Load Frequency Control of AC Microgrid Interconnected Thermal Power System

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Abstract: In this paper, a microgrid (MG) power generation system is interconnected with a single area reheat thermal power system for load frequency control study. A new meta-heuristic optimization algorithm i.e. Moth-Flame Optimization (MFO) algorithm is applied to evaluate optimal gains of the fuzzy based proportional, integral and derivative (PID) controllers. The system dynamic performance is studied by comparing the results with MFO optimized classical PI/PID controllers. Also the system performance is investigated with fuzzy PID controller optimized by recently developed grey wolf optimizer (GWO) algorithm, which has proven its superiority over other previously developed algorithm in many interconnected power systems.

Keywords: microgrid, load frequency control, moth-flame optimization algorithm, fuzzy logic control.

1. INTRODUCTION

For the development of economy and advancement in expectation for everyday comforts of society energy assumes an imperative part. In the recent decade alternative energy sources such as solar, wind, fuel cell and diesel generators etc. are providing cost effective, environmental friendly and better quality of power sources for remote communities and facilities. Thus several small scale generation resources are combined to form microgrid (MG). MGs are low voltage grids that interconnect micro-sources and storage devices via feeders with small loads. The variations of solar/wind energy generation do not coordinate the time conveyance of the demand. Therefore, power generation systems dictate the association of battery storage facility to smooth the time–distribution mismatch between the load and renewable energy sources. The MGs have the alternative to work in an independent mode. However, MGs can be operated in grid connected mode to the medium voltage system. Thus, for reliability and good power quality it can draw additional amount of power when needed and supply when generation exceeds the demand. The system frequency deviates when the generation mismatches the load demand. The principal aspect of load frequency control (LFC) in power system is to maintain system frequency during normal operating condition as well as during the variation in load demands [1]. Literature survey shows that significant works have been done for frequency control of autonomous and interconnected power systems separately [2-14]. A new concept of interconnection of two microgrids is proposed in [6-7]. Frequency regulation of a single area reheat thermal power system with integration of AC MG using iterative
proportional-integral-derivative H∞ control is proposed in [15]. In the present work, same hybrid power system model as proposed in [15] has been considered for load frequency control study. A new bio-inspired optimization algorithm i.e. Moth-Flame Optimization (MFO) algorithm is applied to evaluate optimal gains of the fuzzy based proportional, integral and derivative (PID) controllers. The dynamic performance of the system is studied by comparing the results with MFO optimized classical PI/PID controllers. Also the system performance is investigated with fuzzy PID controller optimized by recently developed grey wolf optimizer (GWO) algorithm, which has proven its superiority over other previously developed algorithm in many interconnected power systems [13-14].

Followed by introduction the paper is organized as follows: modeling of the system under investigation is presented in section II. Section III presents description of controller structure and objective function. In section IV, overview of MFO algorithm is given. Results and discussions are presented in section V. Finally, conclusion is given in section VI.

2. Modeling of the System under Investigation

An AC MG power generation system is interconnected with a reheat thermal power system [15]. The microgrid power generation system includes wind turbine generators (WTG), aqua electrolyzer (AE), fuel cell (FC) and diesel engine generators (DEG) and battery energy storage system (BESS). The detailed model is depicted in Fig. 1.

2.1 Wind turbine generators (WTG)

The generation of power from wind turbine generators relies on the wind speed, which is intermittent in nature. The wind power can be expressed as follows:

\[ P_{WT} = \frac{1}{2} \rho A_R C_p V^3 \]

Where, \( \rho \) is the air density (Kg/m³); \( A_R \) is the swept area of blade (m²); \( C_p \) is the power coefficient, a function of tip speed ratio \( \lambda \) and blade pitch angle \( \beta \); and \( \rho \) is wind speed. The transfer function of the WTG is given by a simple first-order lag, neglecting all non-linearities, as given below,

\[ G_{WTG}(s) = \frac{\Delta P_{WTG}}{\Delta P_{WT}} = \frac{K_{wtg}}{1 + sT_{wtg}} \]  

Where, \( \Delta P_{WTG} \) is change in wind turbine power generation, \( \Delta P_{WT} \) is change in wind power available, \( K_{wtg} \) is gain and \( T_{wtg} \) is the time constant.

2.2 AE

The AE uses part of the power generated in the system for the production of hydrogen, which is used in FC for the generation of power.

\[ G_{AE}(s) = \frac{\Delta P_{AE}}{u_2} = \frac{K_{ae}}{1 + sT_{ae}} \]  

Where, \( \Delta P_{AE} \) is change in AE power corresponding to equivalent of hydrogen production, \( u_2 \) is the control signal output from the controller and input to the AE, \( K_{ae} \) is gain and \( T_{ae} \) is the time constant.
2.3 FC Power generation

The FCs are electrochemical devices that convert chemical energy of fuel into electrical energy. The linearized transfer function model can be written as below,

\[ G_{FC}(s) = \frac{\Delta P_{FC}}{u_2} = \frac{K_{fc}}{1 + sT_{fc}} \quad (4) \]

Where, \( \Delta P_{FC} \) is change in FC power generation, \( u_2 \) is the control signal output from the controller and input to the FC, \( K_{fc} \) is gain and \( T_{fc} \) is the time constant.

2.4 Diesel engine power generator (DEG)

The diesel generator back-up system is operated at times when the output from wind/solar systems fails to satisfy the load and when the battery storage is depleted. A simple transfer function model of wind power generation system is given as,

\[ G_{DEG}(s) = \frac{\Delta P_{DEG}}{u_2} = \frac{K_{deg}}{1 + sT_{deg}} \quad (5) \]

Where, \( \Delta P_{DEG} \) is change in diesel power generation, \( u_2 \) is the control signal output from the controller and input to the DEG, \( K_{deg} \) is gain and \( T_{deg} \) is the time constant.

2.5 BESS

The BESS facilitate storage of energy and supply when at the time of need. It also provides additional damping to power system swings to improve dynamic performance of the system. The transfer function of BESS can be written as follows,

\[ G_{BESS}(s) = \frac{\Delta P_{BESS}}{u_2} = \frac{K_{bess}}{1 + sT_{bess}} \quad (6) \]

Where, \( \Delta P_{BESS} \) is incremental change in BESS power generation, \( u_2 \) is the control signal output from the controller and input to the DEG, \( K_{bess} \) is gain and \( T_{bess} \) is the time constant.

2.6 Power deviation and system frequency variation

The power balance equation is given below [15],

\[ \Delta P_e = \Delta P_{MG} + \Delta P_{TH} - \Delta P_L \quad (7) \]

Where, \( \Delta P_e \) is the error in supplied power, \( \Delta P_{MG} \) is the output power of MG, \( \Delta P_{TH} \) is the output power of the reheat thermal system and \( \Delta P_L \) is the change in load demand.

\[ \Delta P_{MG} = \Delta P_{WTG} + \Delta P_{FC} - \Delta P_{AE} + \Delta P_{DEG} \pm \Delta P_{BESS} \quad (8) \]

Where, \( \Delta P_{WTG} \), \( \Delta P_{FC} \), \( \Delta P_{AE} \), \( \Delta P_{DEG} \) and \( \Delta P_{BESS} \) are the power generated by the WTG, FC, AE, DEG and BESS respectively.

The deviation in the frequency is expressed as follows [15],

\[ \Delta f = \frac{\Delta P_e}{K_{sys}} \quad (9) \]

Where, \( K_{sys} \) is the system frequency characteristic constant of the system. The transfer function for the system frequency variation to per unit deviation in power is stated as,
\[ G_{\text{sys}} = \frac{\Delta f}{\Delta P_g} = \frac{1}{K_{\text{sys}} \left(1 + sT_{\text{sys}}\right)} = \frac{K_p}{1 + sT_p} \] (10)

3 CONTROLLER STRUCTURE AND OBJECTIVE FUNCTION

The structure of the Fuzzy PID controller is adopted from reference [10]. An identical controller is employed in each system. The error inputs to the controllers are the system frequency deviation. Fuzzy PID controller is a combination of fuzzy proportion-integral (PI) and fuzzy proportional-derivative (PD) controllers. The input scaling factors are \( K_1 \) and \( K_2 \) and the output scaling factors are \( K_3 \) and \( K_4 \). Triangular membership functions are used with five fuzzy linguistic variables such as NB (negative big), NS (negative small), Z (zero), PS (positive small) and PB (positive big) for both the inputs and the output. Mamdani fuzzy inference engine is selected for the present work. The two-dimensional rule bases for error, error derivative are inputs and \( u \) as output to fuzzy model. The range of membership function is taken as -10 to 10.

Integral of time multiplied absolute error (ITAE) is used as objective function to find the optimum value of the controller parameters. The objective function \( J \) for controller parameters optimization of the interconnected power system is depicted as below.

\[ J = ITAE = \int_{0}^{t_{\text{sim}}} |\Delta f| \cdot t \cdot dt \] (11)

In the above equation, \( \Delta f \) represents system frequency deviation and \( t_{\text{sim}} \) represents the range of simulation time.

Fig. 1 MATLAB/Simulink model of AC microgrid power sources integrated with a reheat thermal power system
4 Overview of Moth-flame Optimization (MFO) Algorithm

MFO algorithm is first time introduced by Mirjalili in 2015 [16]. The concept behind it is the navigation method of moths in nature. In general, we observe that moths fly spirally around the light, because the light source is very near. Moths fly in night by keeping up an altered edge as for the moon, for going in a straight line for long distances. The moths and flames are both potential solutions. The moths are real pursuit operators that navigate around the search space, whereas flames are the best position for moths that gets so far. In this way, every moth seeks around a flag (flame) and updates it for finding a superior solution in successive iterations.

The MFO algorithm has three fundamental parts that gauges the arrangement and might be expressed as follows:

\[ MFO = (I, P, T) \] (12)

The \( I \) generates a random population of moths and corresponding fitness value. It may be expressed as follows:

\[ I : \phi \rightarrow \{ M, OM \} \] (13)

The \( P \) function is the function that decides the movement of the moths around the search space. This function eventually, returns to its updated form of the matrix of \( M \) after receiving it.

\[ P : M \rightarrow M \] (14)

The \( T \) function returns true if the termination criterion is satisfied and otherwise false.

\[ T : M \rightarrow \{ true, false \} \] (15)

Then, the function \( I \) has to compute the objective function values after generating initial solutions.

There are two other arrays that define the upper and the lower bounds of the variables (\( ub \) and \( lb \)). The matrixes may be stated as follows.

\[ ub = [ub_1, ub_2, ub_3, ..., ub_n, ub_n] \] (16)

\[ lb = [lb_1, lb_2, lb_3, ..., lb_n, lb_n] \] (17)

Where \( ub_i \) and \( lb_i \) represents the upper and the lower bound of the \( i^{th} \) variable.

The position of each moths are updated with respect to a flame using the equation stated below,

\[ M = S(M_i, F_j) \rightarrow M \] (18)

Where \( M_i \) indicate the \( i^{th} \) moth, \( F_j \) indicates the \( j^{th} \) flame, and \( S \) is the spiral function.

A logarithmic spiral function is presented in (19). It defines the next position of a moth with respect to a flame.

\[ S(M_i, F_j) = D_j e^{ib} \cos(2\pi t) + F_j \] (19)

Where \( D_j \) shows the distance of the \( i^{th} \) moth for the \( j^{th} \) flame, \( b \) is a constant for representing the shape of the logarithmic spiral, and \( t \) is a random number in \([-1, 1]\). The variable \( D_j \) may be calculated as follows,

\[ D_j = |F_j - M_i| \] (20)

The best solutions acquired so far are considered as the flames and stored in \( F \) matrix. The number of flames is diminished adaptively over the course of iterations as follows,
\[ \text{Flame number} = \text{round} \left( N - l \times \frac{N - 1}{T} \right) \] (21)

Where \( l \) is the current number of iteration, \( N \) is the maximum number of flames and \( T \) indicates the maximum number of iterations. In the initial steps of iterations there is \( N \) number of flames. The moths update their positions just as for the best flame in the last steps of iterations.

**RESULTS AND DISCUSSION**

The system under investigation is developed in MATLAB/Simulink environment and MFO program is written (in .mfile). MFO algorithm has been executed for 20 times to obtain the optimum controller parameters subjected to minimization of objective function. The population size=20 and maximum number of iteration=20 has been considered for MFO algorithm. The developed model is simulated considering 0.01 p.u. step load perturbation (SLP) at time=0 second. In the system the average change in wind power available is taken as \( \Delta P_{WT} = 0.5 \text{ p.u.} \)

The optimum controller parameters values are provided in Table 1. The performances of various controllers are tested in Fig. 2(a); and in Fig. 2(b) proposed MFO algorithm dominates to GWO algorithm with identical fuzzy PID controller implemented in considered system.

**TABLE I OPTIMUM VALUE OF CONTROLLER PARAMETERS FOR THE TEST SYSTEM**

| System     | Techniques and Controller | MFO tuned PI | MFO tuned PID | MFO tuned Fuzzy PID | GWO tuned Fuzzy PID |
|------------|---------------------------|--------------|---------------|---------------------|---------------------|
| Thermal    |                           |              |               |                     |                     |
|            | MFO tuned PI              |              |               |                     |                     |
|            |                           | \( K_P = 1.0876 \) | \( K_I = 1.9999 \) | \( K_D = 0.2280 \) | \( K_1 = 1.8127 \) |
|            | MFO tuned PID             |              |               |                     |                     |
|            |                           | \( K_P = 0.7259 \) | \( K_I = 1.9998 \) | \( K_D = 1.4612 \) | \( K_2 = 1.4612 \) |
|            | MFO tuned Fuzzy PID       |              |               |                     |                     |
|            |                           | \( K_1 = 1.4781 \) and | \( K_2 = 1.4781 \) and | \( K_3 = 1.6734 \) | \( K_4 = 1.6734 \) |
|            | GWO tuned Fuzzy PID       |              |               |                     |                     |
|            |                           | \( K_1 = 2.3270 \) | \( K_2 = 0.43624 \) | \( K_3 = 0.64693 \) | \( K_4 = 1.8817 \) |
| MG system  |                           |              |               |                     |                     |
|            | MFO tuned PID             |              |               |                     |                     |
|            |                           | \( K_P = 0.5699 \) | \( K_I = 0.7662 \) | \( K_D = 0.9245 \) | \( K_1 = 0.038515 \) |
|            | MFO tuned Fuzzy PID       |              |               |                     |                     |
|            |                           | \( K_1 = 0.0679 \) | \( K_2 = 1.3804 \) | \( K_3 = 0.8665 \) and | \( K_4 = 0.57324 \) |
|            | GWO tuned Fuzzy PID       |              |               |                     |                     |
|            |                           | \( K_1 = 1.2276 \) and | \( K_2 = 0.0001 \) and | \( K_3 = 1.2276 \) and | \( K_4 = 2.0157 \) |

**6 CONCLUSION**

This paper proposed MFO optimized Fuzzy PID controller for load frequency control of a single area reheat thermal power system with integration of AC MG. The simulation results are
compared with MFO optimized classical PI and PID controllers. The results confirm the superior dynamic performance of the system with the proposed controller. The performance of the system is also compared with GWO optimized Fuzzy PID controller for the similar system. The results obtained from simulation inferred the effectiveness of the proposed controller.

APPENDIX

Thermal power system parameter [15]:

\[ K_g = 1.0 \, , \, T_g = 0.08 \, s \, , \, T_i = 0.3 \, s \, , \, K_r = 0.5 \, , \, T_r = 10 \, s \, , \, K_p = 120 \, Hz / \, p.u.MW \, , \, T_p = 20 \, s \, , \, R = 2.4 \, Hz / \, p.u.MW \]

MG power generation system parameters [15]:

\[ K_{w_g} = 1.0 \, , \, T_{w_g} = 1.5 \, s \, , \, K_{ae} = 1.0 \, , \, T_{ae} = 0.08 \, s \, , \, K_{fc} = 0.01 \, , \, T_{fc} = 4 \, s \, , \, K_{deg} = 0.003 \, , \, T_{deg} = 2 \, s \, , \, K_{bess} = -0.003 \, , \, T_{bess} = 0.1 \, s \, , \, \Delta P_{br} = 0.5 \, p.u. \]

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