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Design of a PID Controller with Fractional Order Derivative Filter for Automatic Voltage Regulation in Power Systems

Erdinç Şahin[1*+]

[1]Energy Systems Engineering, Karadeniz Technical University, Trabzon, Turkey
*Corresponding Author and +Speaker: esahin@ktu.edu.tr
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Abstract **–** In this study, a PID controller with fractional order derivative filter (PIDFF) is designed for automatic voltage regulation (AVR) in power systems. In order to ensure maximum transient and steady state performance from the designed controller, the controller parameters and fractional order and gain of the derivative filter are tuned by particle swarm optimization (PSO) algorithm. The PSO algorithm searches the optimum solution in the specified search space for the controller and filter parameters to minimize integral of time-weighted squared error (ITSE) performance metric. The obtained results are compared to reported studies in the literature. As a result, superiority of the PIDFF controller in terms of transient and steady state characteristics is demonstrated. The robustness test of the designed PIDFF controller is also considered.

Keywords *–Fractional calculus, PID controller, Fractional order derivative filter, PSO algorithm, Time domain and robustness analyses*

I. INTRODUCTION

It is aimed to provide the user more reliable, stable and fixed nominal voltage value with automatic voltage regulation (AVR) in power systems. In addition, the actual line losses are minimized by keeping the nominal voltage constant at the scheduled value. The controller in the AVR system adjusts the output voltage of the synchronous generator via the exciter voltage. Thus, the problems that may arise with the change of voltage amplitude level in the connected power systems and the equipment connected to these systems are eliminated. The change in the reference voltage level due to the variable electrical loads and the high inductance effect of the generator windings should be smoothed as quickly as possible [1].

Literature survey shows that PID controller is the most preferred controller structure for AVR system. The design simplicity of PID controller and its strong robustness to changes in system parameters are two important characteristics to prefer this controller type [2]. Some of the studies used PID controller in AVR system are given in [3-8]. A more detailed literature survey of AVR systems designed for PID controller is also available in [8]. In addition, the control methods based on PID controller such as PID plus second order derivative controller ($PIDD^2$) [9], fractional order PID (FOPID) [10, 11], fuzzy logic tuned PID controller (FPID) [12, 13], fuzzy tuned FOPID [14] controllers are also frequently studied in the AVR system.

In controller design process, since the controller parameters have a direct impact on the system dynamic, these parameters should be selected optimally. In recent years, meta-heuristic optimization algorithms have been used generally instead of classical methods which requires high mathematical computations. Some of the algorithms used for the AVR system in the design process of PID and PID-based controllers are: hybrid genetic algorithm and bacterial foraging (GA-BBO) structure [4], artificial bee colony algorithm (ABC) [5], differential evolution algorithm (DEA) [5], biogeography-based optimization (BBO) [6], sine-cosine algorithm (SCA) [7], kidney-inspired algorithm (KIA) [8], chaotic ant swarm algorithm (CAS) [9,10] and the PSO algorithm [5, 9, 11, 13, 15].

Determination of the objective function (OF) is also as important as performances of the above-mentioned optimization algorithms in order to obtain desired dynamic system response. Designers are generally considering integral of error based and user defined objective functions. The integral of the squared error (ISE), integral of the time weighted squared error (ITSE), integral of the absolute error (IAE) and integral of the time weighted absolute error (ITAE) performance metrics are commonly used error-based objective functions. On the other hand, user defined objective functions generally consists of transient response parameters such as maximum overshoot (M_p), rise time (T_r), settling time (T_s), peak time (T_t), and etc.

In PID controller design, the design process is generally performed without considering the derivative kick effect (DKE). DKE, which plays an important role in the efficient operation of the controller, should be taken into consideration especially in real-time applications. As a controller input signal, a sudden change in the error signal results DKE. The instantaneous change of the error causes the derivative value of the error to be too large which causes it to reach the upper limit of the controller signal. To prevent this situation, a first order low pass filter (LPF) is generally used with derivative action of the PID controller.

In most of the PID controller design studies in literature, derivative filter consideration can be found easily. However, in this study, we propose a PID controller with fractional order low pass filter (PIDFF) for derivative action. In literature review, it has been observed that performance of a fractional

filter is not investigated for the derivative effect of classical PID controller in AVR system.

In this study, a PID controller with fractional order derivative filter is designed for AVR system. Improvements in dynamic system response of an AVR system is aimed by using flexible structure of a fractional order filter.

PID controller parameters: proportional coefficient (K_P), integral coefficient (K_I), derivative coefficient (K_D) and fractional filter parameters of derivative action: filter gain (NN) and fractional order (λ) are tuned in the bounded search space with the optimization algorithm used in the design process. In some studies, in the literature, ITSE function has been used as an objective function for controller design in AVR system. In this study, we also consider ITSE function as performance criterion for a fair comparison. The proposed controller is compared to PID controllers designed with different meta-heuristic algorithms reported in literature in terms of transient response characteristics. In addition, robustness test of the designed controller is considered.

In this study, the AVR system model, proposed controller scheme, fractional order filter design and basics of the PSO algorithm are introduced in Section 2. Section 3 presents the simulation results and discussion. Finally, in Section 4, the conclusion is stated.

II. Materials and Method

Under this title, AVR system model, proposed controller structure with fractional order derivative action filter and optimization algorithm are introduced.

A. AVR System Modelling

The AVR system, which is used to keep the output voltage of the synchronous generator at the desired level, consists of four basic components: amplifier, exciter, generator and sensor. The sensor is used for continuous measurement of the output voltage. After the measurement, the error signal is obtained by comparing the desired reference value and measured output signal. The controller uses error signal as an input and generates an appropriate control signal based on error. This control signal is amplified by the amplifier and applied to the generator windings with the help of exciter. Thus, the output voltage of the generator is fixed at the desired level. The schematic representation of the AVR system with the subcomponents consisting of first order transfer functions is shown in Fig. 1.

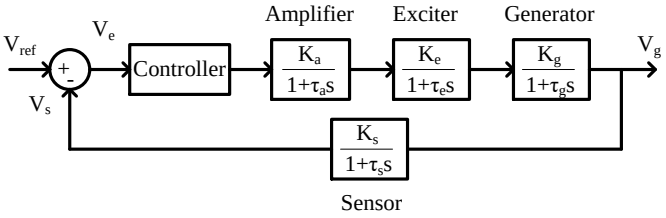


Fig. 1 Schematic representation of the AVR system with controller.

The gain and time constants of the transfer functions of the system components are given in Table 1. In the studies reported in the literature, the parameter values given in Table 1 are mostly taken into consideration.

Table 1. Parameters of subsystems of AVR.

AVR subsystem	Gain	Time constant
Amplifier	K_a=10	τ_a=0.1
Exciter	K_e=1	τ_e=0.4
Generator	K_g=1	τ_g=1
Sensor	K_s=1	τ_s=0.01

B. Controller Structure

As mentioned in the introduction part, PID controller is preferred in many control applications due to its easy design, elimination of disturbance effect and robustness to change of system parameters. A conventional PID controller has three control parameters that must be optimally adjusted. Each of these control parameters have separate effects on the system dynamic. In addition, LPF is used together with derivative action to remove DKE. The parameters of LPF such as gain (NN) may also vary in different type frequency range applications. Whereas, the value of NN is considered as 100 in many studies. Optimization of the NN value will also increase the system dynamics satisfactorily. In this study, a PID controller with fractional order derivative filter is proposed. So, there are two extra parameters of which are filter gain (NN) and fractional order of the LPF (λ) to be optimized in the proposed structure. The block diagram representation of the aforementioned controller structures is shown in Fig. 2 where (a), (b), and (c) represents the conventional PID, PID controller with filter (PIDF), and the proposed PID controller with fractional filter (PIDFF). The transfer functions of these controllers are also given below.

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{1}$$

$$G_{PIDF}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s\frac{NN}{s+NN} \tag{2}$$

$$G_{PIDFF}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s\frac{NN}{s^{\lambda}+NN} \tag{3}$$

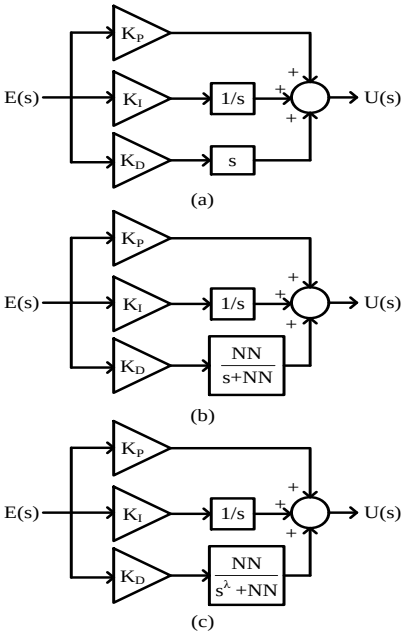


Fig. 2 Block diagram representation of (a) classical PID controller, (b) PIDF controller, and (c) PIDFF controller.

C. Fractional Order Filter Design for Derivative Action

More accurate system modelling or control can be achieved by using the advantage of the flexibility provided by fractional order. In literature, there are many approaches used to compute fractional order of the derivative and integral actions. Grunwald-Letkinov, Riemann-Liouville and Caputo methods are frequently reported in most of the studies in literature [16]. Since, it is complex to calculate fractional order numerically, approximation methods are generally preferred. In this study, we also perform Oustaloup approximation method which converges to a fractional order transfer function with integer transfer functions [17, 18]. This method proposes a band pass filter (BPF) design in the desired frequency range to converge a fractional order derivative (s^{λ}) or integral ($s^{-\lambda}$) operators. Designed BPF is an integer transfer function with zeros, poles and gain. The parameters of this transfer function are given by the following equations.

$$s^{\lambda} \cong K \prod_{k=-N}^{N} \frac{s + w_k^z}{s + w_k^p} \tag{4}$$

$$w_k^z = w_b \left(\frac{w_h}{w_b} \right)^{\frac{k+N+\frac{1-\lambda}{2}}{2N+1}} \tag{5}$$

$$w_k^p = w_b \left(\frac{w_h}{w_b} \right)^{\frac{k+N+\frac{1+\lambda}{2}}{2N+1}} \tag{6}$$

$$K = \left(\frac{w_h}{w_b} \right)^{-\frac{\lambda}{2}} \prod_{k=-N}^{N} \frac{w_k^p}{w_k^z} \tag{7}$$

where N, w_b and w_h represent the approximation order of the considered method, lower and upper bounds of the frequency operating range, respectively. w_k^p and w_k^z are the poles and zeros of the sequence (k). In this study, N and frequency range are considered as 5 and (10^{-3}, 10^{3}) r/s, respectively.

D. PSO Algorithm

The PSO algorithm is an iterative and population-based evolutionary algorithm inspired by the social behaviour of flocks of birds and fish [19]. The PSO algorithm has been successfully applied in many engineering fields such as equality optimization, classification, machine learning, artificial neural networks, control systems, signal processing for many years [20]. In the PSO algorithm, the particles are first randomly placed in the search space and the objective function is calculated at the current position of each particle. The position and objective function value of each particle is stored in the memory. Among these values, local best solution (p_{best}) is selected. Then, the global solution (g_{best}) is obtained from (p_{best}) values. At each iteration, the new position of the particles is updated with the velocity (v) and position (x) equations given below.

$$v_i^{k+1} = w\left(v_i^k\right) + c_1 r_1 (p_i^k - x_i^k) + c_2 r_2 (g_i^k - x_i^k) \tag{8}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{9}$$

where k is the iteration number, i is the particle number, c_1-c_2 are the acceleration constants of which are selected as 2, w is the inertia constant of which value changes linearly from 0.9 to 0.4 based on iteration number. In addition, for this study, population size and iteration number are adjusted as 10 and 50, respectively. Also, repeating the algorithm more than once would be meaningful, and thus optimization algorithm is run 10 times.

It is mentioned in the introduction that ITSE function is employed as the performance metric. There is no special reason for selecting this function as a performance metric. Since, ITSE is preferred in the comparative studies reported in literature, we also consider ITSE function for this study. The mathematical expression of the considered performance index is given in (10) where t, t_{sim}, and e(t) are the time, simulation time and error signal, respectively.

$$\text{ITSE} = \int_{t=0}^{t_{sim}} te(t)^2 \, dt \tag{10}$$

III. Results and Discussion

The aim of the optimization process is to minimize objective function ITSE with respect to bounded search space for controller and filter parameters. The PSO algorithm is employed to solve following constrained optimization problem:

$$\begin{aligned} &\text{Minimize ITSE} \\ &\text{Subject to} \\ &K_{P_{min}} (= 0.01) \le K_P \le K_{P_{max}} (= 2) \\ &K_{I_{min}} (= 0.01) \le K_I \le K_{I_{max}} (= 1) \\ &K_{D_{min}} (= 0.01) \le K_D \le K_{D_{max}} (= 1) \\ &NN_{min} (= 0.01) \le NN \le NN_{max} (= 200) \\ &\lambda_{min} (= 0.01) \le K_d \le \lambda_{max} (= 1) \end{aligned} \tag{11}$$

The schematic representation of the optimization process is depicted in Fig. 3. Five parameters of the proposed controller are searched by PSO algorithm within the given limits in (11) to make the value of the ITSE function minimum.

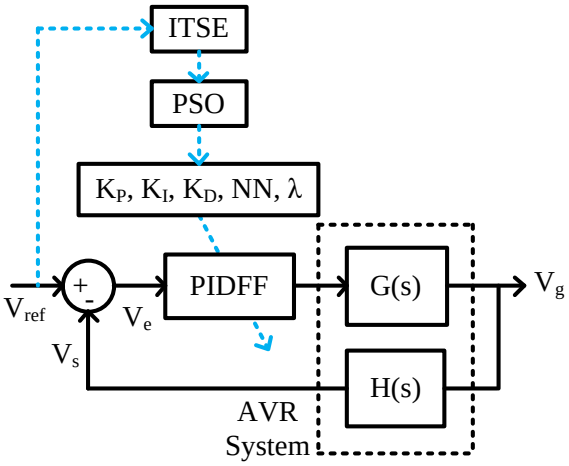


Fig. 3 Schematic presentation of the optimization process.

Graphs showing the change of objective function for each of 10 trials in the optimization process are illustrated in Fig. 4. In addition, the system responses with the controller parameters

obtained from optimization trials on the AVR system are shown in Fig. 5.

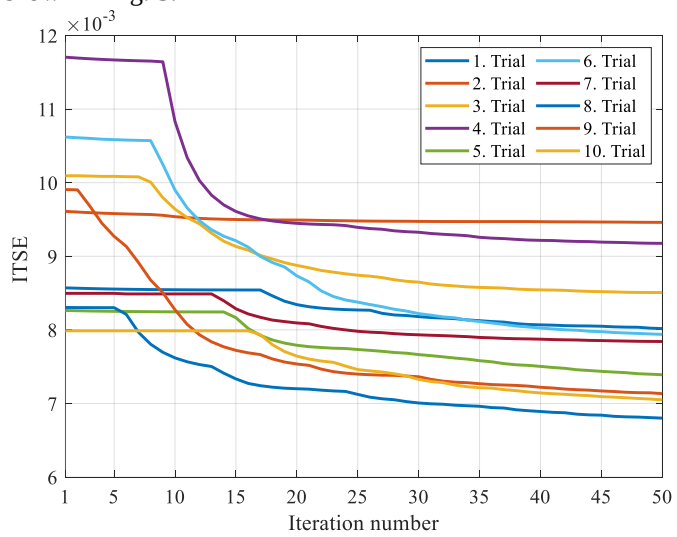


Fig. 4 The change of the objective function for 10 trials.

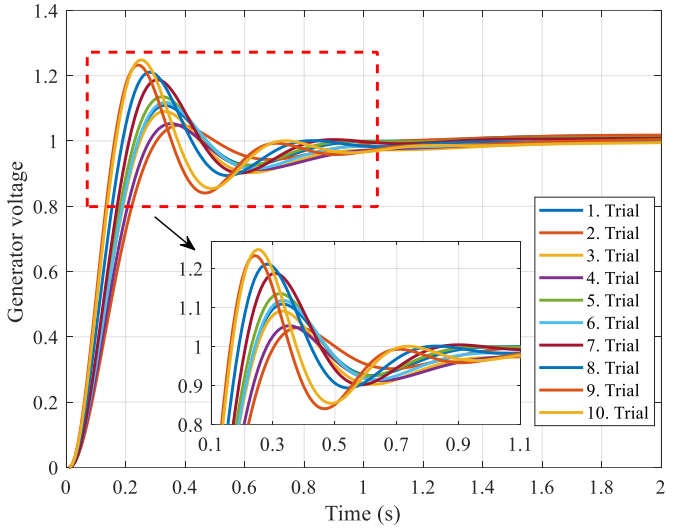


Fig. 5 AVR system step responses with PIDFF controller parameters obtained from 10 trials.

In Fig. 4, the minimum objective function value is obtained as 0.006801 in the 8th trial. The proposed controller ($PIDFF_{8.trial}$) parameters that provide minimum ITSE value are tabulated in Table 2.

Considering the system responses given in Fig. 5, although the ITSE value is 0.009461, the lowest over shoot is achieved by the second trial. The controller parameters of this trial ($PIDFF_{2.trial}$) are also investigated in comparison and the controller parameters are presented in Table 2.

Table 2. Optimized controller and filter parameters with ITSE values

Controller, filter and minimized ITSE values	Trial number	
	2. Trial	8. Trial
K_P	0.7813	1.3837
K_I	0.7374	0.9702
K_D	0.3748	0.6159
NN	112.1	167.88
λ	0.1351	0.4900
ITSE	0.009461	0.006801

The system responses with control parameters obtained in the 2nd and 8th trials for AVR system are compared to some reported results in the literature. The illustration of this comparison is presented in Fig. 6. The maximum over shoot (M_p), settling time (T_s), rising time (T_r), peak time (T_t) and ITSE values of the transient responses of the examined controllers are given in Table 3.

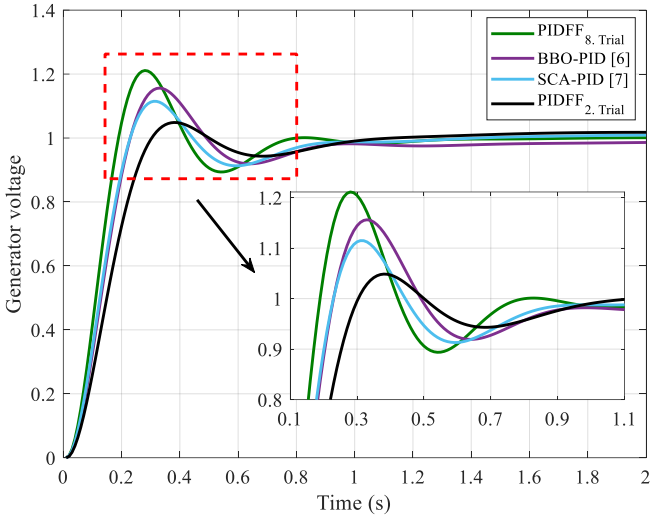


Fig. 6 Step responses of the AVR system controlled by proposed controller and different PID controllers.

Table 3. Transient response characteristics of the controllers.

Controller type	M_p	T_s (%5)	T_r (0.1-0.9)	T_t	ITSE
$PIDFF_{2.\ Trial}$	**1.048**	0.750	0.191	0.37	0.0094
$PIDFF_{8.\ Trial}$	1.211	**0.657**	**0.120**	**0.27**	0.0068
BBO-PID [6]	1.160	0.766	0.149	0.31	0.0077
SCA-PID [7]	1.114	0.724	0.148	0.30	**0.0064**

It is clear from Fig. 6 and Table 3 that although the minimum ITSE value is provided by SCA-PID, $PIDFF_{8.Trial}$ has the best values of T_t, T_r and T_s parameters among the considered controllers. Furthermore, the minimum over shoot value is obtained with $PIDFF_{2.Trial}$. These results show the superiority of the proposed controller structure. On the other hand, we can say that ITSE function is insufficient to provide desired transient response characteristics. Therefore, a user-defined objective function or other error-based objective functions are recommended for optimization procedure.

The results of the robustness test with proposed controllers are given in Table 4. The time constants of the transfer functions of constituting AVR system are changed by ±50% and the ITSE, T_s, and M_p results are observed. As a results of this analysis, we can say that both of the controllers (PIDFF2.Trial and PIDFF8.Trial) react insignificant changes under this scenario.

IV. CONCLUSION

In this study, design of a PID controller with fractional order derivative filter structure is proposed for the control of the AVR system studied frequently in the literature. In controller and filter optimization process, PSO algorithm is employed to minimize ITSE function of which also considered in compared

studies. In conclusion, transient response analysis and robustness test show the superiority and applicability of the proposed PIDFF structure. Also, considering recently introduced meta-heuristic algorithms instead of PSO may provide better PIDFF response in terms of transient response characteristics.

Table 4. Results of robustness analysis of the AVR system controlled by $PIDFF_{2.Trial}$/$PIDFF_{8.Trial}$

Parameter	**Rate of change**	**ITSE**	**M_p**	**T_s (%5)**
Nominal	-	0.00946 / 0.00680	1.0480 / 1.2110	0.75 / 0.66
τ_a	+50%	0.01304 / 0.01161	1.1105 / 1.2719	0.86 / 0.79
	-50%	0.00709 / 0.00338	1.0170 / 1.0985	0.65 / 0.49
τ_e	+50%	0.01474 / 0.00867	1.0479 / 1.1766	0.35 / 0.50
	-50%	0.00717 / 0.00563	1.0727 / 1.2712	0.70 / 0.77
τ_g	+50%	0.01828 / 0.00837	1.0437 / 1.1296	0.39 / 0.47
	-50%	0.00690 / 0.00748	1.1653 / 1.3613	0.64 / 0.80
τ_s	+50%	0.01000 / 0.00799	1.0658 / 1.2450	0.76 / 0.66
	-50%	0.00900 / 0.00585	1.0329 / 1.1794	0.73 / 0.65

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