Application of particle swarm optimisation in load frequency control of interconnected thermal-hydro power systems

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Abstract: This paper presents a solution to the LFC problem based on PSO and genetic algorithm (GA). The controller is constructed for a two-area interconnected thermal-hydro power system. The dynamic model of the power system and the controller design based on the model are elaborated in this paper. Exhaustive simulations are carried out using MATLAB/Simulink platform in order to verify the performance of PID controller in LFC problem under various dynamic conditions. Simulation results proved that PSO tuned controller is attractive to the LFC problem in its stability and robustness.

Keywords: load frequency control; LFC; PID controller; particle swarm optimisation; PSO; genetic algorithm; GA; integral squared error; ISE; integral time absolute error; ITAE.

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1 Introduction

Generation in large interconnected power system comprises of thermal, hydro, nuclear, and gas generation. However, natural choice for AGC falls on either thermal or hydro units. An interconnected power system can be considered as being divided into control areas which are connected by tie lines. In each area, all generator sets are assumed to form a coherent group. The power system is subjected to local variations of random magnitudes and durations. This causes deviation in system frequency and tie line power flow, which give rise to the load frequency problem which is a sub problem of automatic generation control. For satisfactory and stable operation of power system, deviation in frequency and tie line power should be minimised as quickly as possible. A control signal made up of tie-line flow deviation added to frequency deviation weighted by bias factor would accomplish the desired objective. This control signal is known as area control error (ACE) (Kundur, 2000). In an interconnected system, there are many control areas, each of which perform its load frequency control (LFC) with the objectives maintain the magnitude of ACE ‘sufficiently close to 0’ using various criteria. In order to maintain the frequency sufficiently close to its synchronous value over the entire interconnection, the coordination of the control area’s actions is required. As each control area shares in the responsibility for LFC, effective means are needed for monitoring and assessing each area’s performance of its appropriate share in LFC. A number of control strategies exist to achieve better performance. These methods are based on modern control theory (Ogata, 2000), neural network (Shayehi and Shayanfar, 2004), fuzzy system theory (Monga et al., 2010) and genetic algorithm (GA) (Sinha et al., 2008). Due to non-linearity of power system, system parameters are linearised around an operating point. The response of the unit depends upon the turbine dynamics such as time constants and nonlinearities. Linearised models of hydro and thermal units are used for load frequency study. Lot of research work has been reported with linearised models of hydro and thermal units in single area and multi area power systems (Malik et al., 1988; Sinha et al., 2008; Shayehi and Shayanfar, 2004; Monga et al., 2010; Ramakrishna and Bhatti, 2006; Padhy and Tyagi, 2008; Soundararajan, 2010). Most of the research in the area of LFC of single area and multi area hydro and thermal systems has been carried out with low head hydro systems. But the head at various hydro power plants may not be same. Ramakrishna and Bhatti (2006) proposed LFC of hydro power plants at different heads using GA. Particle swarm optimisation (PSO) has been implemented for various power system control applications to obtain better system response (Gaing, 2004; Shivakumar and Lakshmipathi, 2010; Shabib et al., 2010). However, little work has been reported on application of PSO for load frequency in interconnected thermal-hydro power system under various heads. There is a considerable variation in time constants of the hydro turbine and speed governor models at various heads and hence in the transient response.
In this paper the LFC of high, medium and low head hydro power system interconnected with thermal system has been studied.

Conventional proportional-integral-derivative controller has been used for the LFC of interconnected power system. The gains of PID controller have been optimised using PSO technique. The rest of the paper is organised as follows: Section 2 deals with problem formulation which includes system representation and formation of objective function. In Section 3, parameters of PID controller were tuned using PSO based algorithm, simulation analysis is made in Section 4, results and discussion is done in Section 5 and finally conclusion is discussed in Section 6.

2 Problem formulation

2.1 System representation

The control system that is used in this paper is composed of a two area interconnected power system; area 1 comprises of single stage reheat thermal system and area 2 comprises of hydro system. The transfer function block diagram of uncontrolled two area hydro-thermal system is shown in Figure 1. The linearised models of reheat thermal and hydro systems are considered for study.

Figure 1 Transfer function block diagram of an uncontrolled two area hydro-thermal power system
In the model, $\Delta P_{c1}$ and $\Delta P_{c2}$ are the control inputs from the controllers. $\Delta P_{d1}$ and $\Delta P_{d2}$ represents step load changes of %1 of the nominal loading in area 1 and area 2 respectively. $\Delta F_1$ and $\Delta F_2$ are frequency deviations of the control areas and $\Delta P_{tie}$ is the changing of tie-line power. The main objective of this paper is to study the LFC of interconnected hydro-thermal system with low, medium and high head hydro systems. In the two area system considered for the study, the PID controllers with following structure are used.

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s$$ (1)

where $K_p$ is proportional gain, $K_i$ is integral gain and $K_d$ is derivative gain respectively.

The value of $T_W$ i.e. water starting time varies between 1s to 4s for low head to high head. So the parameters of all the governor and hydro turbine changes for low, medium and high head hydro power plants.

2.2 Defining objective function

In a multi-area system the ACE for the $i^{th}$ area is defined as:

$$ACE_i = \Delta P_{tiei} + B_i \Delta F_i$$ (2)

In this paper the effect of two different objective functions is studied for optimisation of parameters: integral squared error (ISE) and integral time absolute error (ITAE) defined as follows:

$$ISE = \int_0^\infty (ACE) dt$$ (3)

$$ITAE = \int_0^\infty t |(ACE)| dt$$ (4)

Based on this performance index ISE and ITAE optimisation problem can be sated as:

Minimise (ISE) or (ITAE)

Subjected to:

$K_p^{min} \leq K_p \leq K_p^{max}$,

$K_i^{min} \leq K_i \leq K_i^{max}$,

$K_d^{min} \leq K_d \leq K_d^{max}$

$K_p$, $K_i$, and $K_d$ are PID controller parameters.

3 Optimal PID tuning using PSO

It is possible to obtain high quality solution within shorter calculation time and stable convergence characteristics with PSO algorithm. PSO uses particles which represents potential solutions of the problem. Each particles fly in search space at a certain velocity which can be adjusted in light of proceeding flight experiences. The projected position of
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The $i$th particle of the swarm $x_i$ and the velocity of this particle $v_i$ at $(t + 1)^{th}$ iteration are defined as the following two equations in this study.

$$V_{iD}^{t+1} = w V_{iD}^t + C_1 r_1 (P_{iD}^t - x_{iD}^t) + C_2 r_2 (g_{iD}^t - x_{iD}^t)$$

$$x_{iD}^{t+1} = x_{iD}^t + v_{iD}^{t+1}$$

where, $i = 1, ..., n$ and $n$ is the size of the swarm, $D$ is dimension of the problem space, $C_1$ and $C_2$ are positive constants, $r_1$ and $r_2$ are random numbers which are uniformly distributed in $[0, 1]$, $w$ is inertia weight constant, $t$ determines the iteration number, $p_i$ represents the best previous position (the position giving the best fitness value) of the $i$th particle, and $g_i$ represents the best particle among all the particles in the swarm. The algorithm of PSO can be depicted as follows (Soundaraj, 2010):

1. Initialise a population of particles with random positions and velocities on $D$-dimensions in the problem space.
2. Evaluate desired optimisation fitness function in $D$ variables for each particle.
3. Compare particle’s fitness evaluation with its best previous position. If current value is better, then set best previous position equal to the current value, and $P_i$ equals to the current location $x_i$ in $D$-dimensional space.
4. Identify the particle in the neighbourhood with the best fitness so far, and assign its index to the variable $g$.
5. Change velocity and position of the particle according to equations (5) and (6).
6. Loop to step 2 until a criterion is met or end of iterations.

At the end of the iterations, the best position of the swarm will be the solution of the problem. It is not possible to get an optimum result of the problem always, but the obtained solution will be an optimal one. In the PSO routine parameters $K_{p,j}$, $K_{i,j}$ and $K_{d,j}$ were taken as control variables. These parameters were obtained simultaneously by solving the constrained optimisation problem given in Section 2.1 using PSO algorithm.

4 Simulation studies

The data for the system considered for this study has been given in Appendix 1. The PID controller gains have been optimised using PSO.

For optimisation of PID gains, the following values of PSO operators were used:

No. of iterations = 30
No. of particles = 15
$C_1 = 0.2$
$C_2 = 0.5$
$w_{max} = 0.9$
$w_{min} = 0.4$
$D = 6$

$r_1, r_2 = \text{random number between } [0 1]$

The initial values for PID gains are selected by trial and error method. The simulations are carried out with the gains obtained from PSO with the fitness function discussed in Section 2.2 for following cases.

**Case 1** Step load increase in thermal area (area 1)

**Table 1** Optimal PID gains for Case 1 with ISE

<table>
<thead>
<tr>
<th>Head of hydro system</th>
<th>Optimal PID gains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{p1}$</td>
</tr>
<tr>
<td>Low</td>
<td>35.4472</td>
</tr>
<tr>
<td>Medium</td>
<td>66.9862</td>
</tr>
<tr>
<td>High</td>
<td>66.2584</td>
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</table>

**Table 2** Optimal PID gains for Case 1 with ITAE

<table>
<thead>
<tr>
<th>Head of hydro system</th>
<th>Optimal PID gains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{p1}$</td>
</tr>
<tr>
<td>Low</td>
<td>16.2726</td>
</tr>
<tr>
<td>Medium</td>
<td>16.3548</td>
</tr>
<tr>
<td>High</td>
<td>16.4096</td>
</tr>
</tbody>
</table>
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Case 2  Step load increase in hydro area (area 2)

Table 3  Optimal PID gains for Case 2 with ISE

<table>
<thead>
<tr>
<th>Head of hydro system</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{p1}$</td>
<td>$K_{i1}$</td>
<td>$K_{d1}$</td>
<td>$K_{p2}$</td>
<td>$K_{i2}$</td>
<td>$K_{d2}$</td>
</tr>
<tr>
<td>Low</td>
<td>0.8224</td>
<td>0.8651</td>
<td>0.6958</td>
<td>0.4232</td>
<td>0.7339</td>
<td>0.3031</td>
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<tr>
<td>Medium</td>
<td>0.7130</td>
<td>0.6991</td>
<td>0.5740</td>
<td>0.6559</td>
<td>0.9455</td>
<td>0.8631</td>
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<tr>
<td>High</td>
<td>0.8641</td>
<td>0.8436</td>
<td>0.8523</td>
<td>0.8652</td>
<td>0.7648</td>
<td>0.6798</td>
</tr>
</tbody>
</table>

Table 4  Optimal PID gains for Case 2 with ITAE

<table>
<thead>
<tr>
<th>Head of hydro system</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{p1}$</td>
<td>$K_{i1}$</td>
<td>$K_{d1}$</td>
<td>$K_{p2}$</td>
<td>$K_{i2}$</td>
<td>$K_{d2}$</td>
</tr>
<tr>
<td>Low</td>
<td>0.4516</td>
<td>0.4990</td>
<td>0.6261</td>
<td>0.3208</td>
<td>0.8676</td>
<td>0.3812</td>
</tr>
<tr>
<td>Medium</td>
<td>0.6776</td>
<td>0.7532</td>
<td>0.2733</td>
<td>0.6195</td>
<td>0.8245</td>
<td>0.4574</td>
</tr>
<tr>
<td>High</td>
<td>1.7626</td>
<td>1.9710</td>
<td>1.4516</td>
<td>1.9164</td>
<td>1.7438</td>
<td>1.9073</td>
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</tbody>
</table>

A digital simulation of the system was performed using MATLAB/Simulink platform over a time period of 100 seconds, for each individual (particle) of the current population. The simulation is performed by considering 1% load perturbation in one area at a time. The value of objective function is calculated and then next population is produced using optimisation algorithm. The procedure is repeated till maximum number of generations (iterations) is reached or algorithm converges to an optimum value. The optimisation process is repeated four times for each of combination namely, PSO using either ISE or ITAE as objective function. From these two sets, results with more number of occurrences are shown in Tables 1, 2, 3 and 4.

For comparative study, PID controller gains have been optimised using GA. For optimisation of PID gains, the following values of GA operators were used:

No. of iterations = 30
Population size = 600
Cross over fraction= 0.2
Mutation fraction = 0.6
Reproduction probability = 0.2

The simulations are carried out with the gains obtained from GA with the fitness function discussed in Section 2.2 for step load increase of 1% of nominal load in thermal area. Table 5 gives optimal PID gains using ISE and ITAE with GA.

Table 5  Optimal PID gains using GA

<table>
<thead>
<tr>
<th>Gains</th>
<th>$K_{p1}$</th>
<th>$K_{i1}$</th>
<th>$K_{d1}$</th>
<th>$K_{p2}$</th>
<th>$K_{i2}$</th>
<th>$K_{d2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISE</td>
<td>4.9860</td>
<td>4.9870</td>
<td>4.9610</td>
<td>0.0250</td>
<td>0.0060</td>
<td>0.0740</td>
</tr>
<tr>
<td>ITAE</td>
<td>4.9200</td>
<td>4.9910</td>
<td>0.9580</td>
<td>0.0090</td>
<td>0.0000</td>
<td>0.0010</td>
</tr>
</tbody>
</table>
Once the optimised parameters are obtained with both algorithms as above, the same were used in the model of Figure 2. Simulation runs were carried out with these values in order to compare the responses obtained by PSO and GA with the objective functions (ISE and ITAE). The performance of LFC is determined in terms of variation in frequency of all the areas and also the variation in agreed tie line flow; the responses below compare the same for both hydro and thermal area.

5 Results and discussion

Figures 3 to 5 gives deviation in area 1 frequency, area 2 frequency and tie line power flow for step load increase in area 1 using PSO algorithm with both ISE and ITAE as objective functions. Figures 9 to 11 give the relative performance with GA for the same case of load perturbation with both the objective functions.

Figures 6 to 8 gives deviation in area 1 frequency, area 2 frequency and tie line power flow for step load increase in area 2 using PSO algorithm with both ISE and ITAE as objective functions.

As obvious from these results, the performance of LFC is better when the objective function used is ITAE as compared with ISE for most of the cases. Although simulation was performed for 100 seconds, graphs are shown for first 50 seconds for clarity. As it can be observed from these results, when ISE is used as objective function oscillations don’t die out soon and remain for longer time. In case of ITAE, however, we get improved damping, though the settling time is almost of the same order.

Figures 12 to 14 compare GA and PSO algorithm. Comparison between GA and PSO is now done by using ISE alone as objective function. From these results it can be seen that the results obtained from both GA and PSO are compatible. It can also be observed that PSO algorithm gives better frequency response.

Figure 15 compares the system response in terms of settling time, undershoot and overshoot. It is observed from these results that PSO algorithm gives better dynamic system response then GA in most of the cases.

Also, settling time increases as head of hydro power system increases.

6 Conclusions

In this paper an attempt has been made to study the response of high, medium and low head hydro power systems interconnected with thermal system. PSO algorithm has been used to optimise the gains of PID controller. GA is also used for comparative study. It has been observed that the low head system response is faster than the high head system. A comparative study has been made between ISE and ITAE performance indices. It is found that the responses obtained by the two algorithms are comparable. Yet, PSO gives a better frequency response than that obtained with GA. It has been observed that the gains obtained with ITAE gave better dynamic response.
Figure 3  Deviation in area 1 frequency for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 3  Deviation in area 1 frequency for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)

Figure 4  Deviation in area 2 frequency for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 4  Deviation in area 2 frequency for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)
Figure 5  Deviation in tie line power for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 5  Deviation in tie line power for step load increase in area 1 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)

Figure 6  Deviation in area 1 frequency for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 6  Deviation in area 1 frequency for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)
Figure 7  Deviation in area 2 frequency for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 7  Deviation in area 2 frequency for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)

Figure 8  Deviation in tie line power for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (see online version for colours)
Figure 8  Deviation in tie line power for step load increase in area 2 (a) low head (b) medium head (c) high head with PSO (continued) (see online version for colours)
**Figure 9** Deviation in area 1 frequency for step load increase in area 1 for low head with GA (see online version for colours)

**Figure 10** Deviation in area 2 frequency for step load increase in area 1 for low head with GA (see online version for colours)
**Figure 11** Deviation in tie line power for step load increase in area 1 for low head with GA (see online version for colours)

**Figure 12** Frequency change in thermal area for step load increase in area 1 (using ISE) (see online version for colours)
Figure 13  Frequency change in hydro area for step load increase in area 1 (using ISE) (see online version for colours)

Figure 14  Changes in tie line power flow for step load increase in area 1 (using ISE) (see online version for colours)
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Figure 15  Comparison between GA and PSO using ISE in terms of (a) settling time (b) overshoot (c) undershoot (see online version for colours)

References

Appendix 1

System data:

Steam turbine

\[ T_p = 0.08; \quad T_i = 0.3s; \quad T_d = 10s; \quad K_r = 0.5; \]

Hydro turbine

<table>
<thead>
<tr>
<th>Head</th>
<th>( T_w ) (Sec)</th>
<th>( T_p ) (Sec)</th>
<th>( T_{ HI} ) (Sec)</th>
<th>( T_{ GH} ) (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1.0</td>
<td>5</td>
<td>28.75</td>
<td>0.2</td>
</tr>
<tr>
<td>Medium</td>
<td>2.2</td>
<td>9.68</td>
<td>112.87</td>
<td>0.3</td>
</tr>
<tr>
<td>High</td>
<td>4.0</td>
<td>14</td>
<td>259</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\[ R_1 = R_2 = 2.4 \text{ Hz/puMW} \]

Power system

\[ K_{p1} = K_{p2} = 120 \text{ Hz/puMW} \]

\[ T_{p1} = T_{p2} = 20s \]

\[ B_1 = B_2 = 0.25 \text{ puMW/Hz} \]

\[ T_{12} = 0.545 \]
### Appendix 2

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δf</td>
<td>Frequency deviation</td>
</tr>
<tr>
<td>i</td>
<td>Subscript referring to area (i = 1, 2...)</td>
</tr>
<tr>
<td>ΔP_{tie(i,j)}</td>
<td>Change in tie line power</td>
</tr>
<tr>
<td>ΔP_{Li}</td>
<td>Load change of i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>R&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Governor speed regulation parameter for i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>T&lt;sub&gt;gi&lt;/sub&gt;</td>
<td>Speed governor time constant for i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>T&lt;sub&gt;ti&lt;/sub&gt;</td>
<td>Speed turbine time constant for i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>T&lt;sub&gt;pi&lt;/sub&gt;</td>
<td>Power system time constant for i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>K&lt;sub&gt;pi&lt;/sub&gt;</td>
<td>Power system gain for i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>ACE&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Area control error of i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>ΔP_{ci}</td>
<td>Control input to i&lt;sup&gt;th&lt;/sup&gt; area</td>
</tr>
<tr>
<td>B&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Frequency bias for i&lt;sup&gt;th&lt;/sup&gt; area</td>
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</table>