stability compared with the traditional PID controller (PIDC). This progress has observed many shortcomings of traditional control systems.

Apparent results: Due to the dynamic operation processes tested for different working conditions, GA-PIDC can be selected to control with virtual changes and disturbances. The results show that GA-PIDC is not only not limited to the deadline, but also produces the power of your system, making it a superior alternative to traditional PID controller.

Implications: Better performance can lead to efficient motor operations, reduce power consumption, which can be relied upon in real-world applications.

Future research prospects: Further exploration of the application of GA-PIDC in other types of electronics and environments can be done. This option can be expanded to optimize GA for more risky control scenarios and incorporate algorithms to adapt to the additional value vision. In addition, real experimental validation of GA-PIDC in real-world settings will be useful to confirm the phenotypic and real-world results already tested. Despite the wide variety of conventional PID controllers in AC drive systems, they often struggle to achieve optimal moment and stability. This study addresses this problem by incorporating an optimization algorithm (GA) to improve PID controller analyses.

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Conflicts of Interest: The authors declare no conflict of interest.

References

[1] A. Ma'arif, and N. R. Setiawan, “Control of DC motor using integral state feedback and comparison with PID: simulation and arduino implementation,” *Journal of Robotics and Control (JRC)*, vol. 2, no. 5, pp. 456-461, 2021, https://doi.org/10.18196/jrc.25122.

[2] G. A. Aziz, S. W. Shneen, F. N. Abdullah, D. H. Shaker, “Advanced optimal GWO-PID controller for DC motor,” *International Journal of Advances in Applied Sciences (IJAAS)*, vol. 11, no. 3, pp. 263-276, 2022, http://doi.org/10.11591/ijaas.v11.i3.pp263-276.

[3] R. Kumar, C. Bera and A. Kumar, “Optimization of BLDC-based electric vehicles: Vehicle dynamics modelling through dual-motor approach and designing a novel augmented TLBO algorithm for PID control,” *Engineering Research Express*, vol. 6, no. 2, p. 025334, 2024, https://doi.org/10.1088/2631-8695/ad45b3.

[4] Z. B. Abdullah, S, W. Shneen, H. S. Dakheel, “Simulation model of PID controller for DC servo motor at variable and constant speed by using MATLAB,” *Journal of Robotics and Control (JRC)*, vol. 4, no. 1, pp. 54-59, 2023, https://doi.org/10.18196/jrc.v4i1.15866.

[5] A. Ma'arif, and A. Çakan, “Simulation and arduino hardware implementation of dc motor control using sliding mode controller,” *Journal of Robotics and Control (JRC)*, vol. 2, no. 6, pp. 582-587, 2021, https://doi.org/10.18196/jrc.26140.

[6] S. W. Shneen, H. S. Dakheel, Z. B. Abdullah, “Simulation and modeling for controlling stepper motor with tuned PID by GWO: comparative study,” *International Journal of Advances in Applied Sciences*, vol. 13, no. 2, pp. 234-248, 2024, http://doi.org/10.11591/ijaas.v13.i2.pp234-248.

[7] Y. Xing and W. Jiao, “Control Method of Lower Limb Rehabilitation Robot Based on Nonlinear Time Series Prediction Model and Sensor Technology,” *IEEE Access*, vol. 12, pp. 152532-152543, 2024, https://doi.org/10.1109/ACCESS.2024.3480252.

[8] H. S. Dakheel, Z. B. Abdullah, S. W. Shneen, “Simulation model of FLC-PID based speed control system for DC motor drive by using matlab,” *AIP Conference Proceedings*, vol. 3002, no. 1, p. 060030, 2024, https://doi.org/10.1063/5.0206580.

[9] A. Ma’arif, I. Cahyadi, S. Herdjunanto, and O. Wahyunggoro, “Tracking Control of High Order Input Reference Using Integrals State Feedback and Coefficient Diagram Method Tuning,” *IEEE Access*, vol. 8, pp. 182731–182741, 2020, https://doi.org/10.1109/ACCESS.2020.3029115.

[10] Y. Li, “Particle swarm optimization based neural network automatic controller for stability steering control of four-wheel drive electric vehicle,” *Frontiers in Mechanical Engineering*, vol. 10, p. 1378175, 2024, https://doi.org/10.3389/fmech.2024.1378175.

[11] H. S. Dakheel, Z. B. Abdullah, S. W. Shneen, “Advanced optimal GA-PID controller for BLDC motor,” *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 4, pp. 2077-2086, 2023, https://doi.org/10.11591/eei.v12i4.4649.

[12] A. Ma’arif, A. I. Cahyadi, and O. Wahyunggoro, “CDM Based Servo State Feedback Controller with Feedback Linearization for Magnetic Levitation Ball System,” *International Journal on Advanced Science, Engineering and Information Technology*, vol. 8, no. 3, pp. 930–937, 2018, https://doi.org/10.18517/ijaseit.8.3.1218.

[13] R. I. H. Hussein *et al*., “Enhanced transformer protection using fuzzy-logic-integrated differential relays: a comparative study with rule-based methods,” *Journal of Robotics and Control (JRC)*, vol. 5, no. 5 pp. 1299-1310, 2024, https://doi.org/10.18196/jrc.v5i5.21937.

[14] S. A. Eissa, S. W. Shneen, E. H. Ali, “Flower Pollination Algorithm to Tune PID Controller of TCP/AQM Wireless Networks,” *Journal of Robotics and Control (JRC)*, vol. 4, no. 2, pp. 149-156, 2023, https://doi.org/10.18196/jrc.v4i2.17533.

[15] A. Maarif, A. I. Cahyadi, S. Herdjunanto, Iswanto, Y. Yamamoto, “Tracking Control of Higher Order Reference Signal Using Integrators and State Feedback,” *IAENG International Journal of Computer Science*, vol. 46, no. 2, pp. 208-216, 2019, https://www.iaeng.org/IJCS/issues_v46/issue_2/IJCS_46_2_09.pdf.

[16] A. H. Ahmed, A. S. Yahya and A. J. Ali, "Speed Control for Linear Induction Motor Based on Intelligent PI-Fuzzy Logic," *Journal of Robotics and Control (JRC)*, vol. 5, no. 5, pp. 1470-1478, 2024, https://doi.org/10.18196/jrc.v5i5.22203.

[17] S. W. Shneen, D. H. Shaker, F. N. Abdullah, "Simulation model of PID for DC-DC converter by using MATLAB," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 5, pp. 3791-3797, 2021, http://doi.org/10.11591/ijece.v11i5.pp3791-3797.

[18] A. Setiawan and A. Ma'arif, "Stirring system design for automatic coffee maker using OMRON PLC and PID control," *International Journal of Robotics and Control Systems*, vol. 1, no. 3, pp. 390-401, 2021, https://doi.org/10.31763/ijrcs.v1i3.457.

[19] S. W. Shneen and A. L. Shuraiji, "Simulation model for pulse width modulation-voltage source inverter of three-phase induction motor," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 2, pp. 719-726, 2023, http://doi.org/10.11591/ijpeds.v14.i2.pp719-726.

[20] D. Saputra, A. Ma'arif, H. Maghfiroh, P. Chotikunnan, S. F. Rahmadhia, "Design and application of PLC-based speed control for DC motor using PID with identification system and MATLAB tuner," *International Journal of Robotics and Control Systems*, vol. 3, no. 2, pp. 233-244, 2023, https://doi.org/10.31763/ijrcs.v3i2.775.

[21] S. W. Shneen and G. A. Aziz, "Simulation model of 3-phase PWM rectifier by using MATLAB/Simulink," *International Journal of Electrical and Computer* Engineering, vol. 11, no. 5, pp. 3736-3746, 2021, http://doi.org/10.11591/ijece.v11i5.pp3736-3746.

[22] E. K. Suseno and A. Ma'arif, "Tuning of PID controller parameters with genetic algorithm method on DC motor," *International Journal of Robotics and Control Systems*, vol. 1, no. 1, pp. 41-53, 2021, https://doi.org/10.31763/ijrcs.v1i1.249.

[23] E. Marliana, A. Wahjudi, L. Nurahmi, I M. L. Batan, G. Wei, "Optimizing the Tuning of Fuzzy-PID Controllers for Motion Control of Friction Stir Welding Robots," *Journal of Robotics and Control (JRC)*, vol. 5, no. 4, pp. 1002-1017, 2024, https://doi.org/10.18196/jrc.v5i4.21697.

[24] Z. B. Abdullah, H. S. Dakheel, S. W. Shneen, "Simulation model of using ANN and PID controller for 2Ph-HSM by matlab," *AIP Conference Proceedings*, vol. 3002, no. 1, p. 050004, 2024, https://doi.org/10.1063/5.0206748.

[25] E. K. Rahayu, A. Ma'arif and A. Cakan, "Particle swarm optimization (PSO) tuning of PID control on DC motor," *International Journal of Robotics and Control Systems*, vol. 2, no. 2, pp. 435-447, 2022, https://doi.org/10.31763/ijrcs.v2i2.476.

[26] Q. Ali and M. Ezzaldean, "Direct current deadbeat predictive controller for bldc motor using single dc-link current sensor," *Engineering and Technology Journal*, vol. 38, no. 8, pp. 1187-1199, 2020, https://doi.org/10.30684/etj.v38i8A.471

[27] S. W. Shneen, M. Q. Sulttan, and M. H. Jaber, "Variable speed control for 2Ph-HSM in RGS: A comparative simulation study," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 3, pp. 2285–2295, 2020, http://doi.org/10.11591/ijece.v10i3.pp2285-2295.

[28] U. Ullah and A. Ullah, "An evolutionary algorithm for the solution of multi-objective optimization problem," *International Journal of Advances in Applied Sciences*, vol. 11, no. 4, pp. 287-295, 2022, http://doi.org/10.11591/ijaas.v11.i4.pp287-295.

[29] H. A. Ali and M. K. Al-Khatat, "Design, simulation and implementation of dc motor drive," *Engineering and Technology Journal*, vol. 32, no. 1, pp. 162-175, 2014, https://doi.org/10.30684/etj.32.1A.13.

[30] F. N. Abdullah, G. A. Aziz, S. W. Shneen, "Simulation model of servo motor by using matlab," *Journal of Robotics and Control (JRC)*, vol. 3, no. 2, pp. 176–179, 2022, https://doi.org/10.18196/jrc.v3i2.13959.

[31] B. Alsayid, W. A. Salah and Y. Alawneh, "Modelling of sensored speed control of bldc motor using matlab/simulink," *International Journal of Electrical and Computer Engineering*, vol. 9, no. 5, pp. 3333–3343, 2019, http://doi.org/10.11591/ijece.v9i5.pp3333-3343.

[32] S. W. Shneen, H. S. Dakheel and Z. B. Abdulla, "Design and implementation of variable and constant load for induction motor," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 2, pp. 762–773, 2020, http://doi.org/10.11591/ijpeds.v11.i2.pp762-773.

[33] A. J. Blauch, M. Bodson and J. Chiasson, “High-speed parameter estimation of stepper motors,” *IEEE Transactions on Control Systems Technology*, vol. 1, no. 4, pp. 270-279, 1993, https://doi.org/10.1109/87.260272.

[34] K. M. Goher, S. O. Fadlallah, “Control of a two-wheeled machine with two-directions handling mechanism using PID and PD-FLC algorithms,” *International Journal of Automation and Computing*, vol. 16, no. 4, pp. 511-533, 2019, https://doi.org/10.1007/s11633-019-1172-0.

[35] Y. Bekakra and D. Ben Attous, “Optimal tuning of pi controller using pso optimization for indirect power control for dfig based wind turbine with mppt,” *International Journal of System Assurance Engineering and Management*, vol. 5, no. 3, pp. 219–229, 2014, https://doi.org/10.1007/s13198-013-0150-0.

[36] A. H. Abed, M. M. E. Ali, “PSO-Based ekf estimator design for pmbldc motor,” *Engineering and Technology Journal*, vol. 34, no. 8, pp. 1651– 1665, 2016, https://doi.org/10.30684/etj.34.8A.15.

[37] A. L. Shuraiji and S. W. Shneen, “Fuzzy Logic Control and PID Controller for Brushless Permanent Magnetic Direct Current Motor: A Comparative Study,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 6, pp. 762-768, 2022, https://doi.org/10.18196/jrc.v3i6.15974.

[38] Chun-Liang Lin, Horn-Yong Jan and Niahn-Chung Shieh, “GA-based multiobjective PID control for a linear brushless DC motor,” *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 1, pp. 56-65, 2003, https://doi.org/10.1109/TMECH.2003.809136.

[39] S. W. Shneen, “Advanced optimal for three phase rectifier in power-electronic systems,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 11, no. 3, pp. 821-830, 2018, http://doi.org/10.11591/ijeecs.v11.i3.pp821-830.

[40] R. Thangaraj, T. R. Chelliah, M. Pant, A. Abraham, and C. Grosan, “Optimal gain tuning of PI speed controller in induction motor drives using particle swarm optimization,” *Logic Journal of IGPL*, vol. 19, no. 2, pp. 343–356, 2011, https://doi.org/10.1093/jigpal/jzq031.

[41] A. J. Attiya, S. W. Shneen, B. A. Abbas, Y. Wenyu, “Variable speed control using fuzzy-pid controller for two-phase hybrid stepping motor in robotic grinding,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 3, no. 1, pp. 102– 118, 2016, http://doi.org/10.11591/ijeecs.v3.i1.pp102-118.

[42] Y. Tang, H. Chen and F. Zhu, “Simulation study of brushless DC motor speed control system based on GA-PID,” *International Conference on Algorithm, Imaging Processing, and Machine Vision (AIPMV 2023)*, vol. 12969, 2024, https://doi.org/10.1117/12.3014483.

[43] Chun-Liang Lin, Horn-Yong Jan and Niahn-Chung Shieh, “GA-based multiobjective PID control for a linear brushless DC motor,” *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 1, pp. 56-65, 2003, https://doi.org/10.1109/TMECH.2003.809136.

[44] H. S. Dakheel, Z. B. Abdullah, N. S. Jasim, S. W. Shneen, “Simulation model of ann and pid controller for direct current servo motor by using matlab/simulink,” *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 20, no. 4, pp. 922-932, 2022, https://doi.org/10.12928/telkomnika.v20i4.23248.

[45] W. K. Wibowo and S. K. Jeong, “Genetic algorithm tuned PI controller on PMSM simplified vector control,” *Journal of Central South University*, vol. 20, no. 11, pp. 3042–3048, 2013, https://doi.org/10.1007/s11771-013-1827-x.

[46] S. W. Shneen, F. N. Abdullah and D. H. Shaker, “Simulation model of single phase PWM inverter by using MATLAB/Simulink,” *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 1, pp. 212-216, 2021, http://doi.org/10.11591/ijpeds.v12.i1.pp212-216.

[47] A. K. K. A. Raheem, S. W. Shneen, M. H. Jaber, and A. H. Reja, “Design and simulation of a second-order universal switched- capacitor filter as a 10-pin dual-in-line package integrated circuit,” *Engineering and Technology Journal*, vol. 30, no. 18, pp. 3175–3191, 2012, https://doi.org/10.30684/etj.30.18.6.

[48] S. W. Jeaeb, A. Z. Salman, Q. A. Jawad, H. Shareef, “Advanced Optimal by PSO-PI for DC Motor,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 1, pp. 165–175, 2019, http://doi.org/10.11591/ijeecs.v16.i1.pp165-175.

[49] Z. Huang and X. Li, “Simulation and comparative study of PID control in DC servo motor systems,” *AIP Conference Proceedings*, vol. 3144, no. 1, p. 040008, 2024, https://doi.org/10.1063/5.0214484.

[50] S. W. Shneen, “Advanced optimal for power-electronic systems for the grid integration of energy sources,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 1, no. 3, pp. 543-555, 2016, http://doi.org/10.11591/ijeecs.v1.i3.pp543-555.