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Effect of derivative filter usage on a pıd controller optimized via pathfinder algorithm: an example of a DC-MSCS

Türev filtresi kullanımının pathfinder algoritması ile optimize edilmiş bir pid denetleyici üzerindeki etkisi: bir DC motor hız kontrol sistemi örneği

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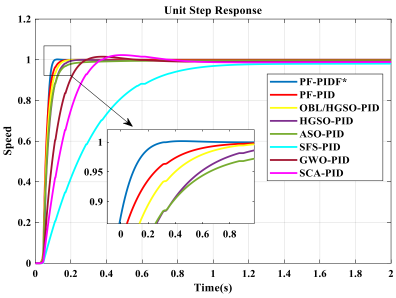
Effect of Derivative Filter Usage on a PID Controller Optimized via Pathfinder Algorithm: An Example of a DC-MSCS

Highlights

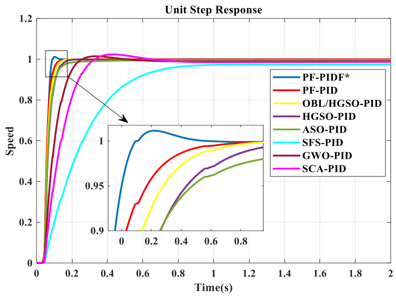
- *Pathfinder is proposed as the optimum controller and algorithm for DC motor speed control*
- *ITAE (integral of the time product absolute error)cost function was used for Pathfinder algorithm*
- *5 different analysis were performed to make comparisons between algorithms and controllers*
- Result of studies were discussed

Graphical Abstract

In this article, Pathfinder-PIDF (PF-PIDF) is proposed as the optimum controller and algorithm for DC motor speed control



(a)



(b)

Algorithm-Controller	Overshoot (%)	Settling time (s) (±2%)	Rising Time (s) (0.1-0.9)	ITAE (%)
PF-PIDF (Proposed)	**None**	**0.0731**	**0.0423**	**0.2755**
PF-PID	None	0.0982	0.0556	0.291
OBL/HGSO-PID	None	0.1163	0.0678	0.8967
HGSO-PID	None	0.1455	0.0848	0.8992
ASO-PID	None	0.1934	0.0869	0.5443
SFS-PID	None	1.2033	0.6568	10.12
GWO-PID	1.52	0.2469	0.1681	2.114
SCA-PID	2.15	0.2168	0.2445	2.922

(c)

Figure. (a) Unit step outputs obtained in simulation for algorithms, (b) Unit step outputs of the algorithms obtained in the simulation for the 2nd case, (c) Transient response analysis parameters for 1st Case of some algorithms in the literature and the proposed algorithm

Aim

This study aims to improve the performance of a DC motor speed control system by using proposed methodology.

Design & Methodology

The algorithm of the proposed system was built and simulation studies were carried out in Matlab/Simulink environment.

Originality

A recently proposed optimization algorithm called as "pathfinder" is utilized for controller design process of this study. Also, in this study, we analyze the derivative filter effect in a PID controller in detail. The obtained results are compared to existing ones in literature. As a result, PF-PIDF controller provides impressive results in terms of transient response analysis, stability analysis and robustness tests.

Findings

It has been seen that the proposed controller structure has the shortest settling time, rise time, the best ITAE value and provides more stable response. Besides, it has also been observed that it is more effective than other algorithms in suppressing the system against the sudden change in the system due to the disturbance load input

Conclusion

It has been seen that the proposed PF-PIDF controller is more successful in suppressing the load disturbance compared to other controllers. In addition, it increases the system stability margin and robustness.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effect of Derivative Filter Usage on a PID Controller Optimized via Pathfinder Algorithm: An Example of a DC-MSCS

Araştırma Makalesi / Research Article

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ABSTRACT

In this article, Pathfinder-Derivative filtered proportional-integral-derivative controller (PF-PIDF) is proposed as the optimum algorithm and controller for DC motor speed control. The Pathfinder algorithm is inspired by the collective behavior of the animal colony and imitates the leadership hierarchy of the herds in order to determine the best meal or hunting ground. The movement of all particles is not regular, they all move randomly. In order to acquire the best parameters of the derivative filtered PID controller (PIDF) controller with the Pathfinder algorithm, the objective function ITAE (Integral of the Time Multiple Absolute Error), one of the commonly used objective functions in the literature, was used. Time solution set analysis, frequency response analysis (bode), robustness analysis, pole-zero map analysis and load disturbance rejection analysis were performed in MATLAB/Simulink software to make comparisons between algorithms and controllers and to testify the sufficiency of the proposed controller. As a result of the studies, it has been seen that the with PIDF Pathfinder algorithm has better performance than the other optimization algorithms in the article.

Keywords: PIDF controller, ITAE, Robustness, DC motor.

Türev Filtresi Kullanımının Pathfinder Algoritması ile Optimize Edilmiş Bir PID Denetleyici Üzerindeki Etkisi: Bir DC Motor Hız Kontrol Sistemi Örneği

ÖZ

Bu makalede DC motor hız kontrolü için en uygun algoritma ve denetleyici olarak Türev Filtreli Pathfinder Algoritmalı Oransal İntegral Türev denetleyici (TFPFA-OİT) önerilmektedir. Pathfinder algoritması, hayvan kolonisinin ortaklaşa davranışlarından esinlenir ve en iyi beslenme veya av alanını belirlemek için sürülerin liderlik aşama sırasını taklit eder. Tüm parçacıkların hareketi düzenli değildir, hepsi rastgele hareket eder. Pathfinder algoritması ile TFPFA-OİT denetleyicisinin en iyi parametrelerini elde etmek için literatürde sık kullanılan amaç fonksiyonlarından; zaman çarpımı mutlak hatasının integrali (ZÇMHİ) başarım ölçütü kullanılmıştır. Algoritmalar ile denetleyiciler arasında karşılaştırma yapabilmek ve önerilen denetleyicinin yeterliliğini kanıtlamak için MATLAB/Simulink yazılımıyla zaman çözüm kümesi analizi, frekans tepkisi analizi (bode), gürbüzlük analizi, kararlılık analizi ve bozucu yük yanıtı analizleri yapılmıştır. Çalışmalar sonucunda TFPFA-OİT makalede yer alan en iyileştirme algoritmalarından daha iyi başarım elde edildiği görülmüştür.

Anahtar Kelimeler: TFPFA-OİT denetleyici, ZÇMHİ, gürbüzlük, DC motor.

1. INTRODUCTION

DC motor position and speed control systems, especially speed control system, are well-known and highly preferred benchmark systems by the researchers who study on the design of optimized controller structures. The main purpose of the studies and also this study for DC motor position and speed control is to reduce the transient and steady state criteria such as maximum overshoot, settling time, rise time and steady state error by using the optimal algorithm and controller. But, the algorithms are proposed to improve success may not find out suitable controller gains due to the inadequacy they offer. For this reason the studies on improvements are going on in that field [1]. Researches generally test the performance of their proposed optimization algorithm on a proportional + integral + derivative (PID) controller by aiming to minimize a user defined objective function or classical performance indices for an improved trajectory tracking of speed or position outputs.

Since it was first formulated in 1922, PID controller have been still popular in a wide range of industrial applications due to its simple implementation and efficiency [2].

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Literature survey shows that PID is one the most used controller type for DC motor speed control system (DC-MSCS). There are various studies which are based on to optimize PID controller parameters for DC-MSCS. The studies that include this purpose can be listed as below.

In reference [1]; Henry gas solubility optimization with opposition-based learning (OBL/HGSO) is used for minimizing the ITAE objective function. In reference [3]; ITAE is applied as an objective function for Sine Cosine Algorithm (SCA) to optimize the PID parameters of a DC-MSCS. In reference [4]; as distinct from the others, Integral Square Error (ISE) and ITAE are used as objective functions for Stochastic Fractal Search algorithm (SFSA). In reference [5]; a novel chaotic version of it [chaotic ASO (ChASO)] is proposed to obtain the suitable parameters of the Fractional-Order-PID (FOPID) controller for DC-MSCS. In reference [6]; grey wolf optimization (GWO) algorithm based (FOPID) controller for DC-MSCS is studied and ITAE is applied as objective function to optimize the PID parameters. In reference [7]; invasive weed optimization (IWO) is used for same purpose but as being objective function ITAE was not preferred. In reference [8]; kidney-inspired algorithm (KA) is used to design KA-based PID controller for DC-MSCS. In reference [9]; to optimize PID controller in DC-MSCS, whale optimization (WOA) and moth-flame optimization (MFO) algorithms are used. In addition to PID and the FOPID [5, 6], there are other types of controller used for DC-MSCS in literature. For example; In reference [10]; a PID-Fuzzy logic controller is proposed for brushless DC motor in dynamic electric vehicle to enhance steady-state success, in reference [11]; cost-effective speed control of a DC motor is studied through fuzzy logic controller (FLC), in [12]; a comparison study is available between PID and artificial neural network (ANN) controller and in reference [13]; a sliding mode controller (SMC) is used for DC-MSCS. These are some controller types applied for properly tuning of controller parameters is an important issue in order to acquire the best controller performance. Instead of using the analytical tuning methods containing high mathematical complexities, meta-heuristic algorithms have a great attention due to their simple applicability and higher efficiency. Although, meta-heuristics algorithms do not guarantee to find global optimum point, they provide very successful results, especially recently introduced ones. HGSO [1], OBL/HGSO [1], SCA [3], SFSA [4], ASO [5], ChASO [5], GWO [6, 14], IWO [7], KO [8, 15], meta-heuristic based algorithms [9] are some of the optimization algorithms employed for PID controller designment to control speed of a DC-motor. There is not an exact algorithm that can find the most suitable parameters of a PID controller for DC-MSCS. Therefore, the study of a latest optimization algorithm to define appropriate parameters of the PID controller for DC-MSCS is an observable problem for researchers.

The one of the recently introduced meta-heuristic algorithm is pathfinder algorithm (PFA) based on the collective movement of an animal colony headed by a leader to find the best feeding area [16]. PFA has gained attention and found in many applications such as speed trajectory optimization [17], controller design process [18], optimal design of combined cooling, heating, and power system [19], optimal reactive power dispatch problem [20], unconstrained and constrained optimization problems [21], and electric distribution network reconfiguration optimization [22].

The one of the important issue of an optimization process is definitely the definition of the objective function (OF). User defined objective functions generally contains transient system characteristics such as rising time (Tr), maximum percentage overshoot (Mp), settling time (Ts), and steady-state error (Sse). Also, in some of the studies, stability characteristics such as gain margin (GM), phase margin (PM), damping ratio, and etc. may be used in an objective function. On the other hand, ITAE, integral of absolute error (IAE), integral of time weighted squared error (ITSE) and integral of squared error (ISE), called as classical error based performance indices, are commonly used objective functions in existing studies [1, 3-7].

In the design process of a PID controller especially in practical applications, derivative action is not used alone because of the derivative kick effect (DKE) has been not considered for many studies. DKE has a critical role in the performance of a PID controller especially for real-time applications. Sudden changes in error signal may result DKE of which may cause the system become unstable. To overcome this undesired situation, it is offered to use a low pass filter (LPF) with derivative action of a PID controller.

In this study, we designed a PID controller with and without considering derivative filter to show its effect on the system dynamic. The DC-MSCS is utilized as a test system since it is popular for PID controller design methods. The proposed controller is optimized by PFA by aiming to minimize ITAE objective function. Since the compared studies utilizes ITAE function, we also use it for a fair comparison. The performance of the controllers has been evaluated from many sides of analysis such as time domain analysis (TDA), frequency domain analysis (FDA), load disturbance rejection analysis (LDRA), robustness analysis (RA), and pole-zero map analysis (PZMA). The obtained results of the proposed controllers are compared to existing literature studies. The considered studies for comparison are tabulated in Table 1 of which also consists of publication year, proposed controller type, optimization algorithm, objective function and analyzing methods. The study results show us that proposed PF-PIDF controller performed better in most comparative criteria than all other selected methods studied in recent years.

Table 1. Considered studies for comparison

Reference number and publication year	Controller type	Optimization algorithm	Objective function	Analyzing method
[2], 2020	PID	OBL/HGSO and HGSO	ITAE	FDA, TDA, LDR, RA
[3], 2017	PID	SCA	ITAE	TDA, RA
[4], 2019	PID	SFS	ISE/ITAE	TDA, FDA
[5], 2019	PID and FOPID	ASO and ChASO	ITAE	FDA, TDA, LDR, RA
[6], 2018	PID and FOPID	GWO	ITAE	TDA, RA
Proposed	PID and PIDF	PFA	ITAE	FDA, TDA, LDR, RA

Frequency domain analysis (FDA), Time domain analysis (TDA), Load disturbance rejection analysis (LDRA), Robustness analysis (RA)

The remaining parts of this study is given as follows. In second section, methodology is presented in sub sections the proposed optimization algorithm (PFA) is explained. In third section, the detailed simulation results are given. Finally, in fourth section, discussions and conclusions are stated.

2. METHOD AND MATERIAL

In this study, to find out the most suitable parameters of a PID controller for DC-MSCS, PFA which is one of the recently introduced meta-heuristic algorithm is used.

This section, broadly tells basic elements of proposed system. For that purpose; primarily, the objective function of the problem defined then PFA which is one of the most important element of the study is explained next DC motor mathematical model is presented finally mathematical model of the proposed PIDF Controller for DC-MSCS and selected parameters are explained.

2. 1. Objective Function

In this study, comparisons were made by using ITAE, which is one of the frequently preferred objective function in the literature. The ITAE improves the transient response, maximum overshoot, rising and settling times of the system. In optimization problems, the lower the value of the ITAE function, the more the controller parameters would be adjusted with minimum error. The equation of this function is given below [5];

$$ITAE = \int_0^{t_{sim}} t.\left|e(t)\right|.dt \tag{1}$$

In this equation, $e(t)$ represents the error, which is the difference between the reference angular velocity and the actual angular velocity, and t_{sim} represents the simulation time.

2. 2. Pathfinder Algorithm (PFA)

PFA as a population based metaheuristic algorithm simulates collective movement of a swarm with a leader. The leader is called as pathfinder in the population. The swarm follows the leader to reach the food in the search space. The updated location of the swarm and the leader are updated mathematically by considering equations given below [16].

$$x_{OM_j}^{i+1} = x_{OM_j}^{i} + \alpha r_1\left(x_{OM_k}^{i} - x_{OM_j}^{i}\right) + \beta r_2\left(x_{PF}^{i} - x_{OM_j}^{i}\right) + \varepsilon \tag{2}$$

$$x_{PF}^{i+1} = x_{PF}^{i} + 2r_3\left(x_{PF}^{i} - x_{PF}^{i-1}\right) + A \tag{3}$$

$$\varepsilon = \left(1 - \frac{i}{i_{max}}\right)u_1 D_{OM_{kj}} \tag{4}$$

$$A = \frac{u_2}{e^{\left(2i/i_{max}\right)}} \tag{5}$$

Pathfinder algorithm is a recently introduced optimization algorithm based on swarm intelligence [16]. It imitates the collective movement of a swarm with a leader called as pathfinder. The swarm follows the leader to move in the search space. The next location formulas, given below, of the leader and the other members are mathematically different from each other. Where *i* is the current iteration, x_{OM_j} is the position vector of the other member *j*, x_{OM_k} is the position vector of the other member *k*, $\alpha r_1 \in [0,2]$, $\beta r_2 \in [0,2]$, $r_3 \in [0,1]$, $u_1 \in [-1,1]$, and $u_2 \in [-1,1]$ are the random numbers, x_{PF} is the position vector of the pathfinder, *A* is the fluctuation coefficient, *ε* is the vibration parameter and $D_{OM_{ij}}$ is the distance between two members. In the point of well comprehension of the algorithm, the Pseudo code of PFA is shown below [16];

More detailed expressions of the algorithm can be found in [16]. The method is applied in optimization problems is explained in the following items:

1. The position of each member of the swarm is considered as promising in the search area. The position that gives the best fitness is chosen as the pathfinder. Thus, the location of the pathfinder is assigned as the best location and this value is not lost in each iteration.

2. The location of the members is updated according to the Pathfinder. During the iterations, the leader may change according to the fitness values of the members. Members can also explore and use hunting or food areas.
3. According to the position of the Pathfinder and other members, the position of each member is updated and they act according to the pathfinder that gives the best fitness. Thus, they approach the neighboring members as well.
4. Random behavior of members causes local optima to stagnate. The vibration vector prevents it from keeping the Pathfinder out of this state.
5. The vector of the ripple rate and approaching the vibration vector to zero value allow exploration but then move to exploitation.

These explanations show that the pathfinder algorithm can be used in optimization problems. The Pathfinder algorithm also allows to stay away from the local optima and thus to offer the best result, thanks to its easy-to-adapt structure. [16]

Algorithm-1 PathFinder

Include the PathFinder parameters
Initialize: The population
Obtain the fitness of initial population
Find out the PathFinder
While** (i<MaxIteration) **do
α and β ←random number in [1,2]
Update the Pathfinder's position through Eq(2)
Test the bound
if** new PathFinder more convenient than old **then
Update PathFinder
end
for** j=2 to MaxIteration **do
Update members' positions through Eq (1)
Test the bound
end for
Calculate the new fitness of members
Find out the best fitness
if** best fitness < fitness of Pathfinder **then
PathFinder←best members
fitness←best fitness
end
for** j=2 to MaxIteration **do
if** new fitness of mem. (j) < fitness of mem. (j) **then
Update members
end
end for
Obtain new A and ε
end while

2.3. DC Motor Model

A dc motor model can be viewed in Figure 1.

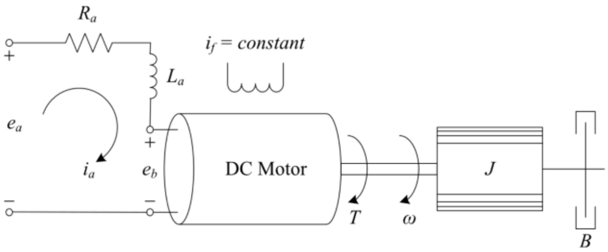

Figure 1. DC motor model [5, 23].

System parameters;

R_a :	Resistance of the armature, [Ω]
L_a :	Inductance of the armature, [H]
i_a :	Current of the armature, [A]
i_f :	Field current, [A]
e_a :	Applied armature voltage, [V]
e_b :	Back emf, [V]
T :	Torque of the motor, [N.m]
ω :	Angular velocity of motor shaft, [rad / s]
J :	Inertia moment of the motor, [kg.m^2]
K_b :	Emf constant, [V.s / rad]
K :	Torque constant of the motor, [N.m / A]
B :	Friction constant of motor, [N. m.s / rad]

Induced emf e_b is directly commensurate to the angular velocity. Angular velocity, $w=\frac{d\phi}{dt}$ [5].

$$e_b = K_b \frac{d\phi}{dt} = K_b w \tag{6}$$

The DC motor speed is controlled by the applied armature voltage. Mathematical expression of the armature voltage is as follows [5],

$$e_a = L_a \frac{di_a}{dt} + R_a i_a + e_b \tag{7}$$

The armature current obtains a torque corresponding to the total of the moments of friction and inertia. The torque equation is [5]:

$$T = J\frac{dw}{dt} + Bw = Ki_a \tag{8}$$

Supposing that each of initial conditions of the system are naught, the Laplace transforms of equations (9)-(11) are as follows [5],

$$E_b(s) = K_b w(s) \tag{9}$$

$$E_a(s) = \left(L_a(s) + R_a(s)\right) I_a(s) + E_b(s) \tag{10}$$

$$T(s) = (Js + Bs)\,w(s) + KI_a(s) \tag{11}$$

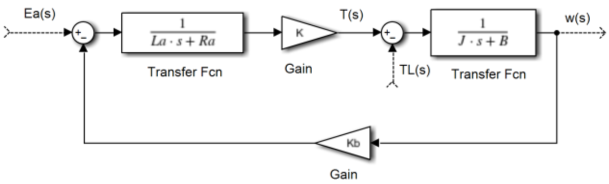

Figure 2. DC motor model in Simulink [5, 23].

DC motor Simulink model is viewed in Figure 2. By considering the motor speed value is an input and the applied armature voltage is an output, the open loop transfer function is written as follows [5, 23];

$$G(s) = \frac{w(s)}{E_a(s)} = \frac{K}{\left(L_a(s) + R_a\right)\left(Js + B\right) + K_b K} \tag{12}$$

2.4. Proposed PIDF Controller for DC-MSCS

A derivative filtered PID (PIDF) controller is proposed alongside the traditional PID controller. Since the derivative controller of the traditional PID controller amplifies the high frequency harmonics, the proposed PIDF controller has a low frequency pass filter.

Table 3. Effects of controllers in closed loop system [27].

	Closed Loop Response	Rising Time	Overshoot	Settling Time	Steady State Error
Proportional Controller	K_p	It decreases	It increases	It varies slightly	It decreases
Integral Controller	K_i	It decreases	It increases	It increases	It is eliminated
Derivative Controller	K_d	It varies slightly	It decreases	It decreases	It varies slightly

This filter is used to reduce high frequency sensor noise and system oscillations [24-26]. The effect of K_p, K_i, K_d controllers in the PID structure on the time response and stability of the system can be seen in the table below [27]. The transfer function of the PIDF controller is as follows;

$$G_{PIDF}(s) = K_P + \frac{K_I}{s} + sK_D\,\frac{N}{s+N} \tag{13}$$

K_P stands for proportional gain constant, K_I for integral gain constant, K_D for derivative gain constant, N for filter coefficient.

Table 2. DC motor parameter values [5].

Parameters	Values
R_a	0.4 Ω
L_a	2.7 H
J	0.0004 kg.m^2
B	0.0022 N.m.s/rad
K	0.015 N.m/A
K_b	0.05 V.s

3. SIMULATION STUDIES

The applications and analyzes of the recommended PID-based controllers for DC motor speed control were carried out in the MATLAB/Simulink software with Intel® core i5 3.11 GHz and 12 GB RAM computer. t_{sim} time was taken as 2.0 s. For the algorithm, the population size and the maximum number of iterations are selected as 20 and 50, respectively. Simulations are performed 10 times. The parameters of the proposed Pathfinder-PIDF controller optimized with ITAE function were obtained as K_p=20, K_i=5.3539, K_d=3.4264 and N=156.9585.

In this section, obtained simulation results are analyzed separately in terms of Time Solution Set Analysis, Frequency Response Analysis, Robustness Analysis, Pole-Zero Map Analysis and Load Disturbance Rejection Analysis.

3.1. Time Solution Set Analysis

Transient state behavior of a system is an oscillatory behavior that shows until it reaches a steady state. The transient behavior is derived from the time solution set response of that system for a given input. In time solution set analysis, used input functions are defined as impulse, step, and ramp.

Table 4. Optimized PID controller parameters for DC motor control.

Algorithm-Controller	K_p	K_i	K_d	N
PF-PIDF (Proposed)	**20**	**5.3539**	**3.4264**	**156.9585**
PF-PID	20	5.3456	3.5415	-
OBL/HGSO-PID	16.9327	0.9508	2.8512	-
HGSO-PID	13.4430	1.2059	2.2707	-
ASO-PID	11.9437	2.0521	2.4358	-
SFS-PID	1.6315	0.2798	0.2395	-
GWO-PID	6.8984	0.5626	0.9293	-
SCA-PID	4.5012	0.5260	0.5302	-

The impulse input is mostly used to examine the stability of the system, the ramp input response is mostly used in the analysis of the steady-state error, and the step input response is used to find out the parameters related to the time domain response of the system. In this study, unit step input is used. The proposed PF-PIDF and PF-PID controller parameters, along with some optimized PID controller parameters for DC motor control in the literature, are given in Table 4.

Comparative unit step responses of the system controlled by the optimized algorithms for DC-MSCS in the literature and the proposed pathfinder algorithm are given in Figure 3.

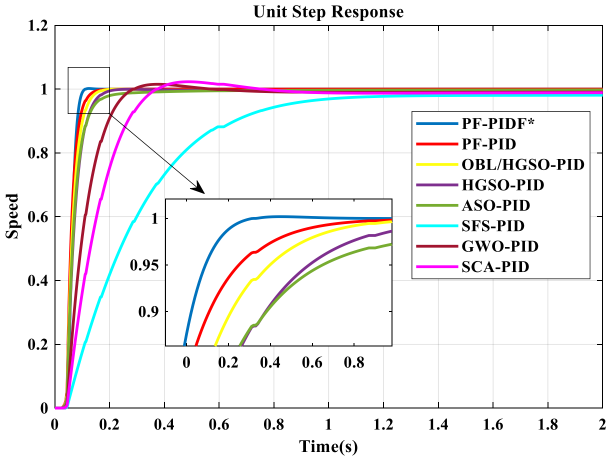

Figure 3. Unit step outputs obtained in simulation for algorithms

With the parameter values given in Table 4, 2s were simulated by applying a unit step input to each controller. As a result of the analysis, the values of the transient response parameters were found. These values are given in Table 5.

Table 5. Transient response analysis parameters of some algorithms in the literature and the proposed algorithm.

Algorithm-Controller	Overshoot (%)	Settling time (s) (±2%)	Rising time(s) (0.1-0.9)	ITAE (%)
PF-PIDF (proposed)	**None**	**0.0524**	**0.0324**	**0.02989**
PF-PID	None	0.0795	0.0447	0.04154
OBL/HGSO-PID	None	0.0946	0.0545	0.9735
HGSO-PID	None	0.1186	0.0684	1.026
ASO-PID	None	0.1535	0.0692	0.7478
SFS-PID	None	1.4475	0.5436	9.001
GWO-PID	1.5062	0.2052	0.1388	2.232
SCA-PID	2.30	0.2031	0.2035	3.07

The desired transient response analysis situation is that the system does not overshoot. Considering the settling time parameter, it was observed that the proposed method reached the desired value in 0.0271s shorter than the PF-PID method, which has the closest settling time value. When rising time parameter is examined, proposed method was performed in 0.0123s shorter than the closest method, PF-PID. In the ITAE parameter, on the other hand, 28% less error rate was achieved than the closest method, PF-PID. As it can be seen from Table 5, proposed PF-PIDF controller has best results due to it has no overshoot and has the least settling and rising times. In the transient response analysis in Figure 3, it is seen that the suggested algorithm performs preferable than the other algorithms with different parameter values in the literature.

3.2. Frequency Response Analysis

The frequency response of a system can be obtained using three different methods which are Bode diagram, Nyquist diagram, Nichols diagram. With these methods, the same information is obtained, but the way they are expressed is different [27]. In this study, Bode diagrams were produced to evaluate the stability performance of the algorithms. Bode command is used in MATLAB to draw the Bode diagram. The Bode diagram is read according to the following three criteria;

Gain margin: The frequency value corresponding to -180° is read in the phase diagram. The amplitude between the point where the read frequency value is found on the gain diagram and the 0dB gain is measured. This amplitude difference is called the gain margin.

Phase Margin: The frequency value corresponding to 0dB is read on the gain diagram. The distance of the read frequency value from the point on the phase diagram to -180° is measured. This measured value is called the phase margin.

Bandwidth: The frequency value corresponding to the -3 dB value is read from the gain diagram. This value read is called the bandwidth.

The frequency response characteristics of the system like gain margin, phase margin and bandwidth are shown in Table 6. According to these parameters comparisons also can be seen with different optimized PID controllers in table. It can be seen from Table 6 that the PIDF controller with PF algorithm is the most stable system considered to the other optimized PID controllers. In terms of bandwidth, the best performance belongs to the proposed algorithm and controller, while 34.82% wider bandwidth is obtained than the PF-PID method, which has the closest bandwidth.

Table 6. Bode results of some algorithms in the literature and the proposed algorithm.

Algorithm-Controller	Gain Margin (dB)	Phase Margin (deg.)	Bandwidth (Hz)
PF-PIDF (Proposed)	**Infinite**	**180**	**66.2**
PF-PID	Infinite	180	49.1
OBL/HGSO-PID	Infinite	180	39.8561
HGSO-PID	Infinite	180	31.7975
ASO-PID	Infinite	180	32.9113
SFS-PID	Infinite	180	4.1183
GWO-PID	Infinite	180	14.9018
SCA-PID	Infinite	180	10.1347

The recommended controller features maximum phase margin 180°, infinite gain margin (minimal delay that destabilizes the system), and maximal bandwidth (broader bandwidth causes shorter rising time). A broad bandwidth enables the system to follow up reference signals with satisfying accuracy.

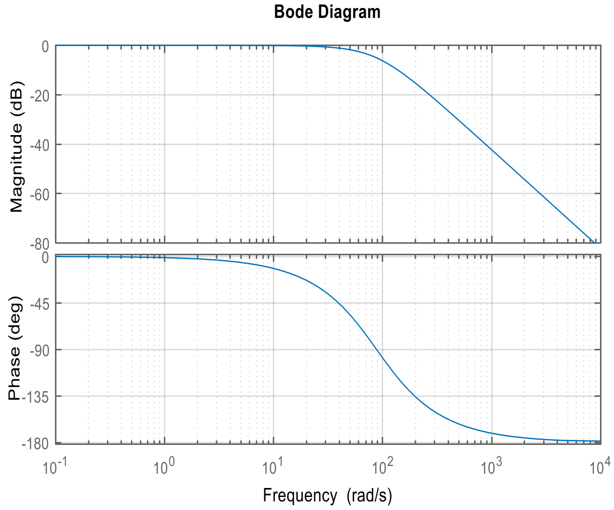

Figure 4. Bode diagram of DC motor speed control system with PF-PIDF controller.

3.3. Robustness Analysis

Robust controller is required to maintain the responsiveness of the system. In abnormal situations, the behavior of the system is monitored and its stability is observed. Changes are made to the values of the parameters to observe the robustness. In this study, two possible cases were observed by changing the R_a value ±25% and K value ±20%. By performing the transient response analysis of the system, ITAE percentages were found and compared with the ITAE percentage outcomes of the previous transient response analyzes. The robustness of the proposed algorithm has also been proven.

Table 7. Values assigned to DC Motor armature resistance R_a and torque constant K parameters.

Cases	R_a	K
1st Case	0.3	0.012
2nd Case	0.5	0.018

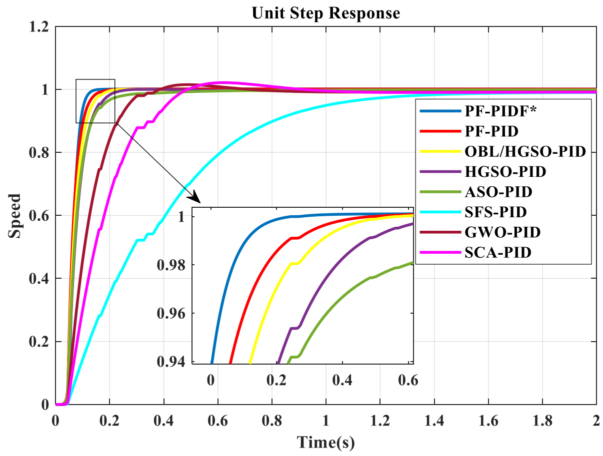

Figure 5. Unit step outputs of the algorithms obtained in the simulation for the 1st case.

In Table 8. for proposed method; overshoot was not observed and when the settling time parameter was taken into account, it reached the desired value in 0.0251s shorter than the PF-PID method, which has the closest settling time value. When rising time parameter is examined, proposed method was performed in 0.0133s shorter than the closest method, PF-PID. In the ITAE parameter, 5.32% less error rate was achieved than the closest method, PF-PID.

Table 8. Transient response analysis parameters for 1st Case of some algorithms in the literature and the proposed algorithm.

Algorithm-Controller	Overshoot (%)	Settling time (s) (±2%)	Rising Time (s) (0.1-0.9)	ITAE (%)
PF-PIDF (Proposed)	**None**	**0.0731**	**0.0423**	**0.2755**
PF-PID	None	0.0982	0.0556	0.291
OBL/HGSO-PID	None	0.1163	0.0678	0.8967
HGSO-PID	None	0.1455	0.0848	0.8992
ASO-PID	None	0.1934	0.0869	0.5443
SFS-PID	None	1.2033	0.6568	10.12
GWO-PID	1.52	0.2469	0.1681	2.114
SCA-PID	2.15	0.2168	0.2445	2.922

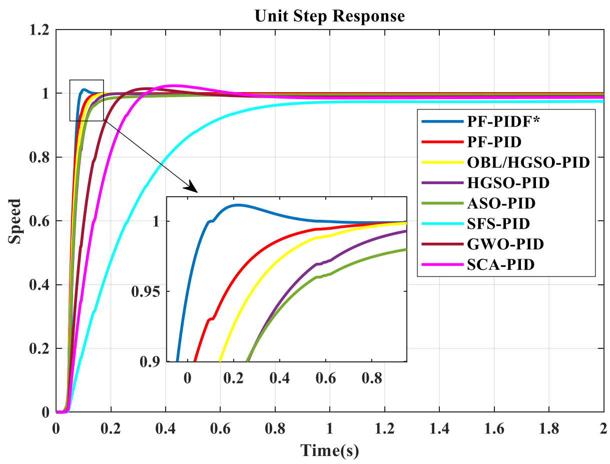

Figure 6. Unit step outputs of the algorithms obtained in the simulation for the 2nd case.

In Table 9. for proposed method; overshoot was observed but when the settling time parameter was taken into account, it reached the desired value in 0.0266s shorter than the PF-PID method, which has the closest settling time value. When rising time parameter is examined, proposed method was performed in 0.0112s shorter than the closest method, PF-PID. In the ITAE parameter, 4.08% less error rate was achieved than the closest method, PF-PID.

Table 9. Transient response analysis parameters for 2nd Case of some algorithms in the literature and the proposed algorithm.

Algorithm-Controller	Overshoot (%)	Settling time (s) (±2%)	Rising Time (s) (0.1-0.9)	ITAE (%)
PF-PIDF (Proposed)	1.15	**0.0402**	**0.0261**	**0.174**
PF-PID	None	0.0668	0.0373	0.1814
OBL/HGSO-PID	None	0.0798	0.0457	1.029
HGSO-PID	None	0.1002	0.0573	1.117
ASO-PID	None	0.1254	0.0570	0.8906
SFS-PID	None	0	0.4647	8.695
GWO-PID	1.45	0.1764	0.1183	2.333
SCA-PID	2.37	0.1851	0.1753	3.218

3.4. Pole-Zero Map Analysis

In the pole-zero map analysis, the poles of the closed-loop transfer function of the system and the damping ratios are found. If the poles are on the left side of the coordinate system i.e. in the -x direction, then the system is stable. Another situation is that if it stays on the right side of the coordinate system i.e. the +x direction, then the system is unstable. The damping ratio, on the other hand, is a measure of the degree of resistance to change in the system response. The Pole-Zero Plot block was used in MATLAB to find the ground curve of the roots. In order to make a comparison, the DC motor initial parameter values and the cases where the parameters change ±20% and ±25% are taken into consideration. When the damping ratio is between 0 and 1, the system has two virtual poles. These systems are called damped. If it is equal to 1, the system has two real poles of the same value. These systems are called critically damped systems. If we look at the ground root curve results of DC motor initial values and the ground root curve results of two possible case studies, it is seen the systems are damped and critically damped. As can be seen from Tables 11 and 12, changes in parameters are ineffective at zeros of the system. They are also stable systems because they each have poles located on the left side of the coordinate plane

Tablo 10. Ground curve of roots results of some algorithms in the literature and the proposed algorithm for DC motor parameter values in Table 2.

Algorithm-Controller	Poles	Zeros	Damping Ratios
PF-PIDF (Proposed)	-78.5+56i -78.5-56i -5.36 -0.281	-5.36 -0.281	0.814 1
PF-PID	-1e+06 -59.1 -5.37 -0.281	-5.37 -0.281	1
OBL/HGSO-PID	-1e+06 -47.2 -5.96 -0.0564	-5.88 -0.0567	1
HGSO-PID	-1e+06 -37.5 -5.92 -0.0905	-5.83 -0.0911	1
ASO-PID	-9.96e+03 -41.6 -4.65 -0.177	-4.72 -0.178	1
SFS-PID	-1e+04 -4.76+2.2i -4.76-2.2i -0.17	-6.63 -0.176	1 0.908
GWO-PID	-9.98e+03 -10.6+1.93i -10.6-1.93i -0.0815	-7.34 -0.0825	1 0.984
SCA-PID	-9.99e+03 -7.21+4.83i -7.21-4.83i -0.117	-8.36 -0.119	1 0.831

Table 11. Ground curve results of some algorithms in the literature and the proposed algorithm for 1st case.

Algorithm-Controller	Poles	Zeros	Damping Ratios
PF-PIDF (Proposed)	-78.5+6.08i -78.5-6.08i -5.35 -0.282	-5.36 -0.281	0.997 1
PF-PID	-1e+06 -39.3 -5.36 -0.282	-5.37 -0.281	1
OBL/HGSO-PID	-1e+06 -31.2 -5.99 -0.0564	-5.88 -0.0567	1
HGSO-PID	-1e+06 -24.8 -5.96 -0.0907	-5.83 -0.0911	1
ASO-PID	-9.97e+03 -28 -4.59 -0.178	-4.72 -0.178	1
SFS-PID	-1e+04 -4.05+1.22i -4.05-1.22i -0.174	-6.63 -0.176	1 0.958
GWO-PID	-9.99e+03 -7.94+3.69i -7.94-3.69i -0.0817	-7.34 -0.0825	1 0.907
SCA-PID	-9.99e+03 -5.7+4.18i -5.7-4.18i -0.117	-8.36 -0.119	1 0.807

Tablo 12. Ground curve results of some algorithms in the literature and the proposed algorithm for 2nd case.

Algorithm-Controller	Poles	Zeros	Damping Ratios
PF-PIDF (Proposed)	-78.5+56i -78.5-56i -5.36 -0.281	-5.36 -0.281	0.814 1
PF-PID	-1e+06 -59.1 -5.37 -0.281	-5.37 -0.281	1
OBL/HGSO-PID	-1e+06 -47.2 -5.96 -0.0564	-5.88 -0.0567	1
HGSO-PID	-1e+06 -37.5 -5.92 -0.0905	-5.83 -0.0911	1
ASO-PID	-9.96e+03 -41.6 -4.65 -0.177	-4.72 -0.178	1
SFS-PID	-1e+04 -4.76+2.2i -4.76-2.2i -0.17	-6.63 -0.176	1 0.908
GWO-PID	-9.98e+03 -10.6+1.93i -10.6-1.93i -0.0815	-7.34 -0.0825	1 0.984
SCA-PID	-9.99e+03 -7.21+4.83i -7.21-4.83i -0.117	-8.36 -0.119	1 0.831

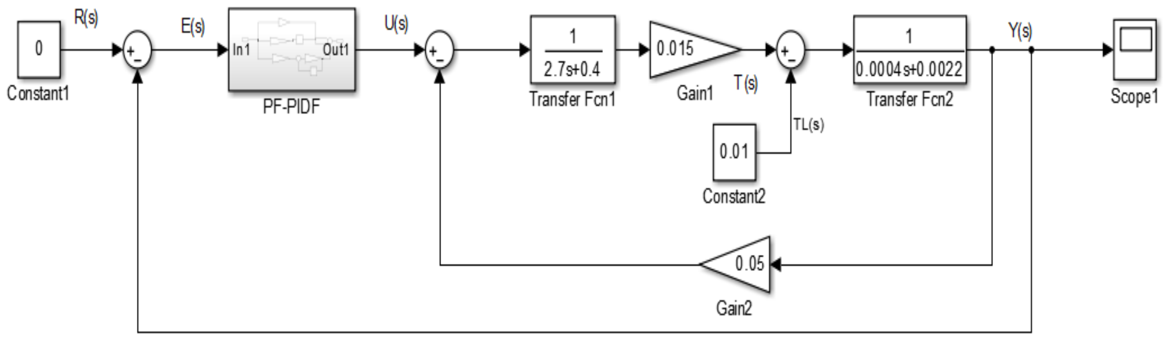

Figure 7. Block diagram representation of DC Motor system with PF-PIDF controller with $T_L = 0.01$ disturbance load input.

3.5. Load Disturbance Rejection Analysis

In this analysis, the change status of the load torque in the DC-MSCS has been examined. When there is a deterioration in the system due to the load torque, the system should bring the output speed response to zero as soon as possible against this deterioration. Performances of the controllers are compared for $T_L = 0.01$ disturbance load input response in Figure 8. As can be viewed from the figure, PF-PIDF has low settling time, rise time and overshoot.

In other words, it has been seen that the proposed PF-PIDF controller is more successful in suppressing the load disturbance in the system compared to other controllers.

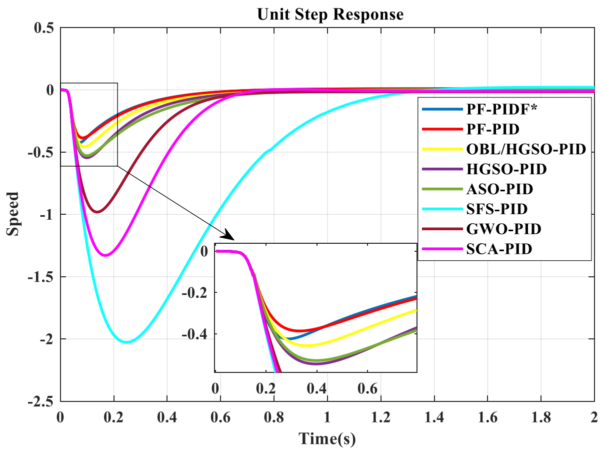

Figure 8. Unit step outputs of disturbance load input algorithms.

4. DISCUSSIONS AND CONCLUSIONS

In order to provide the best control in the DC-MSCS, the PIDF controller which is optimized with the Pathfinder algorithm is designed. The controllers with different approachments in the literature and the recommended PF-PIDF controller were compared. Time solution set analysis, frequency response analysis, robustness analysis, pole-zero map analysis and disturbance load rejection analysis of each controller were performed in MATLAB environment and performance analyzes were compared. In the first analysis, for proposed method overshoot was not observed. On the other hand, an average settling time of 2.19s was obtained in other methods, while the proposed method reached the desired value much shorter time as 0.0524s. It means that settling time of the proposed method 2.137s shorter than the average settling time of other methods. Moreover, when PF-PID is examined as the closest method to proposed one, it was seen that proposed method obtained 0.0271s shorter result according to the PF-PID method. While the average rising time of the other methods was 0.160s, the proposed method performed as 0.0324s i.e. it is 0.1276s shorter time according to the average rising time of other methods. When PF-PID is examined as the closest method to proposed one, proposed method has 0.0123s shorter rising time according to PF-PID method. As considering the ITAE, the average error of the other methods is 2%, while the proposed method error is about 0.03%. When PF-PID is examined as the closest method to proposed one, it was seen that proposed method gave the better results.

In frequency response analysis the proposed method obtained 34.82% wider bandwidth than the PF-PID method with the closest bandwidth. Compared to other algorithms in the literature, in the robustness analysis has 1.15% overshoot only in the 2nd case. Apart from that, it has been seen that it has the shortest settling, rise times, the least ITAE value, a stable structure. For example; in the 1st case, for proposed method overshoot was not observed. On the other hand, an average settling time of 1.864s was obtained in other methods, while the proposed method reached the desired value much shorter time as 0.0731s. It means that settling time of the proposed method 1.791s shorter than the average settling time of other methods. Furthermore, when PF-PID is examined as the closest method to proposed one, it was seen that proposed method obtained 0.0251s shorter result according to the PF-PID method. While the average rising time of the other methods was 0.194s, the proposed method performed as 0.0423s i.e. it is 0.152s shorter time according to the average rising time of other methods. When PF-PID is examined as the closest method to proposed one, proposed method has 0.0133s shorter rising time according to PF-PID method. As considering the ITAE, the average error of the other methods is %2.54, while the proposed method error is about %0.0275. When PF-PID is examined as the closest method to proposed one, it was seen that proposed method again gave the better results. Besides, it has also been observed that it is more effective than other algorithms in suppressing the system against the sudden change in the system due to the disturbance load input. It has been observed that the recommended PF-PIDF based controller is more successful in controlling the speed control of the DC motor compared to other approach controllers in the literature. In addition to the PF-PIDF controller, the PF-PID controller also performed quite well compared to the different approach controllers suggested in the literature. In the robustness analysis, although the PF-PIDF controller exceeded in the 2nd case, the PF-PID controller did not. The PF-PID controller performed better than the proposed PF-PIDF controller in the analysis of the disturbance load input.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS)

Şeymanur BAŞLIK: Modelled the case building, performed the simulation and edited the manuscript.

Erhan SESLİ: Modelled the case building, performed the simulation and edited the manuscript.

Ömür AKYAZI: Modelled the case building, performed the simulation and edited the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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