Whale Optimization Algorithm Based PID Controller Design of Two Area Load Frequency Control with Nonlinearities

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Abstract: The power system is composed of many interconnected areas which have may or may not have multiple sources in it. But for the successful operation of any one of these interconnected systems requires working in synchronization with the rest of the system and also to maintain the tie line power flow as per the scheduled values. Failing to maintain any of these mentioned criteria will give rise to the disturbances in the system and hinders the smooth operation that was being carried. Hence, it requires regular monitoring of these parameters which in general is known as Automatic Generation control (AGC). Here, typically the load frequency control (LFC) is being emphasized on being encountering a disturbance.

The following works presents two interconnected system having thermal power plant in it. The primary aim is to control both the areas low frequencies that is the LFC. This is the controller implemented is PID. Further to optimize its parameter and better the performance of a novel optimization technique is used which is whale optimization algorithm (WOA). The simulation of the system in MATLAB/Simulink generation rate constrain (GRC) is also considered. Specifically, two values of GRC have been considered which are 0.025 and 0.05. The simulation results obtained were compared with that of the system with hybrid Firefly Algorithm-Pattern Search technique (hFA-PS), Bacteria Foraging Optimization Algorithm (BFOA), Genetic Algorithm (GA) and Ziegler Nichols (ZN). The system is tested under different conditions for deviations in frequency and tie line power flow. It is also examined for sensitivity to verify if it’s robustness and effectiveness by comparing it with the system using hybrid firefly patterns search (hFA-PS) based PID.

Keywords: AGC, WOA Algorithm, LFC, PID Controller, Non-linearity.

1. Introduction

In general, interconnected system means linking different resources of technology or manpower. It improves the total efficiency and reliability of the operation. Likewise, the electrical power system is also interconnected to achieve the same benefits. Some of the main advantages getting from such an arrangement are [1],

- Reliability of power supply increases as ensuring continuous flow of power.
- The system involved in the interconnection will share the total load. This may bar the situation of overloading any one system.
- It possesses the infinite bus thus ensuring constant frequency and voltage.
- There will be huge decrease in reserve capacity.
- Overall all operation will be much economical.

As the name suggests an interconnected system consists of two or many power networks linked to each other. Every area is linked via tie line. For the successful operation, the power of tie-line between these areas and their frequency should be at constant level. This task is accomplished via AGC which is installed in every linked area. It manages the generation of the area by tracking continuously the load demand that has to be fulfilled at a time. It accordingly generates the difference of demanded power from power currently generating by the area which in turn will be responded as acceleration or declaration of a particular unit. This difference is termed as Area Control Error (ACE). It will ultimately keep the power of tie line power along with frequency at the desired level [2]. Hence, ACE is the controlled output of AGC. It should be zero so as to have zero error in frequency along with in tie-line power.

AGC is provided to maintain the frequency of areas at the same level whenever there is change. This type of AGC is called as Load Frequency Control (LFC). This problem has been addressed several times in the past and still being addressed with the better solution each time. From traditional ways of controlling via only simple controllers only like Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID) to methods where these controllers are further modified to give better results [5]. The modification has been incorporated using many optimization techniques such as GA, Neural Network (NN), fuzzy logic GA (GA) [6], Particle swarm optimization (PSO) [10] or BFOA etc. Also some recently used developed optimization techniques too like hFA-PS or Teaching learning Based Optimization Technique(TLBO) [11].
A two area non-reheat system has been considered into which LFC is implemented for frequency and tie line power flow maintenance. For it a PID controller has been implemented. Considering the above mentioned techniques to get the best possible solution for the problem a new technique based on hunting strategy of whales is taken into account. This technique is known as WOA.

A. Objective function

Design of a controller is based upon well-defined objective function meeting system requirements and constraints. In this paper, Integral of Time multiply Absolute Error (ITAE) of the frequency deviation of both areas & tie line power are considered as objective functions and are given by[8], functions and are given by [3],

\[ \text{ITAE} = \int_0^{\text{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}|) \cdot t \, dt \]  
(1)

\[ \Delta F_1 \& \Delta F_2 = \text{system frequency deviations}, \Delta P_{tie} = \text{tie line power} \]

The aim is to minimize the J (performance index) which is subjected to,

\[ K_p^{\min} \leq K_p \leq K_p^{\max} \]
\[ K_i^{\min} \leq K_i \leq K_i^{\max} \]
\[ K_d^{\min} \leq K_d \leq K_d^{\max} \]
(2)

2. System model

A. Proposed Two Area Model

Fig. 1. shows a controlled two area interconnected power system of a non-reheat thermal plant. Each area is of 2000MW on which the nominal load is of 1000MW.

They are connected with tie line and different parameter represent by area1 and area 2 so area1 where B1, B2=frequency bias parameters, f1=system frequency (Hz), R1=regulation constant (Hz/unit), Tg1= speed governor time constant (s), T1=turbine time constant (s) and Tp1=power system time constant (s), ACE1=area control error, \( \Delta P_{G1} \) =load demand change, \( \Delta P_{G2} \) =change in governor valve position, \( K_{P1} \) =power system gain, and \( \Delta P_{tie} \) =change in tie line power and where area2 where f2=system frequency (Hz), R2=regulation constant (Hz/unit), Tg2= speed governor time constant (s), T2=turbine time constant (s) and Tp2=power system time constant (s), ACE2=area control error, \( \Delta P_{D1} \) = the load demand change, \( \Delta P_{G2} \) is the change in governor valve position, \( K_{P2} \) is the power system gain, \( T_{s1} \) =synchronizing coefficient(p.u.) [4].

In addition, nonlinear model of a non-reheat turbine has taken into account the generating rate constraint (GRC), where PID controller represent by \( K_p \) is proportional gain, \( K_i \) is the integral gain, and \( K_d \) is differential gain, respectively. The PID controllers in both areas were considered to be identical [4].

3. Whale Optimization Algorithm (WOA)

WOA is the nature inspired technique which falls under the group of meta-heuristic search techniques. It is well known that Whales are the largest living mammal on this entire earth which can have size up to 30 meters and can weigh 180 tons. The species of it are as follows,

- Killer
- Sei
- Humpback
- Right
- Finback
- Blue

These are a mostly predator that never sleeps, in fact half of their brain is always conscious. The reason behind it is that they have to breathe from surface of oceans. They are very intelligent and emotional being [13].

Like human being whales too have spindle cells which are the reason behind human’s emotional, social and judgmental nature. These cells set us aside from rest of the species. But in whales these are almost double in number as compared to us, hence it makes them smart. So whales can think, learn and communicate even become emotional like us but has lower smartness.

They also can develop their own dialect as observed. Whales can either live in group or can live alone but mostly found in group. One kid of it species i.e. Killer whale through their life lives in family. Another member of Whale family which almost as big as school bus is Humpback [14]. Its scientific name is Megaptera novaengliae. Their common preys are krill and small fish herds.

Humpback whale has a very special hunting strategy known as bubble-net feeding method. It is their common social behavior to hunt their prey close to surface. They create bubbles in circles or bubbles in the shape of 9. This is their foraging behavior. The examination an observation regarding this nature was done through surface before the year 2011 [15].

A. Mathematical Modeling

WOA model can be explained in three stages namely,
• Encircling prey
• Spiral bubble net feeding maneuver
• Search for prey

These are one by one explained below.
1) Encircling prey

The prey location is not known at first but it could be finding out and then can be encircled. Here, the present location which can also said to be solution best at a given time is taken as the target prey first for the reason as explained in above line (optimal position at first is not known).

Once the best search agent position is identified all the other search agents will update their position with respect to it. It is shown as follows [15],

\[ \bar{D} = |\overline{C}X^*(t) - \overline{x}(t)| \]  
\[ \overline{x}(t + 1) = \overline{x}^*(t) - \bar{\bar{A}} \bar{\bar{D}} \]  

*t= current iteration

\( \bar{\bar{A}} \& \bar{\bar{C}} = \) coefficient vectors

\( X^* = \) best solution position vector

\( \overline{X} = \) position vector

If after iteration solution obtained is better than the previous one, it must be update. This should be repeated for every solution.

The values \( \bar{\bar{A}} \& \bar{\bar{C}} \) are obtained by,

\[ \bar{\bar{A}} = 2\bar{a} \bar{\bar{r}} - \bar{\bar{a}} \]  
\[ \bar{\bar{C}} = 2, \bar{\bar{r}} \]  

2) Bubble-net attacking method

This stage is the phase of exploitation. There two approaches in it, which are discussed in the following sections.

a) Shrinking Encircling Mechanism

It is done via decreasing \( \bar{a}, \bar{\bar{a}} \) also decreases fluctuation range of \( \bar{\bar{A}} \). \( \bar{\bar{A}} \) values fall between the interval [-a,a]. If the interval in which it falls is [-1,1], then search agent can occupy position between current best agent position and agent’s original position at any point. The figure below depicts the position which is possible from \((X,Y)\) towards \((X^*,Y^*)\). It can be done through by \(0 \leq A \leq 1\) in 2D space.

b) Spiral Updating Position

Calculation of distance whale at \((X,Y)\) from prey at \((X^*,Y^*)\). Humpback whales helical movement is mimicked to create the spiral equation between their respective location,

\[ \overline{x}(t + 1) = \overline{D}^* e^{bl} \cos(2\pi l) + \overline{x}^*(t) \]  

Here, \( \overline{D}^* = |\overline{X}^*(t) - \overline{x}(t)| = \) distance of \(i^{th}\) whale from whale (best solution so far).

\( b = \) constant that defines logarithmic spiral shape

\( l = \) random number in [-1,1]

B. Search for Prey

It is the phase of exploration. In it humpback whales search for the prey randomly w.r.t. each other position. Here, also the search is carried out depending on the \( \overline{X} \) variation. It was used with random number which is either greater than 1 or less than -1. It forces agents to go move away from reference whale. Search agent positions are updated based upon randomly chosen search agent rather than the best one. Hence, global search is possible due to this and |\(\bar{A}\)|>1.

\[ \bar{\bar{D}} = |\overline{C}X^\text{\text{rand}} - \overline{x}| \]  
\[ \overline{x}(t + 1) = X^\text{\text{rand}} - \overline{A} \bar{\bar{D}} \]  

\( \overline{x}^\text{\text{rand}} = \) random position vector (a random whale from current population).

C. PID Controller

Fig. 2. show structure of PID controller. The output in the given controller depends upon the error signal e(t) generated by comparing desired set point with the processed variable. The error is then corrected based on integral, proportional and derivative control that’s why it has been named PID controller [10].

It can be expressed as,

\[ u(t) = K_p e(t) + K_i \int e(t') dt' + K_d \frac{de(t)}{dt} \]  

\( K_p, K_i, K_d \) are all non-negative coefficients for P, I and D respectively.

4. Result and discussions

In this paper a novel WOA is apply for the system having two area interconnected together having non-reheat thermal power system in each. The system also has included influence of GRC too. Both the areas have been provided with PID controller optimized by WOA and using the ITAE as its objective function. The result of this technique has been compared and analyzed with the recent heuristic optimization techniques as hFA-PS, BFOA, GA and ZN based PID controller for same interconnected power system. The simulation result is analyzed with various condition and sensitivity analysis (nominal loading, steam turbine time constant (T_s), steam governor time constant (T_g) and synchronizing coefficients (T_{12}). The various graph plotted with respect to time as change in deviation in area1. The system performance is evaluated by MATLAB/SIMULINK environment. The WOA optimized based PID controller shows superior response than other recently publish algorithm and finally proposed system shows robust and satisfactory result at all disturbance conditions. In this work, the proposed approach tested with two GRC values are taken as 0.025 & 0.05.
A. MATLAB/SIMULINK Implementation of Two Area Load Frequency Control System

Fig. 3. shows a MATLAB/SIMULINK model of two area (thermal-thermal system with no reheat turbine) system. The system is divided in two areas. The PID controller parameters tuned by WOA algorithm. The system evaluated with various deviation and parameters variation as $T_g$, $T_t$, and $T_{12}$ in sec. Table 1 shows different parameter of controller.

![Fig. 3. MATLAB/SIMULINK model of two area load frequency control](image)

<table>
<thead>
<tr>
<th>Controller Gain</th>
<th>PID Controller Parameters Based on hFA-PS</th>
<th>PID Controller Parameters Based on WOA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$GRC = \pm 0.05$</td>
<td>$GRC = \pm 0.025$</td>
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<tr>
<td>$K_P$</td>
<td>0.3834</td>
<td>0.1898</td>
</tr>
<tr>
<td>$K_I$</td>
<td>0.61207</td>
<td>0.3164</td>
</tr>
<tr>
<td>$K_D$</td>
<td>0.4021</td>
<td>0.4528</td>
</tr>
</tbody>
</table>

![Fig. 4. Best cost v/s iteration graph of WOA algorithm](image)

1) Case-1: 5% SLP in Change in Area-1 with $GRC = \pm 0.05$ & $GRC = \pm 0.025$

Fig. 5 to 7 shows that system is better dynamic responses with proposed PID controller tuned WOA algorithm than algorithm based PID. The system shows better response in term of settling times in frequency, tie line power deviation and area control error when system is applied with WOA based PID controller.

![Fig. 5. Area-1 frequency deviation (SLP=5% in Area1, GRC=±0.05)](image)

![Fig. 6. Area-2 Frequency Deviation (SLP=5% in Area-1, GRC=±0.025)](image)

2) Case-2: Sensitivity analysis with $GRC = \pm 0.05$ & $GRC = \pm 0.025$ at nominal loading & $T_t$

Fig. 8 to 10 shows the system performance as sensitivity analysis is check by changing operating conditions and system parameters. These are loading conditions at nominal ratings, $T_t$. The variation in them occurs staring from their values at nominal ratings up to +/-50%. The sensitivity analysis is presented in Table 2 from which it is verified that the obtained values for settling time and ITAE is satisfactory. While comparing it with hFA-PS based PID it has shown better results.

![Fig. 7. $P_t$ Deviation (SLP=5% in Area-1, GRC=±0.025)](image)

![Fig. 9. Area-2 Frequency deviation (Nominal Loading decreases by 50% at GRC=±0.025)](image)
3) Case-3: Sensitivity analysis with $GRC = \pm 0.05$ & $GRC = \pm 0.025$ at $T_g$ & $T_{12}$

Fig. 11 to 13 shows the dynamic response analysis of two areas thermal system with 50% increase/decrease in $T_g$ & $T_{12}$ with different GRC. In this condition system shows superior response then other algorithm. As compared to the other mentioned and tabulated techniques for the system shown the proposed approach with WOA has less time for settling.

<table>
<thead>
<tr>
<th>Change in system Parameters</th>
<th>% Change</th>
<th>Proposed WOA Technique</th>
<th>hFA-PS Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ST(Sec.)</td>
<td>$\Delta F_1$</td>
<td>$\Delta F_2$</td>
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<td>Nominal Loading Condition</td>
<td>0</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5.7</td>
<td>5.2</td>
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<tr>
<td></td>
<td>-50</td>
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<tr>
<td>$T_g$</td>
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<td>-50</td>
<td>5.7</td>
<td>5.9</td>
</tr>
<tr>
<td>$T_{12}$</td>
<td>50</td>
<td>5.2</td>
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</tr>
<tr>
<td></td>
<td>-50</td>
<td>5.1</td>
<td>5.2</td>
</tr>
</tbody>
</table>

5. Conclusion

LFC of two areas thermal-thermal power system proposed in this paper. The system parameters are optimized using WOA with PID controller. The system performance compare with different algorithm as hFA-PS algorithm and some recently publish algorithm as ZN, GA, BFOA as same controller and interconnected power system. The proposed system performance is analysis with various condition as change in area-1 and different parameter variation. The various graphs obtain as frequency and tie line deviation and ACE. The system shown with the approach proposed here is compared with the above mentioned techniques used for the same system as that of the test system so as to verify its dominance over these techniques. Therefore, all the test conditions the approach shown here has verified its credibility and effectiveness in addressing the objectives.

References


