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Optimal Design of $PI^{\lambda}D^{\mu}A^{\nu}$ Controller for Wind Turbine Systems by Cuckoo Search

***Abstract**. The fractional-order proportional-integral-derivative-accelerated (FOPIDA) controller (or $PI^{\lambda}D^{\mu}A^{\nu}$) is the generalization of the PID controller family. It consists of seven parameters, i.e. the proportional gain K_p, the integral gain K_i, the derivative gain K_d, the accelerated gain K_a, the integral order λ, the derivative order μ and the accelerated order ν. All orders (λ,μ and ν) are real rather than an integer. These make the $PI^{\lambda}D^{\mu}A^{\nu}$ controller more flexible in design process for a wide range of dynamic systems. This paper presents the optimal design of the $PI^{\lambda}D^{\mu}A^{\nu}$ controller based on modern optimization approach for a drive train and a pitch control of the wind turbine systems by using the cuckoo search (CS), one of the most powerful metaheuristic optimization techniques. Results obtained by the $PI^{\lambda}D^{\mu}A^{\nu}$ controller will be compared with those obtained by the integer-order proportional-integral-derivative-accelerated (IOPIDA) controller. As results, it was found that the $PI^{\lambda}D^{\mu}A^{\nu}$ controller outperforms the IOPIDA in both input-tracking and load-regulating responses, significantly.*

***Streszczenie.** Regulator FOPIDA (lub PIλDμAν) jest uogólnieniem rodziny regulatorów PID. Składa się z siedmiu parametrów, tj. wzmocnienia proporcjonalnego Kp, wzmocnienia całkowania Ki, wzmocnienia różniczkowania Kd, wzmocnienia przyspieszonego Ka, rzędu całkowania λ, rzędu różniczkowania μ i rzędu przyspieszonego ν. Wszystkie zamówienia (λ, μ i ν) są rzeczywiste, a nie liczby całkowite. Dzięki temu regulator PIλDμAν jest bardziej elastyczny w procesie projektowania dla szerokiej gamy systemów dynamicznych. W artykule przedstawiono optymalny projekt regulatora PIλDμAν oparty na nowoczesnym podejściu do optymalizacji układu napędowego i sterowania nachyleniem systemów turbin wiatrowych z wykorzystaniem przeszukiwania kukułkowego (CS), jednej z najpotężniejszych metaheurystycznych technik optymalizacji. . Wyniki otrzymane przez regulator PIλDμAν zostaną porównane z wynikami uzyskanymi przez regulator proporcjonalno-całkująco-różniczkujący (IOPIDA). W rezultacie stwierdzono, że regulator PIλDμAν znacznie przewyższa IOPIDA zarówno pod względem śledzenia wejścia, jak i odpowiedzi regulacji obciążenia. (**Optymalny projekt kontrolera $PI^{\lambda}D^{\mu}A^{\nu}$ dla systemów turbin wiatrowych firmy Cuckoo Search**)*

Keywords: $PI^{\lambda}D^{\mu}A^{\nu}$ controller, Wind turbine systems, Drive train control system, Pitch control system, Cuckoo search.
Słowa kluczowe: kontroler PI, turbiona wiatrowa

Introduction

The fractional-order proportional-integral-derivative ($PI^{\lambda}D^{\mu}$) controller (or FOPID) was firstly proposed by Podlubny in 1994 [1, 2] as an extended version of the conventional integer-order PID controller (or IOPID). Based on the fractional calculus, the $PI^{\lambda}D^{\mu}$ controller possesses five parameters, i.e. the proportional gain K_p, the integral gain K_i, the derivative gain K_d, the integral order λ and the derivative order μ, (λ and $\mu \in \Re$, where $\Re$ is the real number). Superiority of the $PI^{\lambda}D^{\mu}$ controller to the conventional PID controller has been proved [1, 2]. By literature reviews, the $PI^{\lambda}D^{\mu}$ controller has been successfully conducted in many control applications, for example, process control, automatic voltage regulator (AVR), DC motor control, power electronic control, inverted pendulum control and gun control system. Several design and tuning methods for the $PI^{\lambda}D^{\mu}$ controller have been consecutively launched. Review and tutorial articles of the $PI^{\lambda}D^{\mu}$ controller providing its backgrounds and details have been completely reported [3, 4].

In 1996, the integer-order proportional-integral-derivative-accelerated (IOPIDA) controller was firstly introduced by Jung and Dorf [5]. The IOPIDA has been claimed to deliver faster and smoother response than the IOPID for the higher order plants. In 2017, the fractional-order proportional-integral-derivative-accelerated ($PI^{\lambda}D^{\mu}A$) controller was proposed by Bettou and Charef [6, 7]. Such the $PI^{\lambda}D^{\mu}A$ controller possesses six parameters, i.e. K_p, K_i, K_d, λ, μ, and the accelerated gain K_a, (λ and $\mu \in \Re$). Bettou and Charef reported the optimal tuning of the $PI^{\lambda}D^{\mu}A$ controller for motor position control systems [6] and bioreactor control [7] via the particle swarm optimization (PSO). Later in 2019, the generalized fractional-order proportional-integral-derivative-accelerated ($PI^{\lambda}D^{\mu}A^{\nu}$) controller (or FOPIDA) was then proposed [8, 9]. The $PI^{\lambda}D^{\mu}A^{\nu}$ controller possesses seven parameters, i.e. K_p, K_i, K_d, K_a, λ, μ, and the accelerated order ν, (λ, μ and $\nu \in \Re$). It can be considered as the generalization of the PID controller family including IOP, IOPI, IOPD, IOPID, FOPID and IOPIDA controllers. All seven parameters of the $PI^{\lambda}D^{\mu}A^{\nu}$ controller can be optimized by some powerful metaheuristic optimization techniques [8, 9].

In this paper, an optimal $PI^{\lambda}D^{\mu}A^{\nu}$ controller design based on the modern optimization approach for a drive train and a pitch control of the wind turbine systems by the cuckoo search (CS), one of the most powerful metaheuristic optimization techniques, is proposed. Results obtained by the $PI^{\lambda}D^{\mu}A^{\nu}$ controller designed by the CS will be compared with those obtained by the IOPIDA controller designed by the CS.

$PI^{\lambda}D^{\mu}A^{\nu}$ controller

Regarding to the fractional calculus, the $PI^{\lambda}D^{\mu}A^{\nu}$ controller can be performed by the differential equation as expressed in (1), where $D^{\pm\alpha}$ is the non-integer order fundamental operator ($\alpha \in \Re^+$ stands for the order of differential operation and $\alpha \in \Re^-$ stands for the order of integral operation), $e(t)$ is the error signal regarded as the controller input, $u(t)$ is the control signal regarded as the controller output, orders λ and $\mu \geq 0$, and $\nu \geq 2$ [8, 9]. By taking the Laplace transform, the model in (1) can be performed as the transfer function stated in (2).

$$(1)\quad u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) + K_a D_t^{\nu} e(t)$$

$$(2)\quad G_c(s)\big|_{PI^{\lambda}D^{\mu}A^{\nu}} = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} + K_a s^{\nu}$$

From (2), the proposed $PI^{\lambda}D^{\mu}A^{\nu}$ controller with its seven parameters is the generalization of all types of PID controller family. By taking λ = 1, μ = 1 and ν = 2, it is the conventional IOPIDA controller [5]. ν = 2 gives the $PI^{\lambda}D^{\mu}A$ controller [6, 7]. K_a = 0 gives the $PI^{\lambda}D^{\mu}$ controller [1, 2]. λ = 1, μ = 1 and K_a = 0 give the conventional IOPID controller. λ = 1, K_d = 0 and K_a = 0 give the conventional IOPI controller. K_i = 0, μ = 1 and K_a = 0 give the conventional IOPD controller. K_i = 0, K_d = 0 and K_a = 0 give the conventional IOP controller. It was found that the generalized $PI^{\lambda}D^{\mu}A^{\nu}$ controller is more flexible and gives an opportunity to better adjust the system response of a fractional-order control system.

Drive train model in wind turbine systems

The drive train in wind turbine systems basically consists of the wind turbine rotor, low-speed shaft, gearbox, high-speed shaft, and double-fed induction generator (DFIG) [10]. The schematic diagram of the drive train system is shown in Fig. 1, where $T_A(t)$ is the aerodynamic torque applied from wind turbine speed (velocity of rotor), J_T is the lumped moment of inertia of rotor and low-speed shaft, $\omega_T(t)$ is the turbine-side speed, K_{lss} is the low-speed shaft stiffness, D_{lss} is the low-speed shaft damping factor, $\omega_{gT}(t)$ is the turbine-side gearbox speed, N is the gearbox ratio, $\omega_{gG}(t)$ is the generator-side gearbox speed, K_{hss} is the high-speed shaft stiffness, D_{hss} is the high-speed shaft damping factor, $\omega_G(t)$ is the generator-side speed, J_G is the lumped moment of inertia of generator and high-speed shaft and $T_e(t)$ is the electromagnetic torque generated by the DFIG.

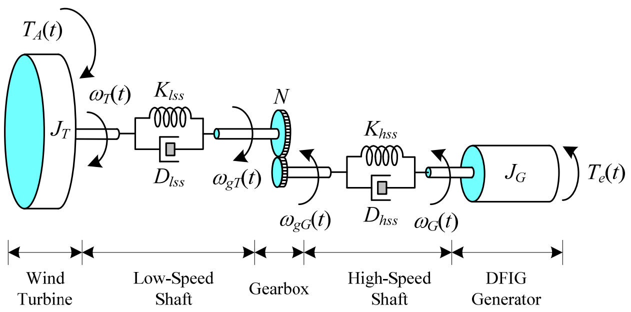

Fig.1. Drive train in wind turbine systems

In this work, the considered drive train system is of the wind turbine of 330-kW [11]. The *s*-domain transfer function model, $G_{p1}(s)$, of the drive train system is given as expressed in (3) [11, 12]. From (3), the drive train system is one of the complicated real-world systems. The model in (3) will be used as the plant model in the design process.

$$(3)\quad G_{p1}(s) = \frac{2.28\times10^{19}s}{\left(\begin{array}{l}9.941\times10^{12}s^5\\ \quad +4.971\times10^{14}s^4+1.024\times10^{17}s^3\\ \quad\quad +7.534\times10^{17}s^2+5.685\times10^{18}s\end{array}\right)}$$

Pitch control model in wind turbine systems

The pitch control system was operated by using hydraulic pressure. It typically includes a time delay for the wind turbine generation system. In this work, the pitch control model of the wind turbine with 275-kW generator [13] is conducted. The *s*-domain transfer function model, $G_{p2}(s)$, of the pitch control system of the wind turbine is given as stated in (4) [11, 13]. The model in (4) will be also used as the plant model in the design process.

$$(4)\quad G_{p2}(s) = \left(\frac{-0.6219s^2-8.7165s-2911}{s^4+5.018s^3+691.3s^2+1949s+1.15\times10^5}\right)e^{-0.25s}$$

Cuckoo search algorithm

The cuckoo search (CS) was firstly proposed by Yang and Deb in 2009 [14, 15] as one of the most efficient metaheuristic optimization techniques. The CS algorithm is inspired by the behaviour of cuckoo species and the Lévy flight behaviour of some birds and fruit flies. There are two key parameters, i.e. a number of cuckoos (n) and a fraction p_a denoting the ability of host birds that can find the cuckoos' eggs. In CS algorithm, a new solutions $x^{(t+1)}$ for cuckoo i can be generated by Lévy distribution as expressed in (5), where Lévy(λ) stands for the Lévy distribution having an infinite variance with an infinite mean as expressed in (6). The step length s of cuckoo flight can be calculated by (7), where u and v are normal distributions as stated in (8). The standard deviations of u and v are expressed in (9). The CS algorithm can be represented by the flow diagram as shown in Fig. 2. Yang and Deb have recommended that n =15 to 40, p_a = 0.2 to 0.25 and λ, β = 1.5 to 2.0 are good for most optimization problems [14, 15].

$$(5)\quad \mathbf{x}_i^{(t+1)} = \mathbf{x}_i^t + \alpha \oplus \text{Lévy}(\lambda)$$

$$(6)\quad \text{Lévy}(\lambda) \approx u = t^{-\lambda},\quad (1<\lambda\le3)$$

$$(7)\quad s = u/|v|^{1/\beta}$$

$$(8)\quad u \approx N(0,\sigma_u^2),\quad v\approx N(0,\sigma_v^2)$$

$$(9)\quad \sigma_u = \left\{\frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta2^{(\beta-1)/2}}\right\}^{1/\beta},\quad \sigma_v = 1$$

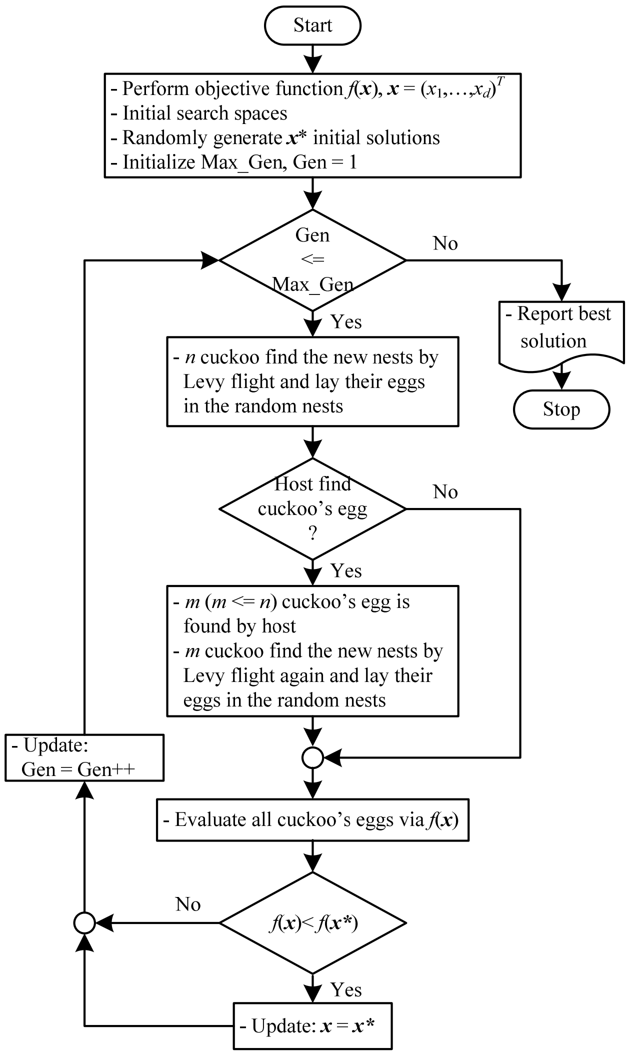

Fig.2. Flow diagram of the CS algorithm

CS-based $PI^{\lambda}D^{\mu}A^{\nu}$ controller design

Based on modern optimization approach, the optimal design of the $PI^{\lambda}D^{\mu}A^{\nu}$ controller for a drive train and a pitch control of the wind turbine systems by the CS can be represented by the block diagram shown in Fig. 3. The objective function $f(\bullet)$ is set as the sum of squared error (SSE) between the reference input signal $R(s)$ and the controlled output signal $C(s)$ of the controlled system as stated in (10) as appeared in [16-18]. The objective function $f(\bullet)$ in (10) will be fed to the CS to be minimized by searching for the optimal values of the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ parameters (K_p, K_i, K_d, K_a, λ, μ and ν). The search process needs to meet the design constrained functions and the search spaces as stated in (11), where t_{r_max} is the maximum allowance of rise time t_r, M_{p_max} is the maximum allowance of maximum percent overshoot M_p, t_{s_max} is the maximum allowance of settling time t_s, e_{ss_max} is the maximum allowance of steady-state error e_{ss}, K_{p_min} and K_{p_max} are the lower and upper bounds of K_p, K_{i_min} and K_{i_max} are the lower and upper bounds of K_i, K_{d_min} and K_{d_max} are the lower and upper bounds of K_d, K_{a_min} and K_{a_max} are the lower and upper bounds of K_a, λ_{min} and λ_{max} are the lower and upper bounds of λ, μ_{min} and μ_{max} are the lower and upper bounds of μ, and ν_{min} and ν_{max} are the lower and upper bounds of ν, respectively.

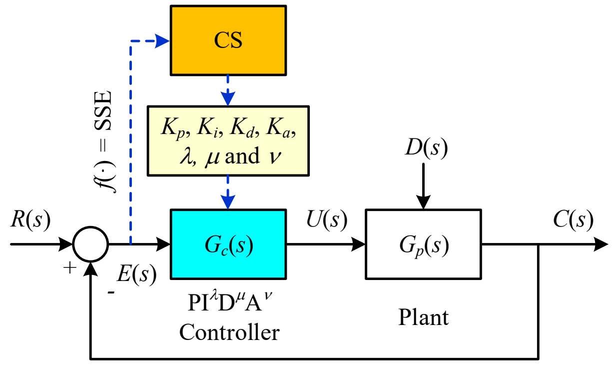

Fig.3. CS-based PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller design

$$\text{(10)}\quad \textbf{Min}\ f(K_p,K_i,K_d,K_a,\lambda,\mu,\nu)=\sum_{i=1}^{N}[R_i-C_i]^2$$

$$\text{(11)}\quad \begin{cases} Subject\ to & t_r \le t_{r\_max}, \\ & M_p \le M_{p\_max}, \\ & t_s \le t_{s\_max}, \\ & e_{ss} \le e_{ss\_max}, \\ & K_{p\_min} \le K_p \le K_{p\_max}, \\ & K_{i\_min} \le K_i \le K_{i\_max}, \\ & K_{d\_min} \le K_d \le K_{d\_max}, \\ & K_{a\_min} \le K_a \le K_{a\_max}, \\ & \lambda_{min} \le \lambda \le \lambda_{max}, \\ & \mu_{min} \le \mu \le \mu_{max}, \\ & \nu_{min} \le \nu \le \nu_{max} \end{cases}$$

Results and discussions

To design the optimal PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers for a drive train and a pitch control of the wind turbine systems. The CS algorithm was coded by MATLAB version 2018b (License No.#40637337) run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM. For designing the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers of a drive train and a pitch control, the search parameters of the CS are priorly set according to the recommendation [14, 15] as follows: n = 15, p_a = 0.25 and λ = β = 1.5. The maximum generation MaxGen = 200 is set as the termination criteria (TC). 50 trials are proceeded by the CS to search for the optimal PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers. The PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers are implemented by MATLAB with FOMCON toolbox [19, 20], where Oustaloup's approximation is realized for fractional order numerical simulation. For comparison with the IOPIDA controllers, λ, μ and ν in (2) are set as follows: λ = μ = 1.0 and ν = 2.0.

<u>**Drive train control:**</u> In this case, the $G_{p1}(s)$ in (3) is used as a plant shown in Fig.3. The design constrained functions and the search spaces in (11) can be set by a preliminary study for designing the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller of this case as stated in (12). For the IOPIDA controller, λ, μ and ν in (12) are fixed as λ = μ = 1.0 and ν = 2.0.

$$\text{(12)}\quad \begin{cases} Subject\ to & t_r \le 0.05\ \text{sec.}, \\ & M_p \le 20.00\%, \\ & t_s \le 0.25\ \text{sec.}, \\ & e_{ss} \le 0.01\%, \\ & 5 \le K_p \le 50, \\ & 10 \le K_i \le 50, \\ & 0 \le K_d \le 0.5, \\ & 0 \le K_a \le 0.01, \\ & 0.5 \le \lambda \le 1.5, \\ & 0.5 \le \mu \le 1.5, \\ & 1.5 \le \nu \le 2.5 \end{cases}$$

After the search process stopped, the IOPIDA and PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers optimized by the CS for the drive train control system are successfully obtained as stated in (13) and (14), respectively.

$$\text{(13)}\quad G_c(s)\big|_{IOPIDA} = 10.38 + \frac{23.02}{s} + 0.13s + 0.002s^2$$

$$\text{(14)}\quad G_c(s)\big|_{PI^{\lambda}D^{\mu}A^{\nu}} = 32.28 + \frac{43.23}{s^{1.25}} + 0.24s^{1.02} + 0.004s^{2.23}$$

The convergent rates of the objective functions in (10) associated with the design constrained functions in (12) proceeded by the CS over 50 trials for the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller design are depicted in Fig. 4. It can be observed that the CS has a good robustness for global convergence with different randomly initial solutions. The convergence rates of IOPIDA controller designed by the CS are omitted because they have a similar form to those in Fig. 4.

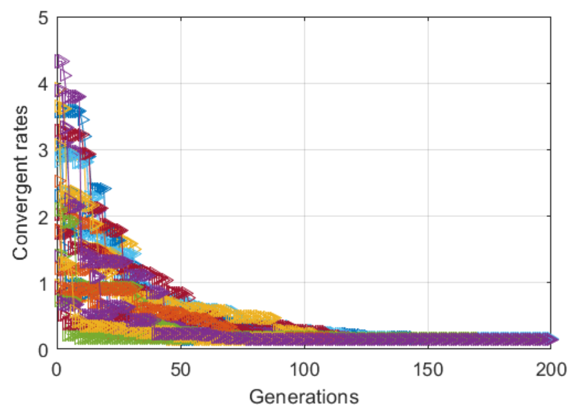

Fig.4. Convergent rates of PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller designed by CS for drive train control system

The unit-step input-tracking response of the drive train system without controller is plotted in Fig. 5. The unit-step input-tracking and unit-step load-regulating responses of the drive train system with the IOPIDA controller in (13) and the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller in (14) are depicted in Fig. 6 and Fig. 7, respectively. Results of input-tracking and load-regulating system responses are summarized in Table 1 and Table 2.

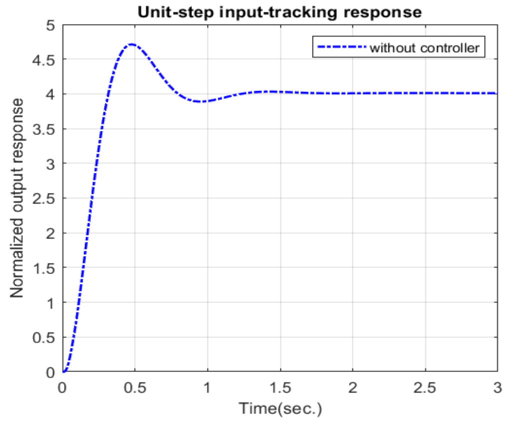

Fig.5. Unit-step input-tracking response of the drive train system without controller

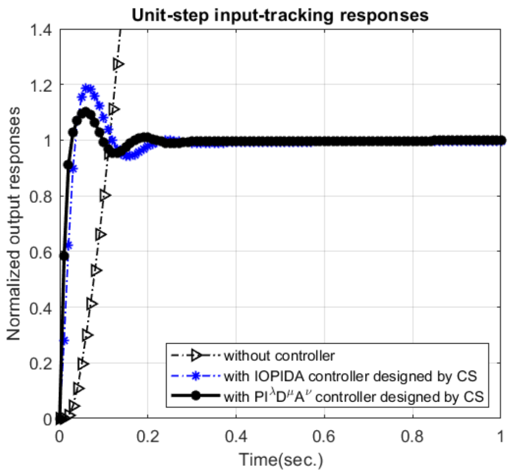

Fig.6. Unit-step input-tracking responses of the drive train system with IOPIDA and PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers designed by CS

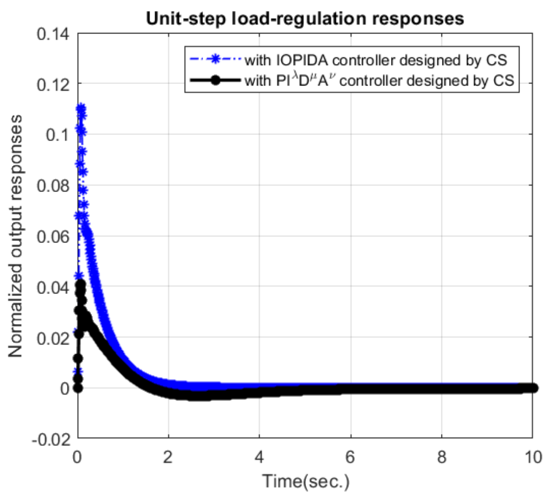

Fig.7. Unit-step load-regulating responses of the drive train system with IOPIDA and PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers designed by CS

Table 1. Results of unit-step input-tracking responses of the drive train control systems

Controllers	Responses			
	t_r (s)	M_p (%)	t_s (s)	e_{ss} (%)
without	0.324	17.78	1.28	300.00
IOPIDA	0.036	18.61	0.21	0.00
PI$^{\lambda}$D$^{\mu}$A$^{\nu}$	0.027	10.25	0.15	0.00

Table 2. Results of unit-step load-regulating responses of the drive train control systems

Controllers	Responses		
	M_{p_reg} (s)	t_{reg} (s)	e_{ss} (%)
without	-----cannot be regulated-----		
IOPIDA	11.06	0.73	0.00
PI$^{\lambda}$D$^{\mu}$A$^{\nu}$	4.07	0.44	0.00

From Figs. 5 - 7 and Tables 1 - 2, where M_{p_reg} is the maximum percent overshoot from load regulation, t_{reg} is the regulating time, it was found that both IOPIDA and PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers are completely optimized by the CS according to the preset design constrained functions in (12). From Fig. 5, the drive train system without controller provides slow response and very high e_{ss}. From Fig. 6 and Table 1, the drive train controlled system with the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller designed by the CS provides smoother input-tracking response than that with the IOPIDA controller designed by the CS. From Fig. 7 and Table 2, the drive train controlled system with the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller designed by the CS provides faster load-regulating response than that with the IOPIDA controller designed by the CS. It can be noticed that the drive train controlled system with the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller designed by the CS can provide very satisfactory responses according to the given design specifications and superior to the IOPIDA controller designed by the CS, significantly.

Pitch control: For this case, the $G_{p2}(s)$ in (4) is used as a plant shown in Fig.3. The design constrained functions and the search spaces in (11) can be set by a preliminary study for designing the PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controller of this case as stated in (15). For the IOPIDA controller, λ, μ and ν in (15) are fixed as λ = μ = 1.0 and ν = 2.0.

$$(15)\quad \begin{cases} Subject\ to & t_r \le 5.00\ \text{sec.}, \\ & M_p \le 5.00\%, \\ & t_s \le 20.00\ \text{sec.}, \\ & e_{ss} \le 0.01\%, \\ & 0 \le K_p \le 5, \\ & -20 \le K_i \le 5, \\ & -1 \le K_d \le 5, \\ & 0 \le K_a \le 0.01, \\ & 0.5 \le \lambda \le 1.5, \\ & 0.5 \le \mu \le 1.5, \\ & 1.5 \le \nu \le 2.5 \end{cases}$$

After the search process stopped, the IOPIDA and PI$^{\lambda}$D$^{\mu}$A$^{\nu}$ controllers optimized by the CS for the pitch control system are successfully obtained as stated in (16) and (17), respectively.

$$(16)\quad G_c(s)\big|_{IOPIDA} = 0.98 - \frac{8.52}{s} - 0.02s + 0.001s^2$$

$$(17)\quad G_c(s)\big|_{PI^{\lambda}D^{\mu}A^{\nu}} = 1.12 - \frac{19.93}{s^{1.14}} - 0.03s^{1.22} + 0.002s^{2.05}$$

The convergent rates of the objective functions in (10) associated with the design constrained functions in (15) proceeded by the CS over 50 trials for the $PI^{\lambda}D^{\mu}A^{\nu}$ controller design are depicted in Fig. 8. It can be seen that the CS has a good robustness for global convergence with different randomly initial solutions. The convergence rates of IOPIDA controller designed by the CS of this case are also omitted because they have a similar form to those in Fig. 8.

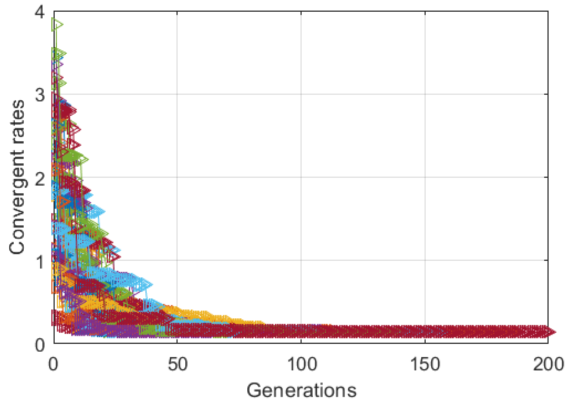

Fig.8. Convergent rates of $PI^{\lambda}D^{\mu}A^{\nu}$ controller designed by CS for pitch control system

The unit-step input-tracking response of the pitch system without controller is plotted in Fig. 9. The unit-step input-tracking and unit-step load-regulating responses of the pitch controlled system with the IOPIDA controller in (16) and the $PI^{\lambda}D^{\mu}A^{\nu}$ controller in (17) are depicted in Fig. 10 and Fig. 11, respectively. Results of input-tracking and load-regulating system responses of this case are summarized in Table 3 and Table 4.

Table 3 Results of unit-step input-tracking responses of the pitch control systems

Controllers	Responses			
	t_r (s)	M_p (%)	t_s (s)	e_{ss} (%)
without	-----cannot be tracked-----			
IOPIDA	4.64	0.00	17.76	0.00
$PI^{\lambda}D^{\mu}A^{\nu}$	4.47	4.61	13.02	0.00

Table 4. Results of unit-step load-regulating responses of the pitch control systems

Controllers	Responses		
	M_{p_reg} (s)	t_{reg} (s)	e_{ss} (%)
without	-----cannot be regulated-----		
IOPIDA	5.49	12.61	0.00
$PI^{\lambda}D^{\mu}A^{\nu}$	5.45	5.84	0.00

From Figs. 9 - 11 and Tables 3 - 4, it was found that both IOPIDA and $PI^{\lambda}D^{\mu}A^{\nu}$ controllers are successfully optimized by the CS according to the preset design constrained functions in (15). From Fig. 9, the pitch system without controller provides the nonminimum phase characteristics that cannot track the input signal. From Fig. 10 and Table 3, the pitch controlled system with the $PI^{\lambda}D^{\mu}A^{\nu}$ controller provides faster input-tracking response than that with the IOPIDA controller. From Fig. 11 and Table 4, the pitch controlled system with the $PI^{\lambda}D^{\mu}A^{\nu}$ controller provides faster load-regulating response than that with the IOPIDA controller. Also, it can be noticed that the pitch controlled system with the $PI^{\lambda}D^{\mu}A^{\nu}$ controller designed by the CS can provide very satisfactory responses according to the given design specifications and superior to the IOPIDA controller designed by the CS, significantly.

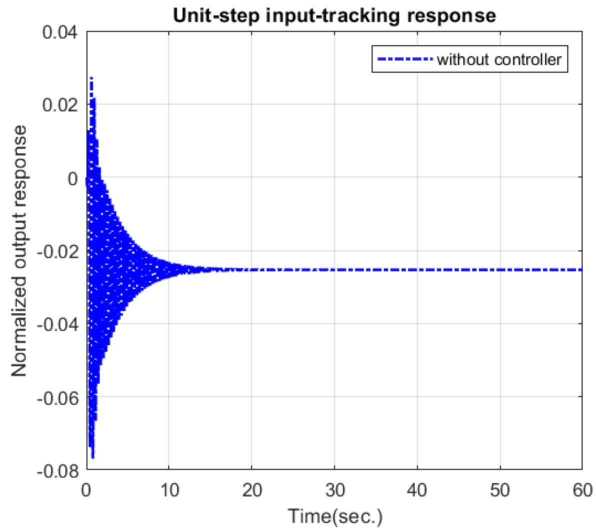

Fig.9. Unit-step input-tracking response of the pitch system without controller

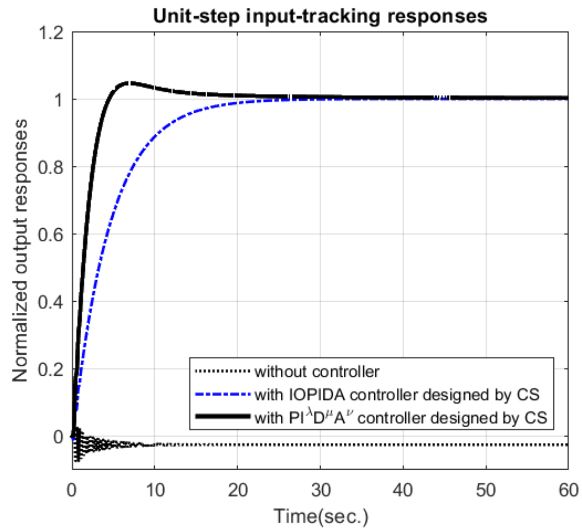

Fig.10. Unit-step input-tracking responses of the pitch system with IOPIDA and $PI^{\lambda}D^{\mu}A^{\nu}$ controllers designed by CS

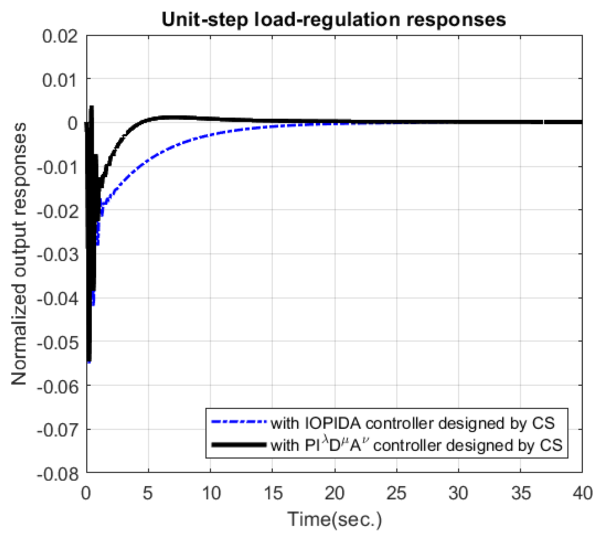

Fig.11. Unit-step load-regulating responses of the pitch system with IOPIDA and $PI^{\lambda}D^{\mu}A^{\nu}$ controllers designed by CS

Conclusions

Designing an optimal $PI^{\lambda}D^{\mu}A^{\nu}$ controller for the wind turbine systems by the cuckoo search (CS) based on modern optimization approach has been presented in this paper. With its seven parameters, the $PI^{\lambda}D^{\mu}A^{\nu}$ controller can be considered as the generalized version of the PID controller family. In order to compare with the conventional IOPIDA controller, the CS algorithm, one of the most powerful metaheuristic optimization techniques, has been utilized in this work to optimize the $PI^{\lambda}D^{\mu}A^{\nu}$ controllers for a drive train and a pitch control of the wind turbine systems. By using the sum of squared error between the reference input signal and the controlled output signal of the controlled system as the objective function and the preset design constrained functions, it was found that the $PI^{\lambda}D^{\mu}A^{\nu}$ controllers designed by the CS for the drive train control system and the pitch control system could provide very satisfactory responses according to the given design specifications and superior to the IOPIDA controllers designed by the CS in both input-tracking and load-regulating responses, significantly. For the future research, the $PI^{\lambda}D^{\mu}A^{\nu}$ controller will be extended to control other real-world systems with the metaheuristics-based control design optimization framework. Also, the implementation of the $PI^{\lambda}D^{\mu}A^{\nu}$ controller in both analog and digital manners will be realized for further development.

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REFERENCES

[1] Podlubny I., *Fractional-Order Systems and Fractional-Order Controllers*, UEF-03-94, Slovak Academy of Sciences, Kosice, (1994)
[2] Podlubny I., Fractional-Order Systems and $PI^{\lambda}D^{\mu}$-Controllers, *IEEE Transactions on Automatic Control*, 44 (1999), 208-214
[3] Shah P., Agashe A., Review of Fractional PID Controller. *Mechatronics*, 38 (2016), 29-41
[4] Chen Y. Q., Petráš I., Dingyü X., Fractional Order Control - A Tutorial, *Proceedings of the American Control Conference*, (2009), 1397-1411
[5] Jung S., Dorf R.C., Analytic PIDA Controller Design Technique for a Third Order System, *Proceedings of the 35th IEEE Conference on Decision and Control*, (1995), 2513-2518
[6] Bettou K., Charef A., Optimal Tuning of Fractional Order $PI^{\lambda}D^{\mu}A$ Controller using Particle Swarm Optimization Algorithm, *Proceedings of the 20th World The International Federation of Congress Automatic Control*, (2017), 8084-8089
[7] Bettou K., Charef A., Optimal Fractional Order $PI^{\lambda}D^{\mu}A$ Controller Design for Bioreactor Control using Particle Swarm Optimization, *Proceedings of the 6th International Conference on Systems and Control*, (2017), 481-486
[8] Puangdownreong D., A Novel Fractional-Order $PI^{\lambda}D^{\mu}A^{\nu}$ Controller and Its Design Optimization Based on Spiritual Search, *International Review of Automatic Control*, 12 (2019), 271-280
[9] Cheunpirom M., Hlangmanthip S., Puangdownreong D., Optimal Tuning of Fractional-Order $PI^{\lambda}D^{\mu}A^{\nu}$ Controller by Cuckoo Search Algorithm, *Proceedings of the 2nd Artificial Intelligence and Cloud Computing Conference*, (2019), 178-183
[10] Naama F.Z., Zegaoui A., Djahbar A., Aillerie M., Simulation and Modeling of a Small Permanent Magnet Synchronous Generator Wind Turbine Directly from Its Datasheet, *Przeglad Elektrotechniczny*, R. 96 NR 7/2020, (2020), 8-12
[11] Perng J.W., Chen G.Y., Hsieh S.C., Optimal PID Controller Design Based on PSO-RBFNN for Wind Turbine Systems, *Energies*, 7 (2014), 191-209
[12] Anderson C.G., Richon J.B., Campbell T.J., An Aerodynamic Moment-Controlled Surface for Gust Load Alleviation on Wind Turbine Rotors, *IEEE Transactions on Control System Technology*, 6 (1998), 577-595
[13] Wang J., Tse N., Gao Z., Synthesis on PI-Based Pitch Controller of Large Wind Turbines Generator, *Energy Conversion and Management*, 52 (2011), 1288-1294
[14] Yang X.S., Deb S., Cuckoo Search via Lévy Flights, *Proceedings of the World Congress on Nature & Biologically Inspired Computing*, (2009), 210-214.
[15] Yang X.S., Cuckoo Search and Firefly Algorithm: Overview and Analysis, *Studied in Computational Intelligence: Cuckoo search and Firefly Algorithm Theory and Applications*, Springer, (2014), 1-26
[16] Khluabwannarat P., Puangdownreong D., Parallel Flower Pollination Algorithm and Its Application to Fractional-Order PID Controller Design Optimization for BLDC Motor Speed Control System, *Przeglad Elektrotechniczny*, R. 96 NR 11/2020, (2020), 78-83
[17] Wongkhead S., Tunyasrirut S., Implementation of a DSP-TMS320F28335 Based State Feedback with Optimal Design of PI Controller for a Speed of BLDC Motor by Ant Colony Optimization, *Przeglad Elektrotechniczny*, R. 97 NR 7/2021, (2021), 7-12
[18] Hamouda N., Babes B., Kahla S., Hamouda C., Boutaghane A., Particle Swarm Optimization of Fuzzy Fractional PD^{μ}+I Controller of a PMDC Motor for Reliable Operation of Wire-Feeder Units of GMAW Welding Machine, *Przeglad Elektrotechniczny*, R. 96 NR 12/2020, (2020), 40-46
[19] Tepljakov A., Petlenkov E., Belikov J., FOMCON: Fractional-Order Modeling and Control Toolbox for MATLAB, *Proceedings of the 18th International Conference on Mixed Design of Integrated Circuits and Systems (MIXDES '11)*, (2011), 684-689
[20] Tepljakov A., Petlenkov E., Belikov J., FOMCON: a MATLAB Toolbox for Fractional-Order System Identification and Control, *International Journal of Microelectronics and Computer Science*, 2 (2011), 51-62