

Linear Active Disturbance Rejection Control Approach for Load Frequency Control Problem Using Diminishing Step Fruit Fly Algorithm

Congzhi Huang and Yan Li

Abstract The diminishing step fruit fly optimization algorithm (DS-FOA) is employed to optimize the performance of the load frequency control (LFC) problem by employing the linear active disturbance rejection control (LADRC) approach. First of all, the LFC problem taking into account the case of a single generator supplying power to a single service area is presented. Second, the general LADRC solution to the problem is given, where the diminishing step fruit fly optimization algorithm (DS-FOA) is employed to optimize the performance of the system with the approach. Third, the performances of the system with the following three control approaches are compared, including the traditional PID control approach, the normal LADRC approach, and the DS-FOA optimized LADRC approach. With the proposed LADRC approach, the system performance is much better than that of the traditional PID controller, and a much better performance is achieved with the proposed DS-FOA optimized LADRC approach. The performance superiority of the proposed approach is also validated by the frequency domain analysis results given.

Keywords Fruit fly optimization algorithm (FOA) • Load frequency control (LFC) • Linear active disturbance rejection control (LADRC) • Power system

1 Introduction

The problem to control the active power output of generating units responding to the disturbances in grid frequency and tie line power exchange within the designated limitation is denoted by the load frequency control issue [1]. Nowadays, it has

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become a hot topic with the aggressive development of smart grid all over the world. The traditional PID control strategy is usually employed to solve the LFC problem. The particle swarm optimized PID control approach is proposed in [2], and the other approaches refer to the model predictive control [3], adaptive fuzzy logic control [4], robust H_∞ control [5], and so on.

However, the performance improvement of the system with the traditional PID control approach is usually limited, while most of the advanced control approaches are difficult to put into practice due to its complex structure. To solve the disturbance rejection control problem widespread in industry, the active disturbance rejection control approach by Han [6] was brought into being. Its core idea is that the total disturbance, including all the internal uncertainties and external disturbance can be estimated with the aid of an extended state observer constructed in real time, and then cancelled by the nonlinear PD control law [7]. However, there were too many parameters to be tuned in the original ADRC approach, and thus it is often difficult to conduct parameter tuning work and put it into practice. Fortunately, the linear version of the ADRC approach emerges at a historic moment in [8], which largely simplified the parameters tuning procedure and thus quickly found a number of applications in practical engineering, see the integrated guidance and control system [9], and the hot strip width and gauge regulation problem [10].

In this paper, a general LADRC approach is introduced, and the DS-FOA is employed to tune the LADRC approach. In addition, the LFC problem for the single area power system with a non-reheated turbine is given for an example. A fourth-order LADRC approach is used to illustrate the effectiveness of the proposed approach. In order to improve the system performance, the DS-FOA is employed to tune the parameters in the LADRC approach, the result is also compared with that of the traditional PID approach in [11] and the normal LADRC approach in [12].

2 LFC Problem Formulation

A linear model of a single area power system with a non-reheated turbine is shown in Fig. 1.

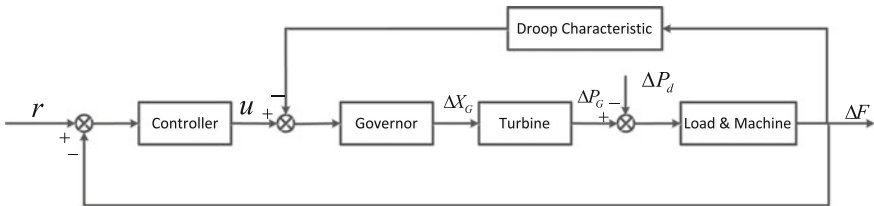


Fig. 1 Linear model of a single area power system

As can be seen from Fig. 1, r is the reference input, u is the controller output, and ΔF is the frequency deviation, which is also the controlled process output in the load frequency control problem. ΔP_d represents the external load disturbance, ΔP_G represents the incremental quantity in generator output, and ΔX_G the incremental quantity in governor valve position.

The plant discussed in this paper is the same with that in [11] consisting of the following three parts: governor, turbine, and load and machine. The dynamics of the governor can be described as $G_g(s) = 1/(T_g s + 1)$, and the turbine model is often represented by $G_t(s) = 1/(T_t s + 1)$. The transfer function of the load and machine is denoted by $G_m(s) = K_p/(T_p s + 1)$. In addition, the droop characteristic is a feedback controller with the gain of $1/R$ so as to improve the system performance.

Since the LFC problem for the power system under consideration is expressed only to relatively small changes in load, so the controller can be used to ensure the frequency deviation as small as possible under small load changes.

3 Linear Active Disturbance Rejection Control Solution

A. Linear Active Disturbance Rejection Control

The typical block diagram for the system with the LADRC approach is shown in Fig. 2.

As shown in Fig. 2, an ESO based on the process input and output data is constructed to estimate the process output its finite time derivatives, and the total disturbance. Consider the following general controlled process:

$$y^{(n)} = g(t, y, \dot{y}, \dots, u, \dot{u}, \dots, w) + bu, \quad (1)$$

where y is the controlled process output variable, u is the control input, and w represents the external disturbance. Taking the estimation value of b as b_0 , it can be rewritten as:

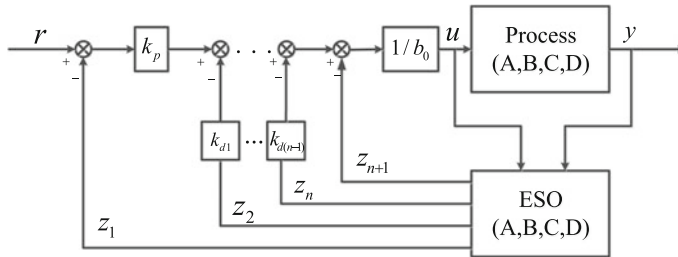


Fig. 2 Block diagram of control system with the LADRC approach

$$y^{(n)} = g(t, y, \dot{y}, \dots, u, \dot{u}, \dots, w) + (b - b_0)u + b_0u = f + b_0u, \quad (2)$$

where $f = g(t, y, \dot{y}, \dots, u, \dot{u}, \dots, w) + (b - b_0)u$ is defined as the total disturbance, including the unknown dynamics as well as all the external disturbances. Define an augmented state vector $x = [x_1, x_2, \dots, x_n, x_{n+1}]^T$, the extended state equation of the original process is given as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dots \\ \dot{x}_n = x_{n+1} + b_0u, \\ \dot{x}_{n+1} = h \\ y = x_1 \end{cases} \quad (3)$$

where the state variables $x_1, x_2, \dots, x_n$ are the process state, $x_{n+1} = f$ added as an augmented state, and $h = \dot{f}$ is the unknown variable representing the first order time derivative of the total disturbance.

Then, the following extended state observer is constructed:

$$\begin{cases} \dot{z}_1 = z_2 + \beta_1(y(t) - z_1) \\ \dots \\ \dot{z}_n = z_{n+1} + \beta_n(y(t) - z_1) + b_0u, \\ \dot{z}_{n+1} = \beta_{n+1}(y(t) - z_1) \end{cases} \quad (4)$$

where the observer gain is denoted by $L = [\beta_1, \beta_2, \dots, \beta_n, \beta_{n+1}]^T$. With appropriate observer gains, the following state variables can be tracked accurately:

$$\begin{aligned} z_1(t) &\rightarrow y(t), z_2(t) \rightarrow \dot{y}(t), \dots, z_n(t) \rightarrow y^{(n-1)}(t) \\ z_{n+1}(t) &\rightarrow f \end{aligned} \quad (5)$$

In order to simplify the parameter tuning procedure of the ESO, all the observer poles are placed at the same place $-\omega_o$, where the observer bandwidth w_o is the only parameter to be tuned. The characteristic equation of the ESO is given as:

$$s^n + \beta_1 s^{n-1} + \dots + \beta_{n-1} s + \beta_n = (s + \omega_o)^n. \quad (6)$$

Then, the ESO gain L can be obtained as follows: $\beta_1 = n\omega_o$, $\beta_2 = 0.5n(n-1)\omega_o^2, \dots, \beta_o = n\omega_o^n$, $\beta_{n+1} = \omega_o^{n+1}$. With the well-tuned ESO, the control law is then designed:

$$u = \frac{-z_{n+1} + u_0}{b_0} \quad (7)$$

This control law reduces the original plant to a cascaded integrator, which can be easily controlled by a PD controller as follows:

$$u_0 = k_p(r - z_1) - k_{d1}z_2 - \dots - k_{d(n-1)}z_n \quad (8)$$

After the gains are selected in order to place all the roots of the closed-loop characteristic equation at the same place $-\omega_c$, where ω_c is the controller bandwidth.

$$s^n + k_{d(n-1)}s^{n-1} + \dots + k_{d1}s + k_p = (s + \omega_c)^n, \quad (9)$$

where the controller parameters $k_p, k_{d1}, \dots, k_{d(n-1)}$ are chosen as follows: $k_p = \omega_c^n, k_{d1} = \omega_c^{n-1}, \dots, k_{d(n-1)} = n\omega_c$.

Now, there are only three parameters to be tuned in the LADRC approach: b_0, ω_c and ω_o . In the following section, the FOA will be employed to tune them so as to achieve better performance.

B. Fruit Fly Optimization Algorithm

The fruit fly optimization algorithm (FOA) proposed by Pan [13] is a kind of swarm intelligent algorithm. Compared with the traditional particle swarm optimization (PSO) algorithm, the FOA can achieve an optimal speed. But it also has its own disadvantages: it is easy to fall into a local optimal solution, and it is easy to become premature. Thus there are many scholars trying to improve the traditional FOA. The diminishing step fruit fly optimization algorithm (DS-FOA) is proposed in [14] to improve the global searching ability at the beginning and ensure the local optimization ability later. In the DS-FOA, the searching step length L changes from a constant variable into a decline variable:

$$L = L_0 - \frac{L_0(G-1)}{G_{\max}}, \quad (10)$$

where L_0 is the initial searching step length, G is the current optimization iteration number and $G_{\max}$ is the max optimization iteration number. The tuning procedure of the DS-FOA optimized LADRC approach is given as follows:

- Step 1 Initialization. Set the max optimization iteration number $G_{\max}$, and the flies population size P .
- Step 2 Generate the initial locations of the fruit fly swarm randomly, $\theta_0 = [(x_{01}, y_{01}), (x_{02}, y_{02}), (x_{03}, y_{03})]$.
- Step 3 Use (10)–(12) to assign each fruit fly a direction and distance randomly, and change the searching step L .

$$X(i) = X_{0i} + L * \text{rand}(1, 1) \quad (11)$$

$$Y(i) = Y_{0i} + L * \text{rand}(1, 1) \quad (12)$$

- Step 4 Take the values of the parameters b_0, ω_c and ω_o into the LADRC approach, and obtain the system error $e(t) = y(t) - r(t)$, where y is the system output,

and r is the set point. The performance index ITAE (Integration of Time multiplied by Absolute Error) can be selected as the fitness function.

$$J = \int_0^{\infty} t|e(t)|dt \quad (13)$$

Based on Eq. (13), the value of performance index J can be easily obtained.

- Step 5 Compute the minimum value of $J_{\min}$ and the location of b_0 , ω_c and ω_o : $\theta_i = [(x_{i1}, y_{i1}), (x_{i2}, y_{i2}), (x_{i3}, y_{i3})]$
- Step 6 Once $J_{\min}$ is obtained, update the initial location as $\theta_0 = [(x_{ib0}, y_{ib0}), (x_{i\omega c}, y_{i\omega c}), (x_{i\omega o}, y_{i\omega o})]$.
- Step 7 Repeat step 3–6. When it comes to achieve maximum iteration number then run out of circulation, and get the final values of b_0 , ω_c and ω_o .

4 Illustrative Examples

The nominal parameters of the non-reheated turbine plant in Fig. 1 are chosen as follows: $K_p = 120$, $T_p = 20$, $T_t = 0.3$, $T_g = 0.08$, and $R = 2.4$. With the given nominal parameters, the process model with droop characteristic can be obtained as $G_p(s) = 250/(s^3 + 15.88s^2 + 42.46s + 106.2)$. To verify the robustness of the proposed approach, the parameters of the system are assumed to vary by $\pm 50\%$. $1/T_t \in [2.564, 4.762]$, $1/T_g \in [9.615, 17.857]$, $1/T_p \in [0.033, 0.1]$, $K_p/T_p \in [4, 12]$, $1/RT_g \in [3.081, 10.639]$.

The PID controller $K(s) = 0.4036 + 0.6356/s + 0.1832s$ was the one adopted in [11]. The LADRC tuning parameters in [12] are selected as follows: the estimation value $b = 250$, the observer bandwidth $\omega_o = 5.15$ and the controller bandwidth $\omega_c = 280$.

In the DS-FOA optimized LADRC approach, the population size is set as 30, the number of iterations is chosen as 20, and the initial searching step length is equal to 1, and the simulation results are presented in Fig. 3. Figure 4 shows the optimization processes of DS-FOA. Table 1 shows the optimization result.

A. Disturbance Rejection Test

After conducting a disturbance rejection test, the performance superiority of the optimized LADRC approach can be verified. With the load demand $\Delta P_d = 0.01$, the responses of the power system with non-reheated turbine and the DS-FOA optimized LADRC approach are shown and compared with the PID and LADRC performance from [11, 12] in Fig. 4.

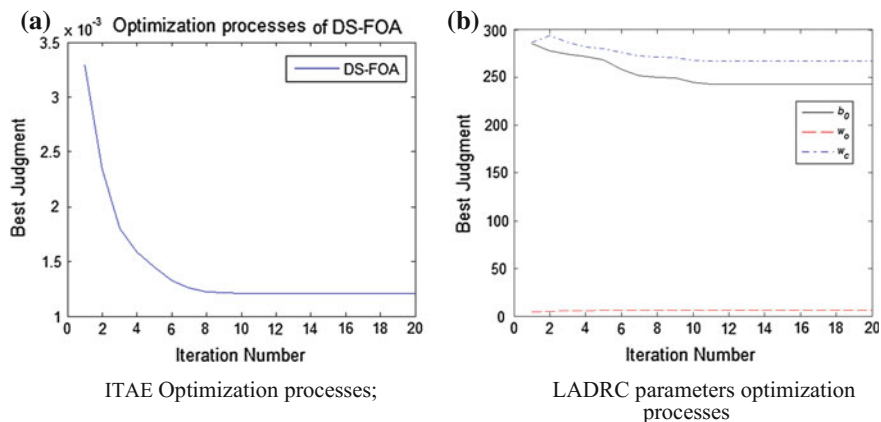


Fig. 3 Optimization processes of DS-FOA

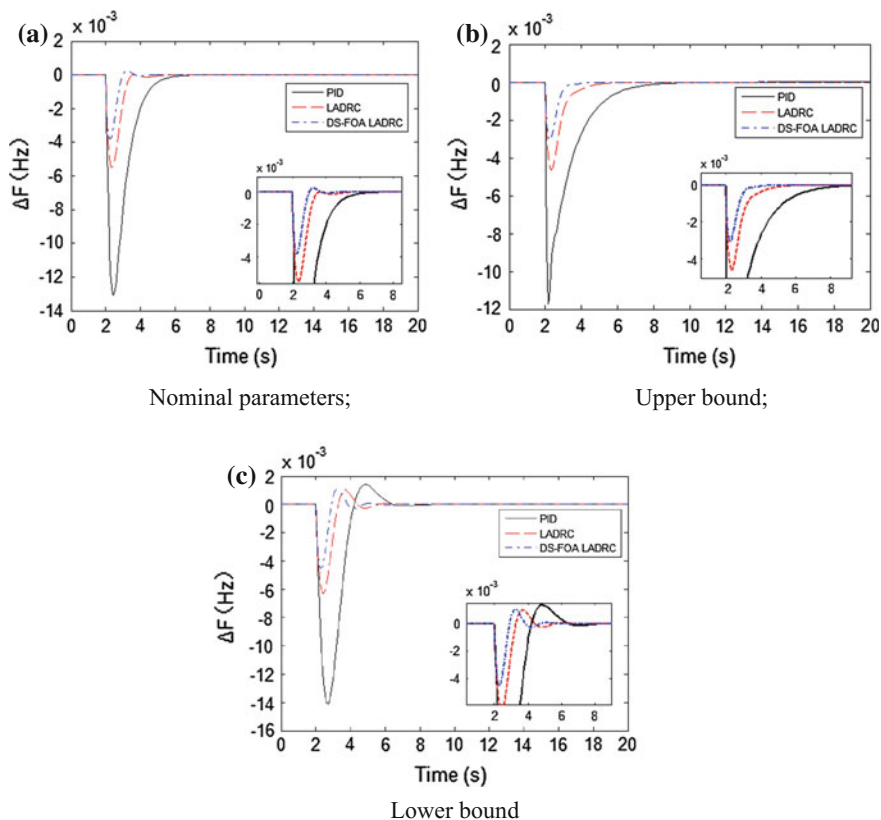


Fig. 4 The responses of power system with a non-reheated turbine and the following three control approaches: PID, LADRC and DS-FOA optimized LADRC approach

Table 1 Result of DS-FOA optimization LADRC parameters

b_0	ω_c	ω_o	ITAE
242.6164	267.1187	6.3466	0.001208

As shown in Fig. 4, the performance of the system with the fourth-order LADRC is much better than that of PID controller. In addition, by using DS-FOA optimize LADRC parameters, the system shows a much better performance.

B. Performances Indices

To further compare the performance of the system with the DS-FOA optimized LADRC approach with that of the PID controller and the normal LADRC approach, the performance indices ITAE are computed and listed in Table 2.

In this table, it is shown that with the DS-FOA optimized LADRC approach in the system, the performance indices are much smaller than the other two control approaches, which explicitly indicates that the performance superiority of the proposed approach.

C. Open Loop Transfer Function Frequency Domain Analysis

For the unit negative feedback control system, the actuator is assumed to be linear and its gain is equal to 1. Its open loop transfer function is $G_{loop}(s) = G_p * G_c$, where G_p is plant transfer function and G_c is controller transfer function. It is easy to know the transfer function of plant G_p and the PID controller G_{cPID} from [11].

$$G_{cPID}(s) = 0.4036 + \frac{0.6356}{s} + 0.1832s \quad (14)$$

In [15], the transfer function of LADRC has been summarized. For this paper, the transfer function of LADRC and DS-FOA LADRC can be expressed as follows:

$$G_{CLADRC}(s) = \frac{2.195 \times 10^7 s^4 + 4.522 \times 10^8 s^3 + 3.493 \times 10^9 s^2 + 1.199 \times 10^{10} s + 1.544 \times 10^{10}}{250s^3 + 2.195 \times 10^7 s^2 + 2.68 \times 10^7 s + 2.693 \times 10^7} \quad (15)$$

$$G_{CDLADRC}(s) = \frac{1.849 \times 10^7 s^4 + 4.602 \times 10^8 s^3 + 4.296 \times 10^9 s^2 + 1.782 \times 10^{10} s + 2.773 \times 10^{10}}{240s^3 + 1.849 \times 10^7 s^2 + 2.371 \times 10^7 s + 2.389 \times 10^7} \quad (16)$$

Table 2 The Performance Indices ITAE

Controller	Optimized LADRC	LADRC	PID
ITAE	0.00121/0.00110/0.00197	0.0069/0.0077/0.0104	0.0302/0.0365/0.0329

Note ITAE performance indices are presented in order as the system with the normal/upper bound/lower bound parameters

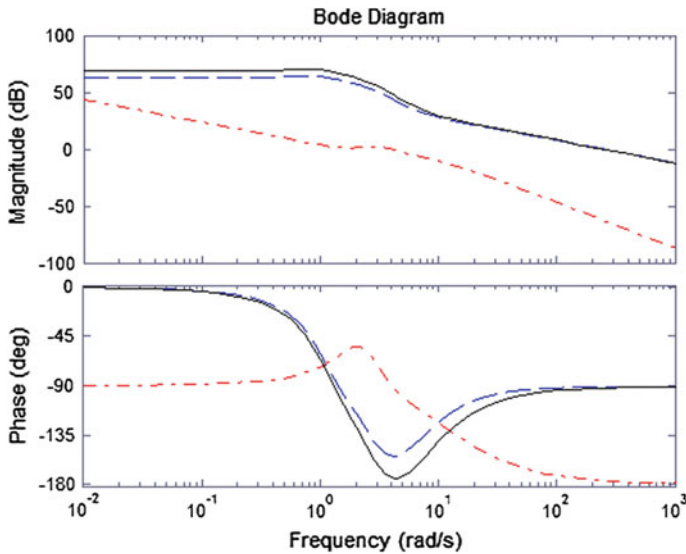


Fig. 5 Frequency domain analysis of PID controller, LADRC and DS-FOA optimized LADRC (solid LADRC; dashed DS-FOA optimized LADRC; dash dotted PID)

Table 3 Open loop transfer function frequency domain analysis

Controller	PM dB (Cut-off frequency rad/sec)
PID	92.3273 (3.8749)
LADRC	89.0296 (249.8372)
DS-FOA LADRC	88.0407 (249.9800)

The Bode plots for the open loop transfer functions of the system with the three controllers are shown in Fig. 5.

As can be seen from Fig. 5 and Table 3, all the three controllers make the system stable. The LADRC increase the cut-off frequency to achieve a better response speed than the traditional PID control approach. By using the DS-FOA optimized LADRC parameters, the system has a higher phase margin in middle frequency so that it has a better dynamic characteristics, which also proves the performance superiority of the proposed approach.

5 Conclusion

In this paper, the DS-FOA optimized LADRC approach is proposed, and its performance superiority is validated by the simulation example. By using DS-FOA tuning the three control parameters of LADRC, b_0 , ω_o and ω_c , the LFC problem in this paper is solved. The performance of LADRC demonstrates the effectiveness

and robustness of the proposed LADRC approach. In addition, by using the DS-FOA, the better parameters of LADRC can be found and the controller achieved better effect and stronger robustness. However, its deficiency is that the performance of the FOA can be improved further, and the optimized parameters of LADRC by DS-FOA for the reheated turbine plant and hydroturbine plant remains a difficult and challenging problem to be further investigated.

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