Lévy Moth-Flame Optimization Algorithm Based Fractional-order Load Frequency Control for Hydro-Thermal Interconnected Power Grid

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Abstract. Load frequency control (LFC) is an important method for frequency regulation in interconnected power grids. It is proposed that an improved moth-flame optimization algorithm based fractional-order PID load frequency control for hydro-thermal interconnection grid. The Lévy flight strategy is introduced into the moth-flame optimization algorithm to optimize the parameters of the fractional-order PID controller to improve the convergence speed and optimization accuracy. In order to verify the effectiveness of the proposed method, a simulation model of LFC system for the three-area hydro-thermal interconnection grid is established. Considering the limitations of the nonlinear factors such as governor dead band (GDB) and generation rate constraint (GRC), the proposed algorithm is used to search for the optimal fractional-order PID controller parameters. The simulation results under step load disturbances show that the proposed method has good robustness and control effect.

1. Introduction

With the continuous development of power systems, research on load frequency control is also increasing. For the LFC system model, from the early single linear model to the nonlinear model considering time delay, saturation and dead band limitation [1]; for the control strategy, from the classic proportional integral control to robust control, sliding mode control and other advanced control strategies [2-4]; for the control methods, from centralized control to distributed control and so on.

At present, the multi-area interconnected power system has developed into a large-scale dynamic system with highly nonlinear, multi-input and multi-output. The traditional load frequency control strategy has been difficult to meet the requirements [5]. The fractional-order control is based on the fractional calculus theory and combines the traditional PID design method. Compared with the traditional control strategy, it has better dynamic performance and robustness. A simple two-area interconnected grid model was established in [6], and the fractional PID controller was used in the LFC and its control performance was verified. In [7], a design scheme based on two-degree-of-freedom
FOPID controller is proposed, and the parameters are optimized by the firefly algorithm. The simulation shows that the scheme is superior in stability time and oscillation reduction.

Since the fractional-order controller has two adjustable parameters compared to the traditional controller, it will be difficult to optimize the tuning of its parameters. The moth-flame optimization (MFO) algorithm was proposed by Seyedali Mirjalili in 2015 [8], which has the advantages of which has the advantages of strong robustness, simple structure and few parameters. Therefore, the algorithm has attracted many scholars to study it. For example, N. Aouchiche applied the MFO algorithm to the maximum power point tracking of the PV array. The simulation results demonstrate the ability of the method to seek GMPPT in the PV array system [9]. In [10], the optimal solution of the MFO algorithm is proposed for the optimal power flow problem of power system. The results of the example show that the MFO algorithm for solving the optimal power flow problem has the advantages of faster convergence speed, higher search accuracy and strong robustness.

In order to further improve the global optimization performance of the MFO algorithm, the Lévy flight strategy is introduced into the standard MFO, and a moth optimization algorithm based on Lévy flight (LMFO) is proposed. Instead of directly calculating the objective function after each update of the position of the moth, the random search mode of the Lévy flight is used to further update the individual position, that is, the search mode combined with the small step size and the occasional large step search, which is applied to the frequency control of three-area hydro-thermal interconnection grid for the first time. The improved moth optimization algorithm is used to coordinate and optimize the fractional-order PID parameters. Simulation results demonstrate the effectiveness of the proposed scheme.

2. Interconnected power system LFC model

In the case of load changes, in addition to maintaining the frequency stability of its own area, it is necessary to maintain the tie line exchange power within the stability margin, so that the control error is zero. Each control area can contain multiple units, wherein the thermal power unit is composed of a governor, a steam turbine and a generator. The hydroelectric unit is composed of a governor, a water turbine and a generator, and respectively constructs a thermal power region and a hydroelectric region load control model, such as Figure 1 and Figure 2. $T_{ni}$ is the time constant of the area $i$ thermal power unit governor, $T_{ni}$ is the time constant of the area $i$ thermal power unit governor, $T_{ni}$ is the time constant of the area $i$ thermal power unit governor, $K_{ri}$ is the reheat coefficient of area $i$, $T_{ri}$ is the reheat time constant of area $i$, $T_{ri}$ is the reheat time constant of area $i$, $T_{ri}$ is the time constant of the area $i$ turbine. $K_{pi}$ is the active frequency conversion coefficient of control area $i$, $T_{pi}$ is the power system time constant of control area $i$, $Bi$ is the frequency deviation coefficient of control area $i$, $Ri$ is the genset adjustment coefficient of control area $i$, $T_{ij}$ is the tie line synchronization factor of control area $i$ and the control area $j$.

![Figure 1. Thermal power unit model](image-url)
In the actual operation of the power grid, it is often limited by many constraints, so it presents a highly nonlinear feature, which greatly increases the difficulty of frequency control of the interconnected power grid. To get closer to the actual LFC system, consider the nonlinear link, the generation rate constraint (GRC) and the governor dead band (GDB). The typical power constraint of the thermal power generating unit generator is generally 0.0017 puMW/s, and the typical value of the power constraint of the hydroelectric generating unit is generally 0.045 puMW/s. The constraint module is shown in Figure 3. By using the description function method to linearize the governor dead band of the thermal power unit governor, the transfer function is as follows:

\[
G_r = \frac{0.8 - 0.24}{\pi} \frac{s}{1 + sT_n}
\]  

Where \( T_n \) is the governor time constant.

Replace the thermal power unit governor in Figure 1 with the transfer function shown in Equation 1, and add the generator power constraint module in Figure 3 to Figure 1 and Figure 2 to obtain a three-area hydro-thermal interconnected power grid load frequency control model considering nonlinear characteristics.

3. Fractional-order controller model

The fractional-order PI\(^\lambda\)D\(^\mu\) controller is extended by the traditional integer-order PID controller based on the fractional calculus. The differential order and the integral order are introduced, so that the adjustable parameters of the controller are increased from 3 parameters of the PID controller to 5 parameters controlled by the fractional-order PI\(^\lambda\)D\(^\mu\), thus providing more control degrees of freedom, greater flexibility and wider adaptation range. The model of the fractional-order PI\(^\lambda\)D\(^\mu\) controller is shown in Figure 4. Its time domain function expression is:

\[
u(t) = K_p e(t) + K_{i_0} D_t^{-\lambda} e(t) + K_D D_t^{\mu} e(t)
\]  

Figure 2. Hydro power unit model

Figure 3. Transfer function model of GRC
Where: $e(t)$ and $u(t)$ are the input and output values of the controller, and $D$ is the fractional calculus operator. The approximate fractional calculus operator is defined by Grunwald-Letnicov (G-L) in fractional calculus, which can be expressed as:

$$a D_t^\alpha f(t) = \lim_{h \to \infty} h^{-\alpha} \sum_{j=0}^{[(t-a)/h]} w_j^\alpha f(t-jh)$$  \hspace{1cm} (3)

Where: $w_j^\alpha = \frac{(-1)^j \Gamma(\alpha + 1)}{j! \Gamma(\alpha - j + 1)}$, it can also be considered as the coefficient of $(1+z)^\alpha$ Taylor expansion at the origin. $[x]$ Means rounding up x, and $h$ is calculating step size.

Discretization of equation (2) can obtain time-domain discrete equations:

$$u_m = K_p e_m + K_I h^\lambda \sum_{j=0}^{m} q_{-\lambda,j} e_{m-j} + K_D h^{-\mu} \sum_{j=0}^{m} q_{u,j} e_{m-j}$$  \hspace{1cm} (4)

According to equation (4), the fractional-order controller can be digitally implemented.

![Fractional-order PID controller model](image)

**Figure 4.** Fractional-order PID controller model

4. Moth-flame optimization algorithm based on Lévy flight

4.1. Basic moth algorithm

The candidate solution to the problem is the moth, and the variable is the position of the moth in space. Moths can move in one, two, and multidimensional spaces by changing their position vectors. Since the MFO algorithm is a population-based algorithm, we use the following matrix to represent the moth collection:

$$M = [m_1, m_2, \ldots, m_n]^T$$  \hspace{1cm} (5)

Where: $n$ is the population size of the moth, and the position of each population is determined by the variable.

Store the fitness value of the moth individual in the matrix $OM$:

$$OM = [OM_1, OM_2, \ldots, OM_n]^T$$  \hspace{1cm} (6)
The flame matrix in the MFO algorithm is a variable matrix of the same dimensions as the moth matrix:

$$F = [f_1, f_2, \ldots, f_n]^T$$  \hspace{1cm} (7)

The corresponding fitness values are stored in the same manner in the matrix OF as follows:

$$OF = [OF_1, OF_2, \ldots, OF_n]^T$$  \hspace{1cm} (8)

The MFO algorithm is inspired by the horizontal navigation mechanism of the moth's night flight. In order to accurately describe the behavior of the moth capturing the flame, the position of the moth update can be expressed by equations.

$$M_i = S(M_i, F_j)$$  \hspace{1cm} (9)

Where: $M_i$ is the position of the i-th moth; $F_j$ is the j-th flame; S is a spiral function.

The logarithmic spiral is the main update mechanism for the position of the moth. The expression is as follows:

$$S(M_i, F_j) = D_i \cdot e^{bt} \cdot \cos(2\pi t) + F_j$$  \hspace{1cm} (10)

Where: $D_i$ is the distance between the i-th moth and the j-th flame; b is the logarithmic spiral shape constant, and the path coefficient $t$ ranges from [-1, 1].

In order to improve the convergence speed and accuracy of the MFO algorithm in the iterative process, an adaptive update mechanism for the number of flames is proposed. The formula is:

$$\text{flame.no} = \text{round} \left( N - l \cdot \frac{N - 1}{T} \right)$$  \hspace{1cm} (11)

Where: $l$ is the current number of iterations; $N$ is the maximum number of flames; $T$ is the maximum number of iterations. At the same time, due to the reduction of the flame, the moth updates its position according to the best flame of the current fitness value in each iteration.

4.2. Lévy flight

The MFO itself also has the disadvantages of being easy to fall into local optimum and the optimization precision is not high, which limits its application range [14]. Therefore, the original algorithm needs to be improved to improve its performance.

Lévy flight is a Markov process proposed by French mathematician Paul Lévy. Its step value is subject to heavy-tailed distribution and has higher search efficiency than traditional Brownian motion. The local small-scale swimming path combined with a wide range of transition paths can ensure that the system does not fall into local optimum [15]. Optimizing the moth optimization algorithm with Lévy flight strategy can expand the search range of the algorithm and increase the diversity of the population, so that the algorithm can easily jump out of the local optimum.
In order to enhance the population diversity of the basic moth optimization algorithm, the Lévy flight strategy is proposed to be introduced into the algorithm. The search path for Lévy flight is calculated as follows:

\[
s = \frac{\mu}{|v|^\beta}
\]  

(12)

Where: \(s\) is the Lévy flight path; \(\mu\) and \(v\) are normal distribution random numbers, obeying the normal distribution shown in equation (13).

\[
\begin{cases}
\mu \sim N(0, \sigma^2) \\
v \sim N(0,1)
\end{cases}
\]  

(13)

\[
\sigma = \left\{ \frac{\Gamma(1 + \beta) \sin (\pi \beta / 2)}{\Gamma[(1 + \beta) / 2] 2^{(\beta-1)/2} \beta} \right\}^{\frac{1}{\beta}}
\]  

(14)

Where: \(\Gamma\) is a gamma function, \(\beta\) is in the range of \((0, 2)\), usually taking \(\beta=1.5\). Levy's search path \(\text{Levy}(\lambda)\) can be obtained by equations (12) ~ (14).

The moth performs a Lévy flight after each position update, and the formula is as follows:

\[
X_{i}^{t+1} = X_{i}^{t} + \mu \text{sign}[\text{rand} - 0.5] \oplus \text{Levy}(\lambda)
\]  

(15)

Where: \(X_{i}^{t}\) is the position vector of the \(i\)-th moth at the iteration number \(t\), \(\mu\) is a random parameter that conforms to a uniform distribution, and rand is a random number between [0, 1]. In formula (15), the combination of sign[\text{rand} – 0.5] and Lévy flight can make the moth's trajectory more random, thus avoiding falling into local optimum and improving the global search ability of the algorithm.

4.3. Algorithm flow

Since the Integral of Time multiplied Absolute Error (ITAE) index has good selectivity for the parameters, the optimal tuning parameters of the controller can be obtained when the ITAE index is the smallest. Its formula is as follows:

\[
J_{\text{ITAE}} = \int_{0}^{T} \left( |\Delta F_1| + |\Delta F_2| + |\Delta F_3| + |\Delta P_{\text{tie}1}| + |\Delta P_{\text{tie}2}| + |\Delta P_{\text{tie}3}| \right) \cdot tdt
\]  

(16)

Where: \(\Delta F_i\) is the system frequency deviation of the \(i\)-th region, \(\Delta P_{\text{tie}i}\) is the change of the tie line power between the regions, and \(T\) is the simulation duration.

The steps for parameter setting of the fractional-order PID in the regional interconnected grid using LMFO are as follows:

1. Set the dimensions of the parameters to be optimized, the moth population search scale, the maximum number of iterations, the logarithmic spiral shape constant, etc.
(2) The position of the moth is randomly generated in the space, and the individual fitness function value of the moth is calculated to check whether the position of the moth exceeds the upper and lower limits.
(3) Find the current best moth position and save it as a flame fitness value matrix.
(4) The number of flames is adaptively updated according to equation (11).
(5) Update the position of the current moth according to the logarithmic spiral function.
(6) Set the Lévy flight steps and flight index, and perform Lévy flight for each moth according to equation (15).
(7) When the algorithm iteration termination condition is satisfied, the optimization result is output, and the program ends, otherwise it returns to step 3.

5. LMFO algorithm verification and simulation analysis
Taking the three-area hydro-thermal interconnected power system as an example, a simulation model is built in Matlab/Simulink, in which area 1 and area 3 are thermal power units and area 2 is a hydroelectric unit. The LMFO algorithm is used to optimize the parameters of the fractional-order PID controller to realize the load frequency control. The initial value of the algorithm is: Moth population size $n=30$; the maximum number of iterations $T=500$; Logarithmic spiral shape constant $b=1.5$; Levy Flight Index $\beta=1.5$.

It is assumed that there is a step load disturbance of $+1\%$ in the area 1, and a step load disturbance of $+2\%$ in region 2 when $t=1s$. The parameters of each area power system are the same as those in [16]. Firstly, in the process of optimization, 30 moths are randomly generated, and the ITAE value of the control performance is calculated for each of the optimized individuals. The convergence optimization curve obtained is shown in Figure 5.Taking area 3 as an example, the dynamic time domain response curve of the system obtained by analyzing and comparing the two algorithms is shown in Figure 6.
The FOPID controller parameters and the ITAE values optimized by the LMFO algorithm are compared with the original MFO algorithm. The results are shown in Table 1. It can be seen that for the same FOPID controller, LMFO gets better controller parameter values, and its ITAE value is 1.4666, which is 35.6% lower than MFO.

| Table 1. Controller parameters and ITAE indicator values |
|----------------------------------------------------------|
| **MFO** | **Area1** | **Area2** | **Area3** | **ITAE** |
| $K_P$ | 1.2491 | 2 | 1.9956 | 2.2764 |
| $K_D$ | 1.7240 | 0.5848 | 1.9828 |
| $K_I$ | 1.2714 | 2 | 0.4069 |
| $\lambda$ | 1.0739 | 0.5305 | 1.3240 |
| $\mu$ | 0.9016 | 1.7625 | 1.2176 |
| **LMFO** | | | | |
| $K_P$ | 1.7465 | 0.8840 | 1.8721 | 1.4666 |
| $K_D$ | 1.9850 | 0.0038 | 1.1099 |
| $K_I$ | 1.0064 | 2 | 0.3297 |
| $\lambda$ | 1.1435 | 0.5093 | 1.3813 |
| $\mu$ | 1.1794 | 0.1000 | 1.2553 |
It can be seen from Figure 6 that the two algorithm-optimized fractional-order controllers can control the variation of the load frequency between ±0.1 Hz, and after optimization using the LMFO algorithm, the area 3 load frequency change tends to be stable after about 6 s. After optimization using the MFO algorithm, it tends to be stable after about 11 s, the overshoot of the load frequency change after optimization by the LMFO algorithm is reduced by approximately 23% compared to the MFO. It can be seen that the LMFO algorithm optimized fractional-order controller has lower overshoot and faster response time than MFO, and the effect of load frequency control is obviously improved. The load frequency deviation curves of the area 1 and 2 can also reach the same conclusion. At the same time, the LMFO-optimized fractional-order controller tie line power variation is significantly reduced in response time and overshoot.

The LMFO algorithm improves the global search ability and has higher optimization precision due to the dynamic adjustment of the step size. From the perspective of system dynamic performance indicators, LMFO-tuned FOPID can respond to external disturbances more quickly and with less overshoot, and has optimal time domain response performance, which can effectively deal with nonlinear problems.

6. Conclusion
Aiming at the problem of area interconnected grid LFC, this paper proposes an optimal design scheme for LMFO optimized fractional-order PID controller. By combining the Lévy flight strategy with the moth-flame optimization algorithm, the step size can be dynamically adjusted. The proposed method can avoid the shortcomings of original moth-flame algorithm, such as low precision and easy to fall into local optimization, and can also improve the convergence speed.

When performing area interconnected grid LFC simulation in MATLAB, the FOPID parameter optimization design based on LMFO can search for the optimal \( K_p, K_d, K_i, \lambda \), and \( \mu \) values. In the case of highly nonlinear severe conditions, good ITAE indicators and dynamic time domain response performance can still be obtained.

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