Optimal PIDA Load Frequency Controller Design for Power Systems via Flower Pollination Algorithm

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Abstract: - The load frequency control (LFC) is normally operated under the proportional-integral-derivative (PID) feedback control loop. However, the proportional-integral-derivative-accelerated (PIDA) controller, firstly proposed in 1996, performed superior response to the PID especially for higher order systems. The optimal PIDA controller design for the LFC is presented in this paper. Based on modern optimization context, the flower pollination algorithm (FPA) is applied to design the optimal PIDA by searching for their appropriate parameters. The method is applicable to power systems with non-reheated and reheated turbines. The responses of the LFC controlled by the PIDA will be compared with those controlled by the PID. Simulation results show that both FPA-based PID and PIDA controllers can improve the damping of the power systems. In contrast, the FPA-based PIDA controller outperforms the FPA-based PID controller by giving less damping in power system responses.

Key-Words: - PIDA Load Frequency Controller, Flower Pollination Algorithm, Modern Optimization

1 Introduction

In electrical power system design and operation, the load frequency control (LFC) is very important. The objective of the LFC, in an interconnected power system, is to maintain the frequency of each area and keep tie-line power flows within some pre-specified tolerances by adjusting the power outputs of the LFC generators to accommodate the fluctuating load demands [1],[2]. The LFC is considered as one of the main and most important topics in the power systems in order to keep the uniform frequency during the load change [1-3]. Because of the increased complexity of modern power systems, advanced control methods were consecutively proposed in LFC. By literatures, many analytical methods, such as, internal model control (IMC) [4] and IMC-based PID controller [5], and modern optimization approaches using metaheuristic techniques, for instance, genetic algorithm (GA) [6], particle swarm optimization (PSO) [7], firefly algorithm (FA) [8], cuckoo search (CS) [9] and flower pollination algorithm (FPA) [10], have been successfully launched for optimal PID-LFC design.

The PIDA controller was firstly introduced in 1996 by Jung and Dorf [11]. Because the PIDA possesses three zeros, it has been claimed to deliver faster and smoother response than the PID for the higher order plants. The PIDA controller has been successfully applied to torsional resonance suppression [12], motor speed control [13], automatic voltage regulator (AVR) control [14],[15] and liquid-level control [16],[17].

Among metaheuristic optimization techniques, the flower pollination algorithm (FPA), firstly proposed by Yang in 2012 [18], is one of the newest and most efficient metaheuristic optimization techniques. The FPA algorithm mimics the behaviour of pollination of flowering plant in nature. By literatures, the performance evaluation of the FPA against many standard test functions was proposed [18],[19]. The FPA outperformed GA and PSO. The FPA algorithms were proved for the global convergent property [20] and successfully applied to many real-world engineering problems, for example, pressure vessels design, disc break design, electrical power system, image processing, wireless sensor networking, structural engineering, control system design and model identification. The state-of-the-art and its applications of the FPA have been reported [21-23].

In this paper, designing an optimal PIDA controller for LFC problem via the FPA is presented. The power systems conducted in this work include non-reheated and reheated turbines. Results obtained by the PIDA controller designed by the FPA will be compared with those obtained by the FPA-based PID controller. The rest of the paper is arranged as follows. Problem formulation of the optimal PIDA-LFC designed by the FPA is described in section 2. The FPA algorithm for the PIDA controller design is given in section 3. Results and discussions are illustrated in section 4, while conclusions are given in section 5.

2 FPA-Based PIDA-FLC Formulation

For the case of a single generator supplying power to a single area, and two types of turbine, i.e. non-reheated and reheated turbines, used in generation, the LFC operation under PIDA control loop can be represented by a block diagram as shown in Fig. 1, where $G_g(s)$, $G_t(s)$, $G_m(s)$ and $G_d(s)$ are transfer function models of governor, turbine, load-machine and droop dynamics, respectively, ΔP_d is load disturbance (p.u.MW), ΔP_G is an incremental change in governor output (p.u.MW), ΔX_G is an incremental change in governor valve position, r is reference input, e is error signal, u is control signal and Δf is an incremental frequency deviation (Hz).

Once considering only relatively small changes in load, the LFC problem can be adequately represented by the linear model [1],[24]. The droop characteristic in Fig. 1 is a feedback gain to improve the damping properties of the power system. It is generally set to $1/R$ before load frequency control design [1-3],[24]. Referring to Fig. 1, $G_c(s)$ is the PIDA transfer function as expressed in (1), where K_p, K_i, K_d and K_a are proportional, integral, derivative and accelerated gains, respectively.

$$\left.\begin{aligned} G_c(s) &= K_p + \frac{K_i}{s} + K_d s + K_a s^2 \\ &= \frac{K_a s^3 + K_d s^2 + K_p s + K_i}{s} \end{aligned}\right\} \tag{1}$$

For non-reheated turbine, $G_g(s)$, $G_t(s)$ and $G_m(s)$ are stated in (2), (3) and (4), respectively, where T_g is time constant of governor, T_t is time constant of turbine, T_m is time constant of electric system and K_m is electric system gain [24].

$$G_g(s) = \frac{1}{T_g s + 1} \tag{2}$$

$$G_t(s) = \frac{1}{T_t s + 1} \tag{3}$$

$$G_m(s) = \frac{K_m}{T_m s + 1} \tag{4}$$

For reheated turbines, the turbine dynamics $G_t(s)$ is expressed in (5), where T_r is a time constant of reheat turbine and c is the portion (percentage) of the power generated by the reheat process in the total generated power [24].

$$G_t(s) = \frac{cT_r s + 1}{(T_r s + 1)(T_t s + 1)} \tag{5}$$

Based on modern optimization, the FPA-based PIDA-LFC design framework can be represented by a block diagram as visualized in Fig. 2. Once zero-input reference (r = 0) is activated, Δf is then set as the objective function to be minimized by searching for the appropriated values of the PIDA parameters corresponding to their search spaces and inequality constrained functions as expressed in (6) where, K_{p_min} and K_{p_max} are search spaces of K_p, K_{i_min} and K_{i_max} are search spaces of K_i, K_{d_min} and K_{d_max} are search spaces of K_d, K_{a_min} and K_{a_max} are search spaces of K_a, PO_{reg} is percent overshoot of regulation, PO_{reg_max} is maximum allowance of PO_{reg},

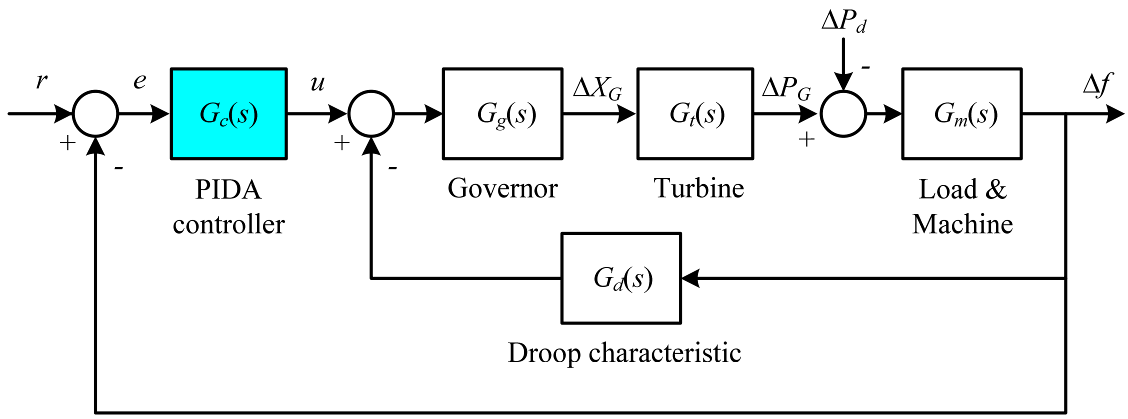

Fig. 1 LFC with PIDA controller.

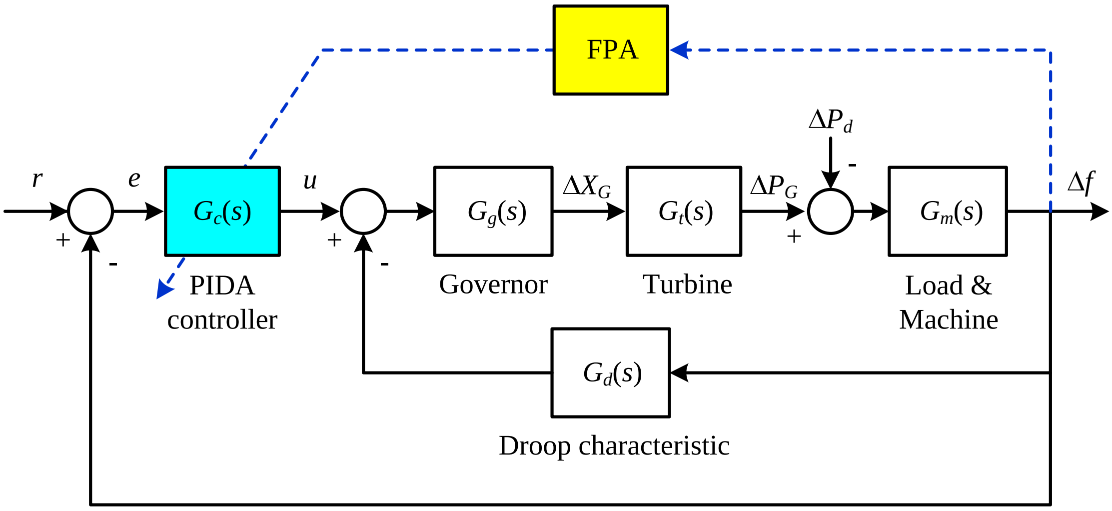

Fig. 2 FPA-based PIDA LFC design framework.

t_{reg} is recovering time, t_{reg_max} is maximum allowance of t_{reg}, e_{ss} is steady-state error and e_{ss_max} is maximum allowance of e_{ss}. The FPA algorithm for designing an optimal PIDA controller will be described in next section.

$$\left.\begin{aligned} &\textbf{Minimize} \quad \Delta f(K_p, K_i, K_d, K_a) \\ &\text{Subject to} \quad K_{p\_min} \le K_p \le K_{p\_max}, \\ &K_{i\_min} \le K_i \le K_{i\_max}, \\ &K_{d\_min} \le K_d \le K_{d\_max}, \\ &K_{a\_min} \le K_a \le K_{a\_max}, \\ &PO_{reg} \le PO_{reg\_max}, \\ &t_{reg} \le t_{reg\_max}, \\ &e_{ss} \le e_{ss\_max} \end{aligned}\right\} \tag{6}$$

3 FPA Algorithm

There are two major forms of flower pollination in nature, i.e. self-pollination (Autogamy for the same flower and Geitonogamy for different flowers of the same plant) and cross-pollination (Allogamy for different plants). Self-pollination, regarded as the local pollination, usually occurs at short distance without pollinators. Cross-pollination, regarded as the global pollination, usually occurs at long distance with biotic pollinators, such as bees and birds. Lévy flight can be adopted for biotic pollinator behaviour in cross-pollination.

The FPA algorithm proposed by Yang [18] is based on four particular rules as follows:

- Biotic and cross-pollination are global pollination process via Lévy flight (Rule-1).
- Abiotic and self-pollination are local pollination process with random walk (Rule-2).
- Pollinators such as insects can develop flower constancy, which is equivalent to a reproduction probability that is proportional to the similarity of two flowers involved (Rule-3).
- Local pollination and global pollination can be controlled by a switch probability $p \in [0, 1]$ (Rule-4).

A solution $\boldsymbol{x}_i$ is equivalent to a flower and/or a pollen gamete. For global pollination, flower pollens are carried by pollinators. With Lévy flight, pollens can travel over a long distance. Therefore, Rule-1 and flower constancy in Rule-3 can be expressed in (7), where $\boldsymbol{g}^*$ is the current best solution found among all solutions at the current generation/ iteration t, and L stands for the Lévy flight that can be approximated by (8), while $\Gamma(\lambda)$ is the standard gamma function as stated in (9). In the case when $\lambda = n$ is an integer, $\Gamma(n) = (n\text{-}1)!$.

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + L(\boldsymbol{x}_i^t - \boldsymbol{g}^*) \tag{7}$$

$$L \approx \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, \quad (s >> s_0 > 0) \tag{8}$$

$$\Gamma(\lambda) = \int_0^\infty t^{\lambda-1}e^{-t}dt \tag{9}$$

For local pollination, Rule-2 and Rule-3 can be represented by (10), where $\boldsymbol{x}_j$ and $\boldsymbol{x}_k$ are pollens from the different flowers of the same plant species, while ε stands for random walk by using uniform distribution in [0,1]. Once setting $a = 0$ and $b = 1$ in (11), it is called a standard uniform distribution.

Flower pollination activities can occur at all scales, both local and global pollination. In this case, a switch probability or proximity probability p in Rule-4 is used to switch between common global pollination to intensive local pollination.

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \varepsilon(\boldsymbol{x}_j^t - \boldsymbol{x}_k^t) \tag{10}$$

$$\varepsilon(\rho) = \begin{cases} 1/(b-a), & a \le \rho \le b \\ 0, & \rho < a \text{ or } \rho > b \end{cases} \tag{11}$$

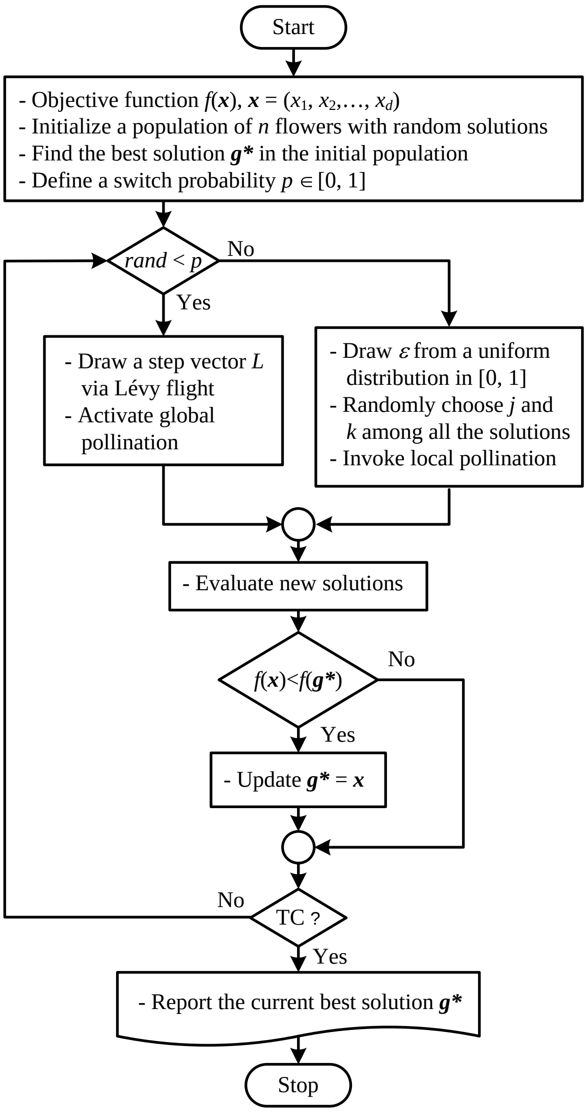

Fig. 3 Flow diagram of FPA algorithm.

The FPA algorithm can be summarized by the flow diagram as shown in Fig. 3. From Yang's research reports [18],[19], the number of pollens n = 25, switch probability p = 0.8 and λ = 1.5 works better for most applications and are recommended parameter set based on preliminary parametric studies. In order to design an optimal PIDA controller for LFC, the FPA algorithm can be applied as follows.

Step-0 Initialize the objective function and Δf in (6) and constraint functions associated with their search spaces in (6). Randomly generate a population of n = 25 flowers. Fine the best solution $\boldsymbol{g}^*$ among initial population. Define a switch probability p = 0.8 (or 80%). Set MaxGen as the termination criteria (TC) and Gen = 1 as a generation counter.

Step-1 If Gen ≤ MaxGen, go to Step-2. Otherwise go to Step-4.

Step-2 If rand < p, draw a step vector L via Lévy flight in (8)-(9) and activate global pollination in (7) to generate a new solution $\boldsymbol{x}$. Otherwise draw a uniform distribution $\varepsilon \in$ [0, 1] in (11). Randomly select j and k among all solutions. Invoke local pollination in (10) to generate a new solution $\boldsymbol{x}$.

Step-3 If $f(\boldsymbol{x}) < f(\boldsymbol{g}^*)$, update solution $\boldsymbol{g}^* = \boldsymbol{x}$ and update Gen = Gen+1. Otherwise update Gen = Gen+1. Go to Step-1 to proceed next generation.

Step-4 Report the best solution found (K_p, K_i, K_d and K_a) and stop the search process.

4 Results and Discussions

In this work, the FPA algorithm was coded by MATLAB version 2017b (License No.#40637337) run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM. For all cases, the inequality constrained functions in (6) will be performed as stated in (12). Based on Yang's recommendations [18],[19], n = 25, p = 0.8 and λ = 1.5 are then set. Also, MaxGen = 200 is then defined as TC and 50 trials are conducted to find the best parameters of the PIDA controller (K_p, K_i, K_d and K_a) for each LFC problem. By comparison, K_a = 0 in (12) will be set for FPA-based PID controller design.

$$\text{Subject to} \quad \left.\begin{aligned} & 0 \le K_p \le 10, \\ & 0 \le K_i \le 10, \\ & 0 \le K_d, K_a \le 4, \\ & PO_{reg} \le 2.0\%, \\ & t_{reg} \le 10 \text{ sec.}, \\ & e_{ss} \le 0.01\% \end{aligned}\right\} \tag{12}$$

4.1 Case-I (Non-Reheated Turbine)

For the power system with a non-reheated turbine, the model parameters are given as follows [24]: K_m = 120, T_m = 20 sec., T_t = 0.3 sec., T_g = 0.08 sec., and R = 2.4. Referring to Fig. 1, the plant model, $G_p(s)$, with droop characteristic is then expressed in (13). For the Case-I, $G_p(s)$ in (13) can be rewritten as stated in (14).

$$G_p(s) = \frac{G_g G_t G_m}{1 + G_g G_t G_m / R} \tag{13}$$

$$G_p(s) = \frac{250}{s^3 + 15.88s^2 + 42.46s + 106.2} \tag{14}$$

Once the search process stopped, the FPA can successfully provide the optimal parameters of the PID and PIDA controllers for a LFC power system with a non-reheated turbine as expressed in (15) and (16), respectively. The convergent rates of the objective functions in (6) associated with inequality constrained functions in (12) proceeded by the FPA over 50 trials are depicted in Fig. 4. Responses of a LFC power system with a non-reheated turbine once a load disturbance ΔP_d = 0.01 p.u.MW is applied are plotted in Fig. 5.

$$G_c(s)\big|_{PID} = 0.5036 + \frac{0.5356}{s} + 0.1832s \tag{15}$$

$$G_c(s)\big|_{PIDA} = 2.9548 + \frac{2.5962}{s} + 1.2825s + 0.2514s^2 \tag{16}$$

Referring to Fig. 5, it can be observed that both FPA-based PID and PIDA controllers can improve the damping of a power system with a non-reheated turbine. Results obtained by the FPA-based PID and the FPA-based PIDA for Case-I are summarized in Table 1. It can be noticed that the FPA-based PIDA controller can give less damping in power system response.

Table 1 Results obtained by FPA-based PID and FPA-based PIDA (Case-I).

Controllers	**Load Regulation Responses**		
	PO_{reg} (%)	t_{reg} (sec.)	e_{ss} (%)
without	63.3950	8.2614	0.7020
PID	1.0210	7.4206	0.00
PIDA	0.2576	3.2801	0.00

4.2 Case-II (Reheated Turbine)

For the power system with a reheated turbine, the model parameters are given as follows [24]: K_m = 120, T_m = 20 sec., T_t = 0.3 sec., T_g = 0.08 sec., R = 2.4, T_r = 4.2 sec. and c = 0.35. With these values, $G_p(s)$ in (13) becomes (17).

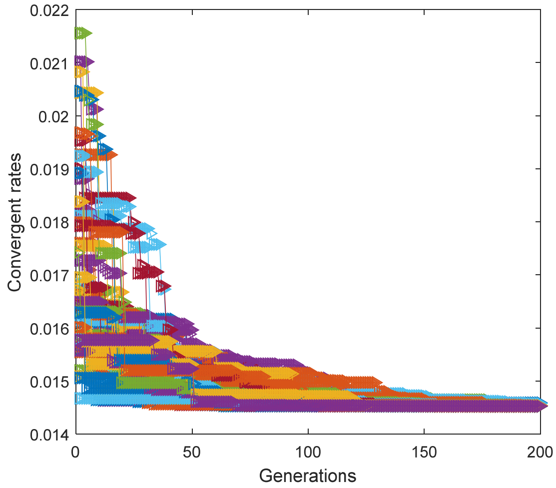

Fig. 4 Convergent rates of a LFC power system with a non-reheated turbine (Case-I).

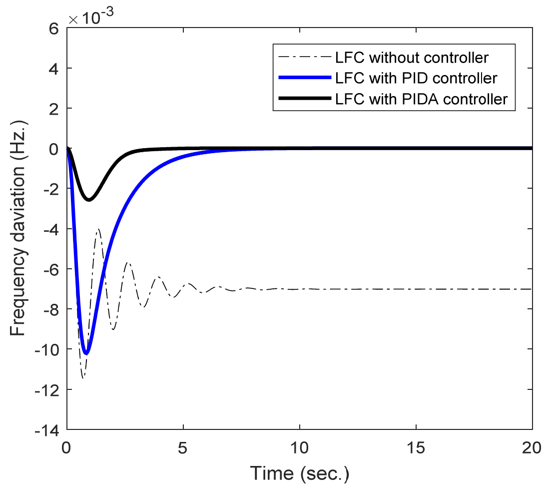

Fig. 5 Responses of a LFC power system with a non-reheated turbine (Case-I).

$$G_p(s) = \frac{87.5s + 59.52}{s^4 + 16.12s^3 + 46.24s^2 + 48.65s + 25.3} \tag{17}$$

When the search process stopped, the FPA can successfully give the optimal parameters of the PID and PIDA controllers for a LFC power system with a reheated turbine as expressed in (18) and (19), respectively. The convergent rates of the objective functions in (6) associated with inequality constrained functions in (12) proceeded by the FPA over 50 trials are plotted in Fig. 6. Responses of a LFC power system with a reheated turbine once a load disturbance ΔP_d = 0.01 p.u.MW is applied are depicted in Fig. 7.

$$G_c(s)\big|_{PID} = 2.7935 + \frac{1.2735}{s} + 0.7866s \quad (18)$$

$$G_c(s)\big|_{PIDA} = 6.8105 + \frac{9.4498}{s} + 2.0502s + 0.1494s^2 \quad (19)$$

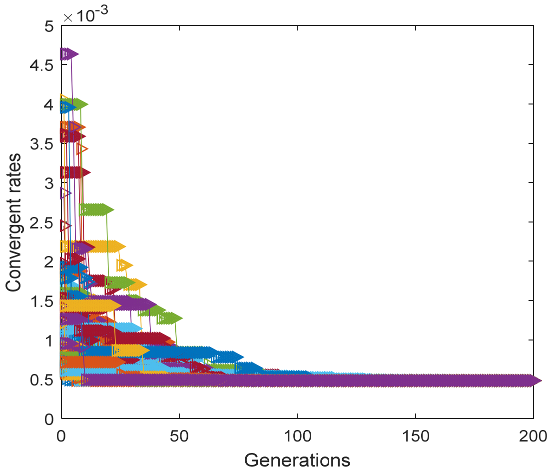

Fig. 6 Convergent rates of a LFC power system with a reheated turbine (Case-II).

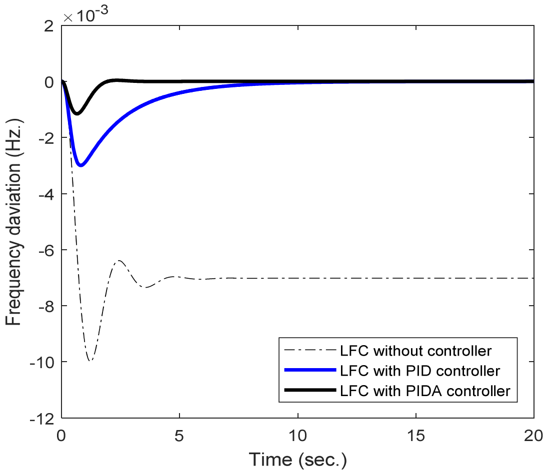

Fig. 7 Responses of a LFC power system with a reheated turbine (Case-II).

From Fig. 7, it was found that both FPA-based PID and PIDA controllers can improve the damping of a power system with a reheated turbine. Results obtained by the FPA-based PID and the FPA-based PIDA for Case-II are summarized in Table 2. It can be concluded that the FPA-based PIDA controller can give less damping in power system response than the FPA-based PID controller.

Table 2 Results obtained by FPA-based PID and FPA-based PIDA (Case-II).

Controllers	Load Regulation Responses		
	PO_{reg} (%)	t_{reg} (sec.)	e_{ss} (%)
without	42.3859	6.7405	0.7017
PID	0.2998	7.2633	0.00
PIDA	0.1157	1.8946	0.00

5 Conclusions

Designing an optimal PIDA controller for LFC in power systems by the FPA has been proposed in this paper. Based on modern optimization, the PIDA-LFC design has been formulated as the inequality constrained optimization problem. Once the load disturbance was occurred in power systems, the frequency deviation set as the objective function has been minimized by searching for the appropriate values of the PIDA's parameters within given search spaces and constrained functions. In this work, the power systems including non-reheated and reheated turbines have been conducted. Simulation results have shown that the FPA-based PID and the FPA-based PIDA controllers could improve the damping of the power systems. However, the FPA-based PIDA controller could provide less damping in both cases than the FPA-based PID controller, significantly. For the future trends of research interests, other types of turbines, such as gas, wind, hydro and thermal turbines will be investigated. The FPA-based multi-area PIDA-LFC design will be extended. Finally, optimal design of the fractional-order PID controller for LFC control will be studied.

References:

[1] P. Kundur, *Power System Stability and Control*, McGraw-Hill, New York, 1994.

[2] O. I. Elgerd, *Electric Energy Systems Theory: An Introduction*, McGraw-Hill, New Delhi, 1983.

[3] H. Shayeghi, H. A. Shayanfar and A. Jalili, Load Frequency Control Strategies: A State-of-the-Art Survey for the Researcher, *Energy Conversion and Management*, Vol. 50, 2009, pp. 344-353.

[4] J. Srinivas and B. Ramesh, Load Frequency Control (LFC) using Internal Model Control (IMC), *International Journal of Recent Trends in Engineering & Research (IJRTER)*, Vol. 3, No. 6, 2017, pp. 90-100.

[5] S. J. Beevi, R. Jayashree and P. Anbumalar, Load Frequency Control using IMC based PID Controller, *International Journal of Scientific & Engineering Research*, Vol. 5, No. 4, 2014, pp. 24-28.
[6] S. K.Bhagat, B. Rai and A. Kumar, GA based Internal Model Controller Design for Load Frequency Control in Power System via Reduced Order Model, *International Journal of Engineering Science Invention*, Vol. 3, No. 3, 2014, pp. 17-26.
[7] A. M. Jadhav, K. Vadirajacharya and E. T. Toppo, Application of Particle Swarm Optimisation in Load Frequency Control of Interconnected Thermal-Hydro Power Systems, *International Journal of Swarm Intelligence*, Vol. 1, No. 1, 2013, pp. 91-113.
[8] K. Naidu, H. Mokhlis and A. H. A. Bakarb, Application of Firefly Algorithm (FA) Based Optimization in Load Frequency Control for Interconnected Reheat Thermal Power System, *Proceedings of the 2013 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT)*, 2013.
[9] A. Y. Abdelaziz and E. S. Ali, Cuckoo Search Algorithm Based Load Frequency Controller Design for Nonlinear Interconnected Power System, *International Journal of Electrical Power Energy Systems*, Vol. 73, 2015, pp. 632-643.
[10] D. Lakshmi, A. P. Fathima and R. Muthu, A Novel Flower Pollination Algorithm to Solve Load Frequency Control for a Hydro-Thermal Deregulated Power System, *Circuits and Systems*, Vol. 7, 2016, pp. 166-178.
[11] S. Jung and R. C. Dorf, Analytic PIDA Controller Design Technique for a Third Order System, *Proceedings of the* 35*th IEEE Conference on Decision and Control*, 1996, pp. 2513-2518.
[12] D. Puangdownreong and S. Suwannarongsri, Torsional Resonance Suppression via PIDA Controller Designed by the Particle Swarm Optimization, *Proceedings of the ECTI–CON2008*, 2008, pp. 673-676.
[13] S. Sornmuang and S. Sujitjorn, GA-Based PIDA Control Design Optimization with an Application to AC Motor Speed Control, *International Journal of Mathematics and Computers in Simulation*, Vol. 4, No. 3, 2010, pp. 67- 80.
[14] D. Puangdownreong, Application of Current Search to Optimum PIDA Controller Design, *Intelligent Control and Automation*, Vol. 3, No. 4, 2012, pp. 303-312.
[15] D. Puangdownreong, S. Sumpunsri, M. Sukchum, C. Thammarat, S. Hlangnamthip and A. Nawikavatan, FA-Based Optimal PIDA Controller Design for AVR System, *The iEECON2018 International Conference*, 2018, pp. 548-551.
[16] C. Thammarat, K. Lurang, D. Puangdown-reong, S. Suwammarongsri, S. Hlangnamthip and A. Nawikavatan, Application of Bat-Inspired Algorithm to Optimal PIDA Controller Design for Liquid-Level System, *The iEECON2018 International Conference*, 2018, pp. 556-559.
[17] A. Nawikavatan, T. Jitwang, C. Thammarat and D. Puangdownreong, Application of Cuckoo Search to Optimal PIDA Controller Design for Three-Tank Liquid-Level Control System, *Proceedings of the 2018 International Conference on Engineering and Natural Science (ICENS2018)*, 2018, pp. 51-59.
[18] X. S. Yang, Flower Pollination Algorithm for Global Optimization, *Unconventional Computation and Natural Computation*, *Lecture Notes in Computer Science*, Vol. 7445, 2012, pp.240-249.
[19] X. S. Yang, M. Karamanoglu and X. He, Multi-Objective Flower Algorithm for Optimization, *Procedia Computer Science*, Vol. 18, 2013, pp.861-868.
[20] X. He, X. S. Yang, M. Karamanoglu and Y. Zhao, Global Convergence Analysis of the Flower Pollination Algorithm: A Discrete-Time Markov Chain Approach, *Procedia Computer Science*, Vol. 108C, 2017, pp.1354-1363.
[21] D. Puangdownreong, Optimal State-Feedback Design for Inverted Pendulum System by Flower Pollination Algorithm, *International Review of Automatic Control (IREACO)*, Vol. 9, No. 5, 2016, pp.289-297.
[22] D. Puangdownreong, C. Thammarat, S. Hlungnamtip and A. Nawikavatan, Application of Flower Pollination Algorithm to Parameter Identification of DC Motor Model, *Proceedings of the iEECON–2017*, Vol. 2, 2017, pp.711-714.
[23] Z. A. A. Alyasseri, A. T. Khader, M. A. Al-Betar, M. A. Awadallah and X. S. Yang, Variants of the Flower Pollination Algorithm: A Review, *Nature-Inspired Algorithms and Applied Optimization*, *Studies in Computational Intelligence*, Vol. 744, 2018, pp. 91-118.
[24] W. Tan, Unified Tuning of PID Load Frequency Controller for Power Systems via IMC, *IEEE Transactions on Power Systems*, Vol. 25, No. 1, 2010, pp. 341-350.