ARTICLE IN PRESS

Computers and Electrical Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

FOPID controller with fractional filter for an automatic voltage regulator[☆]

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ARTICLE INFO

Keywords:
Automatic voltage regulator
Fractional filter
Fractional order PID
Sine–cosine algorithm
Robustness analysis

ABSTRACT

This article presents a novel fractional order proportional–integral–derivative (FOPID) controller with fractional filter for an automatic voltage regulator (AVR) system. The proposed controller has seven independent parameters to be set. These parameters are optimally tuned by using sine–cosine algorithm (SCA) capable of balancing exploration and exploitation phases to find the optimal solution. The optimally tuned controller named as SCA-FOPIDFF is employed to enhance the performance of the AVR system. In order to show the effectiveness of the proposed controller, a FOPID controller with integer filter called as SCA-FOPIDF, a traditional FOPID controller without filter called as SCA-FOPID, a PID controller with fractional filter called as SCA-PIDFF, and a PID controller with integer filter called as SCA-PIDF are also designed for the AVR system using the SCA with the same objective function. In addition, the superiority of the proposed controller is also validated by the comparison with published studies proposing optimally tuned PID and FOPID controllers for the AVR system. Frequency response characteristics of the proposed controller obtained from bode analysis are presented. Finally, the robustness of the designed controllers are examined separately against both parameter uncertainties in the AVR system and external disturbances injected into the AVR system. Considering the overall results presented, it is clear that the fractional filter in the proposed SCA-FOPIDFF controller has significantly improve the AVR system performance and that the proposed controller can be successfully applied to the AVR system.

1. Introduction

Real power losses in power generating units is a general issue needing to be solved. Researchers study on automatic voltage regulator (AVR) systems to minimize these power losses. The main aim of these AVR systems is to keep generator voltage at the desired level with high accuracy. Ensuring this accuracy increases the durability of equipment designed with the rated voltage in a power system network. In addition, the stability and robustness of the AVR system remarkably affect the safety of the power system [1]. Therefore, increasing the efficiency of the AVR system by developing new control techniques is still a current and important issue. In particular, improvement of the transient response of the AVR system within the stability limits is heavily studied.

Until now, several control methods have been proposed by researchers to control generator voltage of the AVR system in order to achieve better system response. Proportional–integral–derivative (PID) controller [2–4], fractional-order PID controller [5,6], fuzzy logic controller [7], sliding mode controller [8], and fractional high-order differential feedback controller [9] are some of the

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[☆] This paper was recommended for publication by associate editor Dr. J. Garcia-Alfaro.

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https://doi.org/10.1016/j.compeleceng.2020.106895
Received 12 April 2020; Received in revised form 23 October 2020; Accepted 26 October 2020

Please cite this article as: Mustafa Sinasi Ayas, Erdinc Sahin, *Computers and Electrical Engineering*, https://doi.org/10.1016/j.compeleceng.2020.106895

proposed control techniques. Despite this wide varieties, the researchers have more focused on the PID controller or its combinations due to its functionality and simple control structure.

1.1. Literature review

As with other controllers, parameters of a PID controller need to be well tuned in order to obtain satisfying system response. In other words, to get the best system response, it is necessary to optimally tune the parameters of the PID controller. However, depending on the industrial application, this optimally tuning process is a significant challenge. In recent years, meta-heuristic optimization algorithms have been preferred over traditional tuning methods such as Ziegler–Nichols and Cohen–Coon and trial-error-tuning approach, since in most cases they cannot achieve the optimal results [3,10].

As with the other industrial applications, researchers have designed PID controllers for the AVR system using evolutionary algorithms. Genetic algorithm (GA) [2], cuckoo search (CS) algorithm [3], sine–cosine algorithm (SCA) [4], chaotic ant swarm (CAS) algorithm [5], improved kidney inspired algorithm (IKA) [10], artificial bee colony (ABC) [11], differential evolution (DE) [11], particle swarm optimization (PSO) [2,12], continuous fire fly algorithm (CFA) [13], symbiotic organisms search (SOS) algorithm [14], salp swarm algorithm (SSA) [15], bacterial foraging optimization algorithm (BFOA) [16], gravitational search algorithm (GSA) [17], ant lion optimizer (ALO) [18], local unimodal sampling (LUS) algorithm [19], pattern search algorithm (PSA) [20], and biogeography-based optimization (BBO) [21] have been employed to optimally tune the parameters of the PID controller for the AVR system.

In addition to PID controller, FOPID controller providing more flexible design opportunities in many engineering fields has also utilized in AVR system to enhance generator voltage quality. Although the FOPID controller has more design flexibility thanks to its two additional parameters compared to the traditional PID controller, it is a more difficult controller to design as five independent parameters need to be tuned. To tune these parameters in AVR system, GA [5], PSO [5], CAS [5], multi-objective extremal optimization (MOEO) [6], SCA [22], and simulated annealing optimization (SAO) [23] algorithms have been used in the AVR system.

In the aforementioned studies, researchers aim to improve the AVR system response in terms of transient response characteristics such as percentage overshoot, settling time, peak time and rise time and steady-state error. Although the purpose of the researchers is in the same direction, they have preferred different type of algorithms since none of the algorithms ensure to find the best controller parameter in the AVR system. In other words, employing a different algorithm can achieve better controller parameters, resulting in better AVR system response.

As another way of improving the AVR system response, researchers have also considered different type of objective functions in their optimization algorithms mentioned above. Integral of time-weighted absolute error (ITAE) [13,15,17–19], integral of absolute error (IAE) [17–19], integral of time-weighted squared error (ITSE) [11,15,17–19,21], and integral of squared error (ISE) [17–19] are the error-based objective functions utilized in AVR system. In addition, user defined objective functions containing a combination of percentage overshoot, settling time, peak time, rise time, steady-state error, phase margin, and gain margin are also employed for AVR system [2–5,9,10,13,14,16–18,20]. A popular user defined objective function including percentage overshoot, settling time, rise time and steady-state error was presented in [2]. This objective function has been commonly preferred by researchers to make a fair comparison between their proposed approach and the available approaches in the literature.

1.2. Motivation of the present work

In the light of the designed PID and FOPID controllers for the AVR system mentioned in literature review section, it can be concluded that researchers achieved a stable and satisfying AVR system response by using either traditional PID controller or its more flexible version, i.e. FOPID controller. Furthermore, that the AVR system responses obtained by the FOPID controller is better than the responses achieved by the PID controller is deduced from FOPID controlled studies. However, neither PID controlled studies nor FOPID controlled ones did not employ a filter in their controllers. Note that a low pass filter should be utilized in derivative part of both the PID and the FOPID controller to solve realizability problem. Moreover, derivative kick effect, which occurs as a result of instantaneous change in controller input signal, i.e. error signal, should be eliminated by using a low pass filter in derivative part of the controllers.

By considering all the aforementioned comments, this paper aims to design both PID and FOPID controller with filters to improve the AVR system response. Moreover, controllers are designed not only with integer order but also with fractional order filter.

In this paper, SCA is used in controller design process. Because SCA is able to avoid local minimum solution, explore different regions of the search space and converge towards to global solution effectively compared to well-known optimization algorithms such as PSO, GA, bath algorithm (BA), GSA, and flower pollination algorithm (FPA) [24]. Furthermore, SCA has been applied to many engineering problems successfully since its first release. Power flow scheduling of hybrid power systems [25], partial shading detection for photovoltaic (PV) arrays [26], and controller optimization for load-frequency control of hybrid power systems [27] are some of the engineering applications of SCA published in 2020.

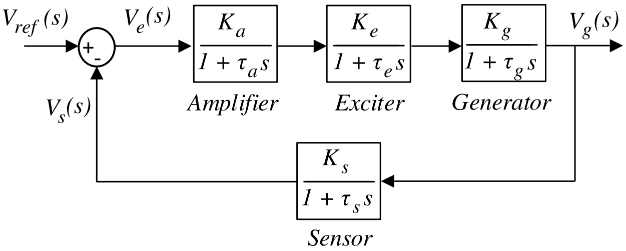


Fig. 1. Block diagram of an AVR system without any controller.

1.3. Contribution of the present work

The main purpose of this paper is to design a FOPID controller with fractional filter, called as SCA-FOPIDFF, for an AVR system to achieve a better system response than the available studies in the literature. The SCA-FOPIDFF has seven independent parameters all of which are optimally tuned by SCA in which a popular user defined objective function given in [2] is used. In addition, a FOPID controller with integer filter called as SCA-FOPIDF, a traditional FOPID controller without filter called as SCA-FOPID, a PID controller with fractional filter called as SCA-PIDFF, and a PID controller with integer filter called as SCA-PIDF are also designed for the AVR system using SCA with the same objective function to see the effect of the filters on the AVR system response in terms of transient response characteristics. A SCA tuned PID controller without filter is not designed in this paper since it was presented in the literature [4]. The designed five different controllers, i.e. SCA-FOPIDFF, SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, and SCA-PIDF, are tested on the AVR system. For each controller, time-domain analysis, frequency-domain analysis, and robustness analysis including both robustness against parameter uncertainties and external disturbance are carried out in this paper.

The main contributions of this study are sixfold.

1. The first FOPID controller with fractional filter, i.e. SCA-FOPIDFF, design is proposed for an AVR system and its effectiveness is demonstrated.
2. For an AVR system, during design process of a FOPID controller with fractional filter, an evolutionary algorithm (SCA) is utilized for the first time.
3. A FOPID controller with integer filter, i.e. SCA-FOPIDF, is designed for an AVR system for the first time and its superiority on the SCA-FOPID not having any filter is shown.
4. An evolutionary algorithm (SCA) is used for the first time in the design process of a FOPID controller with integer filter for an AVR system.
5. A PID controller with fractional filter, i.e. SCA-PIDFF, design for the AVR system is presented for the first time in the literature. Its advantage on the PID controller with integer filter (SCA-PIDF) and PID controller without filter (SCA-PID) is demonstrated.
6. The effects of both the integer order and the fractional order filters in the PID and FOPID controller are analyzed.

The rest of the paper is organized as follows. The modeling of an AVR system is described in Section 2. The details of a FOPID controller are presented in Section 3. In Section 4, a brief explanation of the optimization algorithm used in this study, i.e. SCA, is given. Design process of the proposed controllers (SCA-FOPIDFF, SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, SCA-PIDF) for the AVR system using SCA is presented in Section 5. Simulation results and discussions are presented in Section 6 in detail. Finally, conclusions are given.

2. AVR system model

An AVR system, consisting of amplifier, exciter, generator, and sensor components, aims to keep output voltage of a synchronous generator stationary at a desired level [1,2,28]. An AVR system without any controller can be constructed as in Fig. 1, where each component of the AVR system is modeled by a first order transfer function with gain K and time constant τ. The values of the parameters K and τ vary within certain ranges given in Table 1, [1,2,5,28–30].

In this study, the parameters of the AVR system components are set to $K_a = 10$, $\tau_a = 0.1$, $K_e = 1$, $\tau_e = 0.4$, $K_g = 1$, $\tau_g = 1.0$, $K_s = 1$, and $\tau_s = 0.01$ by considering the studies [1,2,5,28–30]. Step response of the uncontrolled AVR system with these parameters is shown in Fig. 2. The obtained result indicates that a large steady-state error, long settling time, and high overshoot occurred in the response. Therefore, the steady-state and transient region characteristics of the AVR system require to be improved.

3. Fractional order PID controller

A FOPID controller bases on fractional calculus allowing differentiation and integration with non-integer orders. This non-integer operators provide more flexible design opportunities in many engineering fields such as control theory, signal processing, robotics, etc. Therefore, fractional calculus has attracted researchers' attention especially in control system area. Riemann–Liouville, Grunwald–Letnikov, and Caputo definitions are well-known and commonly used fractional calculus definition. In addition

Table 1
Transfer functions of the AVR system components Table 1 [1,5,28–30].

	Transfer function	Limits of parameters		Used parameters
		Gain	Time constant (s)	
Amplifier	$T(s) = K_a/(1+\tau_a s)$	$10 \leqslant K_a \leqslant 40$	$0.02 \leqslant \tau_a \leqslant 0.1$	$K_a = 10,\ \tau_a = 0.1$
Exciter	$T(s) = \frac{K_e}{1+\tau_e s}$	$1 \leqslant K_e \leqslant 10$	$0.4 \leqslant \tau_e \leqslant 1.0$	$K_e = 1,\ \tau_e = 0.4$
Generator	$T(s) = \frac{K_g}{1+\tau_g s}$	$0.7 \leqslant K_g \leqslant 1.0$	$1.0 \leqslant \tau_g \leqslant 2.0$	$K_g = 1,\ \tau_g = 1.0$
Sensor	$T(s) = \frac{K_s}{1+\tau_s s}$	$0.9 \leqslant K_s \leqslant 1.1$	$0.001 \leqslant \tau_s \leqslant 0.06$	$K_s = 1,\ \tau_s = 0.01$

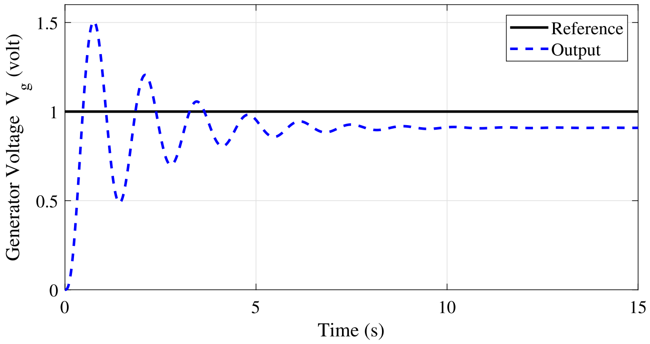


Fig. 2. Step response of the AVR system without any controller.

approximation methods are also commonly preferred because of calculation difficulties of the mentioned definitions. Oustaloup approximation method is one of these approximation methods and it employs integer transfer functions to converge fractional order transfer function.

In this study, fractional transfer functions are designed with a 5th order Oustaloup method approximated transfer function in the frequency range of $w \in \left[10^{-5}, 10^{5}\right]$ r/s.

A FOPID controller containing fractional integrator and differentiator is written in the form of $PI^{\lambda}D^{\mu}$, where λ and μ are the orders of the integrator and differentiator, respectively. (1) depicts general transfer function of a FOPID controller, whose block diagram is shown in Fig. 3d, with proportional, integral and derivative gains of K_P, K_I, and K_D, respectively.

$$G_{FOPID}(s) = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \tag{1}$$

where λ and μ are the order of integrator and differentiator, respectively. Different from traditional PID controller, a FOPID controller has two more parameters, i.e. λ and μ, required to tune. Although these additional parameters provide more design flexibility to control system, they increase the complexity of the controller and make parameter tuning process more difficult compared to traditional PID controller.

4. Sine–cosine algorithm

Sine–cosine algorithm (SCA) is a recently developed heuristic optimization technique based on sine and cosine trigonometric functions [24]. Sine and cosine mathematical functions are used to explore and exploit the unknown search space. The algorithm has a simple structure and provides effective solutions in multidimensional search space. Compared to well-known optimization algorithms such as PSO, GA, BA, GSA, and FPA, SCA is able to avoid local minimum solution, explore different regions of the search space and converge towards to global solution effectively.

As in the other evolutionary algorithms, SCA starts from random positions corresponding to initial solutions in search space. These random solutions are used to calculate an objective function value. In order to achieve the best solution corresponding to the best objective function value, the positions are required to be updated . In general, exploration and exploitation phases are performed for position update during an evolutionary algorithm optimization process. In SCA, both of the phases are combined and the positions are updated using (2) where X_i^t and P_i^t represent the current position and destination position in ith dimension at tth iteration, respectively.

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 sin(r_2)\left|r_3 P_i^t - X_i^t\right|, & r_4 < 0.5 \\ X_i^t + r_1 cos(r_2)\left|r_3 P_i^t - X_i^t\right|, & r_4 \geq 0.5 \end{cases}. \tag{2}$$

In (2), r_1, r_2, r_3, and r_4 are random numbers, | . | calculates the absolute value, and $sin(.)$ and $cos(.)$ represent sine and cosine trigonometric functions. According to original SCA article [24], r_1, r_2, and r_4 should be randomly selected in the range of [−2,

Table 2
The parameters required to be tuned in controller design process.

Controller	Parameters	# of parameters
FOPIDFF	K_P, K_I, K_D, λ, μ, NN, λ_f	7
FOPIDF	K_P, K_I, K_D, λ, μ, NN	6
FOPID	K_P, K_I, K_D, λ, μ	5
PIDFF	K_P, K_I, K_D, NN, λ_f	5
PIDF	K_P, K_I, K_D, NN	4
PID	K_P, K_I, K_D	3

Table 3
Optimized controller parameters for the AVR system.

Controller	Controller parameters					Filter parameters	
	K_P	K_I	K_D	λ	μ	NN	λ_f
SCA-FOPIDFF[a]	1.9770	0.4655	0.3696	1.0912	1.3266	236.4229	0.0455
SCA-FOPIDF[a]	1.9806	0.2072	0.3046	1.2137	0.3434	167.8371	–
SCA-FOPID[a]	1.4509	0.6567	0.3076	1.1442	1.2145	–	–
SCA-PIDFF[a]	0.6751	0.4927	0.2814	–	–	48,9453	0.0104
SCA-PIDF[a]	0.6828	0.4199	0.2495	–	–	258.1575	–
SCA-FOPID [22]	1.5447	0.5691	0.2389	1.3522	1.3195	–	–
SA-FOPID [23]	0.7837	0.5027	0.2307	1.0103	1.0727	–	–
CAS-FOPID [5]	1.0537	0.4418	0.2510	1.0624	1.1122	–	–
PSO-FOPID [5]	1.6264	0.2956	0.3226	1.3183	1.1980	–	–
GA-FOPID [5]	1.6947	0.8849	0.3964	1.0248	1.1296	–	–
SCA-PID [4]	0.9826	0.8337	0.4982	–	–	–	–
BBO-PID [21]	1.2464	0.5893	0.4596	–	–	–	–
ABC-PID [11]	1.6524	0.4083	0.3654	–	–	–	–
CAS-PID [5]	0.6746	0.6009	0.2618	–	–	–	–

[a] Represents the proposed controllers.

2], [0, 2π], and [0, 1], respectively. The last random parameter representing random weight of the destination position is selected either $r_3 < 1$ or $r_3 > 1$.

The random value r_1, which is the amplitude of the sine and cosine functions, can also be adaptively adjusted to balance exploration and exploitation phases by using (3).

$$r_1 = a - t\frac{a}{T} \tag{3}$$

where t and T represent the current and maximum iteration numbers, respectively, and a is a constant value. (3) implies that $r_1$linearly decreases to 0.

The implementation of the SCA is described as follows:

Step 1. Initialize the search agents with random positions.
Step 2. Calculate objective function values of the search agents by using predefined objective function.
Step 3. Update the destination position (P) with the best objective function value so far.
Step 4. Update the values of r_1, r_2, r_3, and r_4.
Step 5. Update the position of each search agents to their new position by using (2).
Step 6. Increase iteration number, go to step 2 and repeat the steps until stopping criterion is met.
Step 7. As the global optimum solution, return the best position corresponding to the best objective function value.

5. Design of the proposed controllers by SCA

Design process of the main proposed controller, i.e. SCA-FOPIDFF, and the other proposed controllers, i.e. SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, and SCA-PIDF, for the AVR system using SCA is presented in this section. The block diagram of these controllers and their transfer functions are depicted in Fig. 3 which also contains traditional PID controller. Considering the block diagrams, it is concluded that a traditional PID controller has three different parameters to be set, while there are seven different parameters to be set for a FOPIDFF controller. The parameters required to be tuned for each controller are given in Table 2.

In this study, SCA is employed to minimize the following objective function proposed by Gaing [2]

$$f(\theta) = (1 - e^{\beta})(M_p + E_{ss}) + e^{\beta}(t_s - t_r) \tag{4}$$

where θ is parameter vector, $\beta = 1$ and M_p, t_s, t_r, and E_{ss} represent percentage overshoot, settling time, rise time, and steady-state error. θ contains the parameters, which is given in Table 2, to be tuned for the controller.

In SCA, population size and total iteration number are set to as 50 and 100, respectively. In order to design the aforementioned five different controllers (SCA-FOPIDFF, SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, and SCA-PIDF) SCA is employed for 10 times since the algorithm starts from random initial positions corresponding to the solutions. Generally, for an optimization process, a terminating

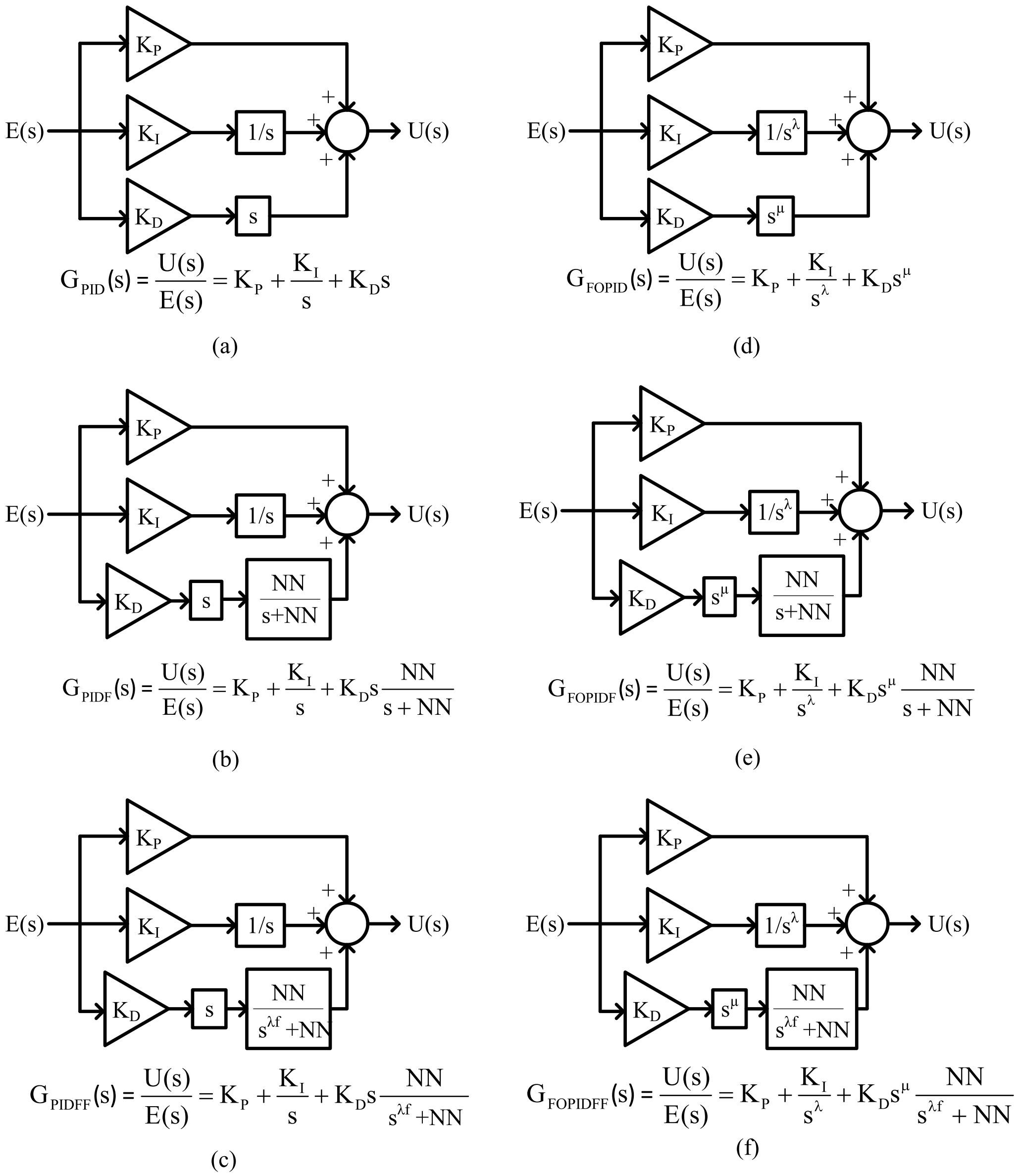


Fig. 3. Block diagram of the controllers and their transfer functions. a: PID, b: PIDF, c: PIDFF, d:FOPID, e:FOPIDF, f: FOPIDFF.

condition is determined to stop the algorithm. This may be a desired numerical value for a variable. If the algorithm reaches the lower value of the desired condition, it can be said that the finishing condition is satisfied. Whereas, such a finishing condition is not suitable for optimization problems in control engineering applications. Because the algorithm may not achieve to reach the desired value even performing hundreds or thousands of iteration which takes a very long time. For this reason, as another way for optimization process, the algorithm can be employed for several times (5, 10, 15 or more) and the best iteration can be used for the system. The powerful metaheuristic algorithms such as the SCA can handle random initial position issue in a limited search space successfully. In this study, for each proposed controller, the SCA is employed for 10 times corresponding 10 different trials. The obtained cost function values in these 10 trials are so close to each other satisfying that the SCA is capable of reaching the optimal controller parameter values. Should be not that there is not a major difference among these 10 trial results. The best obtained optimized controller parameters are given in Table 3 which also includes other PID and FOPID controllers proposed by the researches and compared in this study.

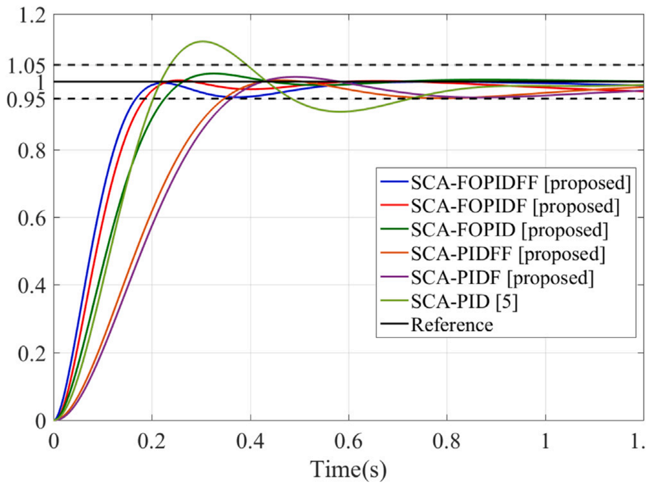


Fig. 4. Step response of the AVR system with different controllers.

Table 4
Obtained transient response characteristics, steady-state errors and performance value.

Controller	Transient Response Characteristics				
	M_p (%)	t_s (s) ∓5%	t_r (s) 0.1 → 0.9	E_{ss}	$f(\theta)$
SCA-FOPIDFF[a]	0.1262	**0.1670**	**0.1230**	0	**0.0170**
SCA-FOPIDF[a]	0.4297	0.1860	0.1340	0	0.0218
SCA-FOPID[a]	2.4223	0.2260	0.1660	0	0.0374
SCA-PIDFF[a]	0.5260	0.3460	0.2500	0	0.0386
SCA-PIDF[a]	1.4314	0.3610	0.2600	0	0.0462
SCA-FOPID [22]	**0.0100**	0.2183	0.1549	0	0.0234
SA-FOPID [23]	0.52	0.4057	0.2653	0	0.0547
CAS-FOPID [5]	0.1678	0.3037	0.2223	0	0.0319
MOEO-FOPID [6]	3.2038	0.1800	0.1300	0	0.0386
PSO-FOPID [5]	0.0953	0.4563	0.1375	0	0.1209
GA-FOPID [5]	9.26	0.3395	0.1298	0	0.1361
SCA-PID [4]	11.41	0.724	0.148	0	0.2844
MOEO-PID [6]	4.5081	0.3900	0.2800	0	0.0689
BBO-PID [21]	15.52	0.766	0.149	0	0.3281
ABC-PID [11]	25.01	0.920	0.156	0	0.4391
CAS-PID [5]	1.76	0.355	0.243	0	0.0523

[a] Represents the proposed controllers.

6. Simulation results and discussions

The implementations of the proposed controllers for the AVR system and their analyses are performed in Matlab/Simulink simulation platform at a computer having core i7 3.6 GHz CPU and 8 GB RAM. All simulations are carried out with sampling period of 1 ms. The analyses made in this study contain

- Time-domain analysis (step response)
- Frequency-domain analysis (bode diagram)
- Robustness analysis (robustness against parameter uncertainties and external disturbance)

6.1. Time domain analysis

For the same AVR system controlled by different controllers (SCA-FOPIDFF, SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, SCA-PIDF, and SCA-PID), transient and steady-state responses for a unit step reference input are analyzed in this section. Note that the controller parameters are given in Table 3.

The obtained generator voltage V_g responses and their corresponding transient response characteristics such as percentage overshoot (M_p), settling time (t_s), and rise time (t_r) are given in Fig. 4 and Table 4, respectively. Table 4 also presents the values of the defined objective function ($f(\theta)$) which is calculated by (4). That the proposed SCA-FOPIDFF has the best step response in terms of objective function $f(\theta)$ can be concluded from Table 4. Moreover, a short settling time and rise time are obtained by the

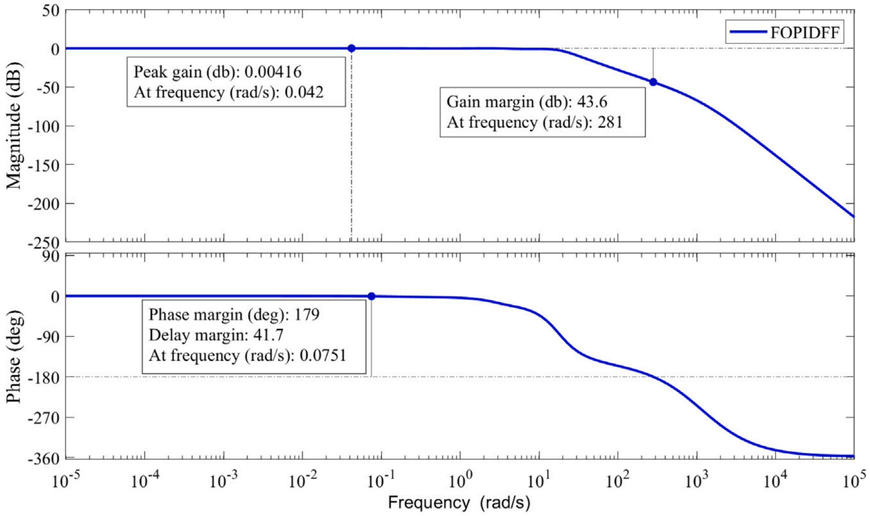


Fig. 5. Bode diagram of the AVR system with FOPIDFF controller.

Table 5
The obtained results of frequency domain analysis.

Controller	Peak gain (dB)	Phase margin (deg)	Delay margin (s)	Bandwidth (rad/s)
SCA-FOPIDFF[a]	0.00416 (at 0.042 rad/s)	179 (at 0.0751 rad/s)	41.7	18.911
SCA-FOPIDF[a]	0.127 (at 3.01 rad/s)	159 (at 3.68 rad/s)	0.756	17.082
SCA-FOPID[a]	0.0379 (at 0.263 rad/s)	165 (at 2.33 rad/s)	1.24	13.406
SCA-PIDFF[a]	0.003 (at 0.275 rad/s)	175 (at 0.413 rad/s)	7410	9.2640
SCA-PIDF[a]	1.08e−12 (at 1.83e−8 rad/s)	180 (at 0 rad/s)	Inf	8.8072
SCA-PID [4]	1.09 (at 9.17 rad/s)	87.3 (at 11.9 rad/s)	0.128	14.821

[a] Represents the proposed controllers.

proposed SCA-FOPIDFF. Table 4 also shows the positive effect of the fractional filter used in SCA-FOPIDFF and SCA-PIDFF when compared to integer filter in SCA-FOPIDF and SCA-PIDF, respectively. More clearly, overshoot of 0.1262%, settling time of $0.1670s$, rise time of 0.1230, and objective function value $f(\theta)$ of 0.0170 are obtained by SCA-FOPIDFF, whereas overshoot of 0.4297%, settling time of $0.1860s$, rise time of 0.1340, and objective function value $f(\theta)$ of 0.0218 are attained by SCA-FOPIDF. Similarly, SCA-PIDFF which has fractional filter provides less overshoot, settling and rise time, and objective function value compared to SCA-PIDF having integer filter. As a result, using the proposed SCA-FOPIDFF controller, the best transient response characteristics and objective function value is obtained in the AVR system.

6.2. Frequency domain analysis

Frequency response characteristics of the proposed controllers are presented in this subsection. Comparison is performed among the proposed PID and FOPID controllers having different type derivative action filters and SCA based PID controller [4]. In this regard, bode plot of the AVR system with SCA-FOPIDFF controller is shown in Fig. 5 where phase margin, peak gain, and delay margin are depicted as 179°, 0.00416 dB, and 41.7 s. Frequency response characteristics such as peak gain, phase margin, delay margin and bandwidth are tabulated in Table 5. That the proposed SCA-FOPIDFF controller provides a very small peak gain, higher phase margin, increased delay margin, and the widest bandwidth range among the compared controllers can be concluded from Table 5. Note that higher bandwidth results less rising time, as obtained by SCA-FOPIDFF (Tables 4 and 5). In addition, delay margin means the maximum time delay of which the system can overcome instability. It is clear from Table 5 that the SCA-PIDF has the infinity time delay which is the best obtained result among the proposed controllers. Also, SCA-FOPIDFF has longest time delay among the fractional order controllers. Phase margin, i.e. another frequency response characteristic, defines the amount of phase shift that can be injected without making the system unstable. From Table 5, the SCA based PIDF and FOPIDFF have the greatest amount of phase margin compared to the other proposed controllers. Finally, peak gain is the greatest value in the magnitude graph of the bode analysis. As noted in Table 5, the peak gain values of SCA-based PIDF, PIDFF and FOPIDFF are approximately 0.

6.3. Robustness analysis

The robustness of the proposed controllers are examined separately against both parameter uncertainties in the AVR system and external disturbances injected into the AVR system in the following subsections. The controllers are expected to overcome existing uncertainties and disturbances and react reasonably and stably.

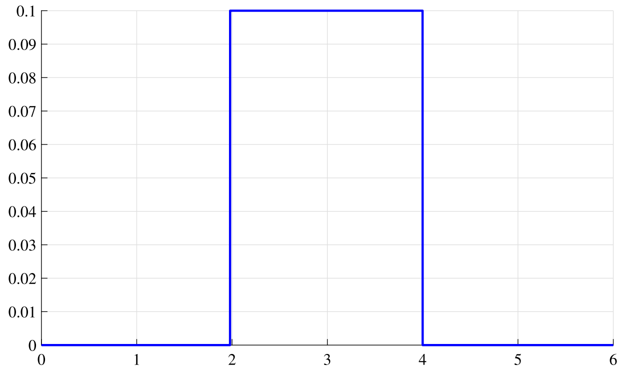


Fig. 6. Load disturbance signal injected to the AVR system.

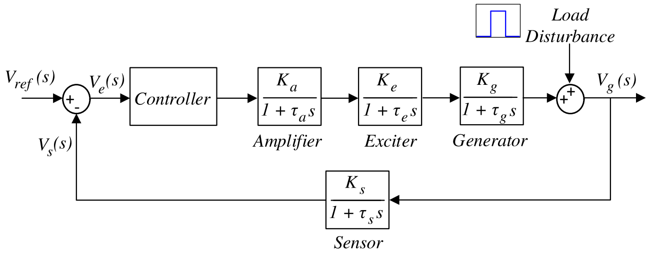
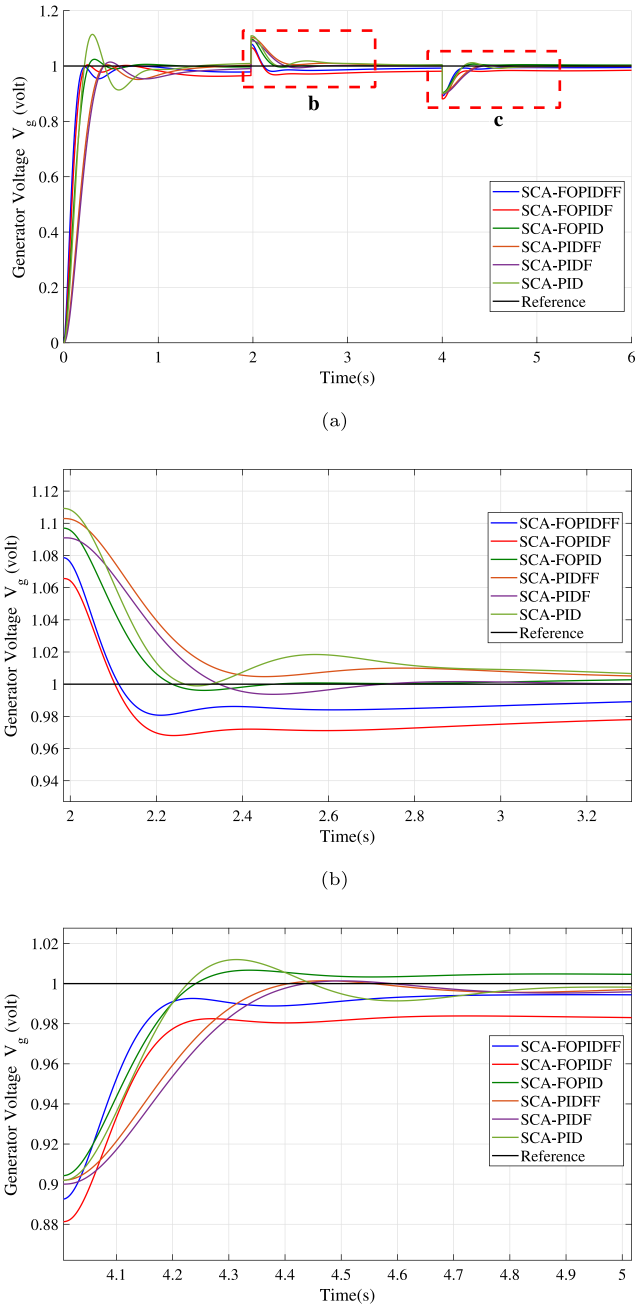


Fig. 7. Block diagram of an AVR system without any controller.

Table 6
Obtained transient response characteristics under parameter uncertainties.

	t_r (s) 0.1 → 0.9	M_p (%)	t_s (s) ∓5%	t_r (s) 0.1 → 0.9	M_p (%)	t_s (s) ∓5%	t_r (s) 0.1 → 0.9	M_p (%)	t_s (s) ∓5%	t_r (s) 0.1 → 0.9	M_p (%)	t_s (s) ∓5%
Controller	τ_a (ROC=−50%, $\tau_a = 0.05$)			τ_e (ROC=−50%, $\tau_e = 0.2$)			τ_g (ROC=−50%, $\tau_g = 0.5$)			τ_s (ROC=−50%, $\tau_s = 0.005$)		
SCA-FOPIDFF[a]	0.261	**0.12612**	0.411	**0.067**	6.9366	0.485	**0.062**	13.3053	**0.357**	**0.133**	**0.12622**	**0.185**
SCA-FOPIDF[a]	0.243	0.40808	**0.382**	0.073	7.322	**0.408**	0.068	14.395	0.371	0.143	0.40856	0.201
SCA-FOPID[a]	0.168	0.43464	0.409	0.098	4.3285	0.504	0.09	12.0818	0.47	0.174	1.0512	0.238
SCA-PIDFF[a]	0.283	0.49546	0.784	0.614	0.32475	1.016	0.141	**9.5488**	1.107	0.259	0.5235	0.36
SCA-PIDF[a]	0.287	0	0.783	0.169	**0.27784**	1.105	0.146	10.1893	1.251	0.268	0.40334	0.374
SCA-PID [4]	**0.128**	1.1565	0.606	0.095	16.5171	0.849	0.088	25.529	0.875	0.152	9.1268	0.721
	τ_a (ROC=−25%, $\tau_a = 0.075$)			τ_e (ROC=−25%, $\tau_e = 0.3$)			τ_g (ROC=−25%, $\tau_g = 0.75$)			τ_s (ROC=−25%, $\tau_s = 0.0075$)		
SCA-FOPIDFF[a]	**0.11**	0.12617	0.402	**0.095**	2.1493	0.429	**0.091**	4.705	0.404	**0.127**	**0.12622**	**0.175**
SCA-FOPIDF[a]	0.122	0.40836	0.365	0.102	2.4016	**0.416**	0.098	5.2103	0.375	0.138	0.4086	0.193
SCA-FOPID[a]	0.158	0.43523	**0.223**	0.133	2.5995	0.475	0.127	5.7268	**0.277**	0.17	1.6962	0.232
SCA-PIDFF[a]	0.25	0.51011	0.785	0.207	**0.39897**	0.906	0.194	3.8158	0.904	0.254	0.52473	0.353
SCA-PIDF[a]	0.259	**0**	0.372	0.216	0.64035	0.967	0.202	**4.5979**	0.977	0.264	0.90251	0.367
SCA-PID [4]	0.137	7.1371	0.657	0.122	13.5866	0.66	0.118	17.1704	0.653	0.15	10.2477	0.723
	τ_a (ROC=+25%, $\tau_a = 0.125$)			τ_e (ROC=+25%, $\tau_e = 0.5$)			τ_g (ROC=+25%, $\tau_g = 1.25$)			τ_s (ROC=+25%, $\tau_s = 0.0125$)		
SCA-FOPIDFF[a]	**0.134**	**2.5012**	**0.181**	**0.152**	1.5376	**0.209**	**0.159**	1.2731	**0.228**	**0.119**	**0.8478**	**0.161**
SCA-FOPIDF[a]	0.145	3.8582	0.199	0.165	2.1631	0.229	0.174	1.6122	0.246	0.13	1.4905	0.179
SCA-FOPID[a]	0.176	6.1905	0.422	0.197	3.5024	0.267	0.208	2.2001	0.284	0.162	3.2275	0.22
SCA-PIDFF[a]	0.256	3.8179	0.353	0.29	**1.4455**	0.4	0.31	1.503	0.435	0.246	1.0275	0.34
SCA-PIDF[a]	0.266	4.8569	0.369	0.3	2.6476	0.414	0.319	**0.28354**	0.447	0.256	1.9893	0.355
SCA-PID [4]	0.158	14.6727	0.79	0.171	9.8927	0.728	0.177	7.2429	0.736	0.145	12.6567	0.726
	τ_a (ROC=+50%, $\tau_a = 0.15$)			τ_e (ROC=+50%, $\tau_e = 0.6$)			τ_g (ROC=+50%, $\tau_g = 1.5$)			τ_s (ROC=+50%, $\tau_s = 0.015$)		
SCA-FOPIDFF[a]	**0.145**	**4.9757**	**0.194**	**0.181**	3.1853	**0.251**	**0.203**	2.49	0.314	**0.115**	2.1577	**0.155**
SCA-FOPIDF[a]	0.157	6.8581	0.414	0.195	4.4459	0.268	0.217	2.962	0.312	0.126	2.6607	0.174
SCA-FOPID[a]	0.187	9.3917	0.533	0.228	5.6449	0.759	0.25	3.9074	0.343	0.159	4.1074	0.215
SCA-PIDFF[a]	0.26	6.678	0.614	0.328	**2.8979**	0.449	0.374	2.8208	0.529	0.242	**1.6339**	0.813
SCA-PIDF[a]	0.275	7.7845	0.673	0.337	4.1673	0.463	0.382	**1.3125**	0.536	0.252	2.5753	0.35
SCA-PID [4]	0.168	17.2368	0.852	0.195	8.8629	0.507	0.209	4.1353	**0.287**	0.143	13.9327	0.728

[a] Represents the proposed controllers.



(a)

(b)

(c)

Fig. 8. (a) Step response of the AVR system with different controllers under load disturbance; (b–c) Zoomed versions of red rectangular areas depicted in (a).

6.3.1. Effect of parameter uncertainties in AVR system

As parameter uncertainties of the AVR system, time constant values of the system given in Table 1 are considered. τ_a, τ_e, τ_g and τ_s values, i.e. time constants of the AVR system, are changed separately within the range of ∓50% of their nominal values with step size of 25% as if there are uncertainties. The values of the changed time constants are given inside Table 6 which contains obtained transient response characteristics under the parameter uncertainties. It can be understood from the table that all controllers ensure that the AVR system operates in a stable area, even if there are major uncertainties. In addition, the proposed SCA-FOPIDFF provides the best results in 31 of 48 of the transient response characteristics, giving the best result in approximately 65% of the characteristics. The other proposed controllers, i.e. SCA-FOPIDF, SCA-FOPID, SCA-PIDFF, SCA-PIDF provide the best results in 3, 2, 5, and 5 of 48 characteristics, respectively. The traditional PID controller of which the parameters are tuned using SCA by considering the same objective function given in (4), i.e. SCA-PID [4], provides the best results in 2 of 48 characteristics.

6.3.2. *Effect of load disturbance in AVR system*

Robustness of the proposed controllers against external disturbances are analyzed in this section. A signal given in Fig. 6 is injected into the AVR system as a load disturbance. The signal is a rectangular one having rising and falling edges at times 2s and 4s with a length of 0.1 which corresponds to +10% and −10% of the reference input. Fig. 7 shows the general block diagram of the AVR system subjected to load disturbance. To examine the performances of the different controllers under load disturbance, corresponding time domain responses are obtained. Fig. 8 demonstrates disturbance responses under both +10% and −10% load disturbance at time interval $t \in [2~\mathrm{s}~~4~\mathrm{s})$ and $t \in [4~\mathrm{s}~~6~\mathrm{s})$, respectively. Furthermore, Fig. 8 also shows the nominal step response of the AVR system at time interval $t \in [0~\mathrm{s}~~2~\mathrm{s})$. Zoomed versions of the rising and falling edges occurred because of the load disturbance are also given in Fig. 8 to make more clear comparison among the controllers. When Figs. 8(b) and 8(c) considered, that faster response with less settling time is obtained by SCA-FOPIDFF is concluded.

7. Conclusion

In this paper, thanks to flexibility of fractional calculus, a novel FOPID controller with fractional filter is proposed to improve the regulating performance of a commonly used AVR system. In controller design process, SCA which is a simple but effective optimization algorithm is employed to optimally tune the controller parameters. In addition, five different controllers are also designed to show the effectiveness of the proposed SCA-FOPIDFF controller and to highlight the positive effect of the fractional filter in the proposed controller. All the designed controllers and some different PID and FOPID controllers whose parameters are optimally tuned in the literature are applied to the same AVR system. Time domain analysis are carried out for the aforementioned controllers and the superiority of the proposed controller is demonstrated. The stability of the AVR system with different controllers are analyzed using bode diagrams. Moreover, the robustness of the designed controllers are examined separately against both parameter uncertainties in the AVR system and external disturbances injected into the AVR system. Consequently, the results presented in this paper indicate that the proposed SCA-FOPIDFF controller has significantly enhance the regulating performance of the AVR system thanks to its fractional filter.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.compeleceng.2020.106895.

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