Bat inspired algorithm based optimal design of model predictive load frequency control

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ABSTRACT

Bat inspired algorithm (BIA) has recently been explored to develop a novel algorithm for distributed optimization and control. In this paper, BIA-based design of model predictive controllers (MPCs) is proposed for load frequency control (LFC) to enhance the damping of oscillations in power systems. The proposed model predictive load frequency controllers are termed as MPLFCs. Two-area hydro-thermal system, equipped with MPLFCs, is considered to accomplish this study. The suggested power system model considers generation rate constraint (GRC) and governor dead band (GDB). Time delays imposed to the power system by governor-turbine, thermodynamic process, and communication channels are accounted for as well. BIA is utilized to search for optimal controller parameters by minimizing a candidate time-domain based objective function. The performance of the proposed controller has been compared to those of the conventional PI controller based on integral square error (ISE) technique and the PI controller optimized by genetic algorithms (GA), in order to demonstrate the superior efficiency of the BIA-based MPLFCs. Simulation results emphasis on the better performance of the proposed MPLFCs compared to conventional and GA-based PI controllers over a wide range of operating conditions and system parameters uncertainties.

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Introduction

In large scale power systems, load frequency control (LFC) represents a very crucial issue during generation-load mismatches. Automatic generation control (AGC) system is responsible for maintaining the scheduled system frequency and the tie-line power during normal and abnormal operating conditions [1–3]. The function of an AGC system is usually termed as LFC [2]. In an interconnected power system, LFC is accomplished via two different control loops namely primary and supplementary speed control.

Over the past six decades, several approaches have been applied for LFC designs. Among various types of LFCs, proportional–integral (PI) controllers are commonly used thanks to its structure simplicity and its better dynamic response. On the contrary, performance of PI controllers is degraded significantly when the system complexity increases [4]. The preliminary results on optimal control designs of LFC were firstly presented in [5,6]. The challenge of optimal control, to achieve good performance, is the complex non-linear mathematical equations in large-scale systems. A robust dynamic output feedback designs of $H_\infty$ and $H_2/H_\infty$ based LFCs via linear matrix inequalities (LMIs) have been addressed in [7]. However, such LMI-based design does not account for system nonlinearities and results in a controller with the same plant order, which in turn makes the design very complex especially for large scale power systems. Actually, different conventional control strategies are being used for LFCs. Methodologies for conventional design of PI and proportional–integral–derivative (PID) controllers are limited by slow, lack of efficiency and poor handling of system nonlinearities. Artificial Intelligence (AI) techniques like fuzzy logic control (FLC), artificial neural networks (ANNs), genetic algorithms (GAs), particle swarm optimization (PSO), ant colony optimization (ACO) and artificial bee colony (ABC) have been applied for LFC to overcome the limitations of conventional methods [8–20]. Genetic algorithms (GAs) have been extensively considered for the design of LFC. The parameters of optimal PID and fractional order PID controllers have been optimized via GAs for an interconnected two-area power system [8,9]. In [10], the parameters of PID sliding-mode based LFC of multi area power systems are optimized by GAs considering nonlinearities. Tuning of decentralized controllers for a realistic system comprising generation rate constraint (GRC),

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dead band, and time delays, is addressed in [11]. The application of PSO for optimizing an integral controller and a PI controller, is reported in [12]. The authors of [13] tuned the PI controllers via PSO using a new cost function and compared their results with [12]. The design of a fuzzy logic PI controller based LFCs via multiple tabu search (MTS) algorithm, is presented in [14]. In [15], a robust PID design based on the imperialist competitive algorithm (ICA) has been considered for LFC application. Bacterial foraging optimization algorithm (BFOA) has been suggested by Ali et al. for optimizing PI and PID-based LFCs for a two-area power system with and without GRC [16,17]. Maiden application of BFOA to optimize integral controller gains, governor speed droop and the frequency bias parameters has been investigated for a three-area unequal thermal systems [18]. Optimizing the gains of PID controllers in a nonlinear hydro-thermal system via ACO has been addressed in [19]. In [20], Elsisi et al. considered the application of ABC optimization for optimal tuning of PID controllers in a two-area power system.

Over the last few decades, the interest in model predictive control (MPC) has progressed significantly. Progressive interest in MPC results from its fast response and stability against nonlinearities, constraints and parameters uncertainties [21]. These powerful features of MPC will enhance the performance of proposed MPLFCs. The authors of [22–25], presented some primary results on MPC applications in LFC. In [22], MPC has been applied in a multi-area power system for economic dispatch. In [23], a new state contractive constraint-based predictive control scheme was used for LFC of a two-area interconnected power system. This MPC algorithm consists of a basic finite horizon and an additional state contractive constraint. In [24], feasible cooperation-based MPC method was used in distributed LFC instead of centralized MPC while parameter uncertainties and GRC were not considered. In [25], Mohamed et al. presented the decentralized MPC-based LFC of multi-area interconnected power system where the controller of each area was designed separately. However, the design did not account for the GRC that was only considered while model simulation. Remarkably, such design may lead to a degraded system performance once the interactions between different areas become significant.

This paper proposes the application of BIA for optimal tuning of MPC-based LFCs in two area interconnected power system to damp out low-frequency oscillations. The MPC control design is formulated as an optimization problem where BIA is devoted to search for optimal controller parameters by minimizing a candidate time-domain based objective function. Realistic constraints imposed by GRC, GDB and time delays, are considered in the suggested design algorithm. The performance of the proposed BIA-based MPC is evaluated by comparison with conventional and GA-based PI controllers. Simulations results on a two-area test system are presented to confirm the superiority of the proposed method compared with other design methods. Furthermore, robustness of the proposed BIA-based MPLFCs is tested against system parameters uncertainties.

**BIA optimization**

**Bat inspired algorithm**

This search algorithm has been developed based on the echolocation behavior of bats in locating their victims. The prime foundations of BIA optimization were firstly introduced by Yang [26]. These bats emit a series of ultrasound pulses and listen for the echoes that bounce back from the surrounding objects. The bandwidth of released ultrasound waves varies depending on the species and increases using harmonics. These waves are reflected with time delays and different sound levels which enable each bat to catch a specific prey. Optimization via BIA has been considered for optimal tuning of decentralized power system stabilizers (PSSs) in a multimachine power system [27]. Recently, BIA has been utilized to search for optimal parameter setting of dual mode PI controllers [28]. A summary of the basic steps, involved in BIA optimization, is given below.

Step 1. All bats utilize echolocation to sense distance and classify between prey and barrier.

Step 2. Each bat flies with a velocity \( v_i \) at position \( x_i \), having fixed frequency \( f_{\text{max}} \) varying wavelength \( \lambda \), and loudness \( L_0 \) to seek a prey. The bat tunes the frequency of its emitted pulse in the range \( f_{\text{min}}, f_{\text{max}} \) and adjusts the rate of pulse emission \( r \) in the range of \([0,1]\) according to target closeness.

Step 3. Frequency, loudness and pulse emission rate of each bat are varied.

Step 4. Their loudness changes from a large value \( L_0 \) to a minimum constant value \( L_{\text{min}} \).

The position \( x_i \) and velocity \( v_i \) of each bat are updated during the optimization process where the positions \( x_i^t \) and velocities \( v_i^t \) at a time step \( t \), are computed as follows:

\[
 f_i = f_{\text{min}} + (f_{\text{max}} - f_{\text{min}}) \lambda, \quad \lambda \in [0,1] \tag{1}
\]
where $\xi$ is a random vector derived from a uniform distribution function. The current global best location $x^*$ is obtained after comparing all locations among all bats. Since the velocity is given $v_i = \lambda f_{x_i}$, a variance in either $f_i$ or $x_i$ results in a velocity change. To initialize the algorithm, every bat is randomly assigned a frequency $f_i \in [f_{\text{min}}, f_{\text{max}}]$. For the local search, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk.

$$x_{\text{new}} = x_{\text{old}} + t \xi, \quad t \in [-1, 1]$$

where $\xi$ is a random number and $t \xi$ is the mean loudness of all bats at this time step. Once a bat gets its prey, its loudness decreases, however the rate of its pulse emission increases and then loudness can be selected as any value of convenience. Zero loudness indicates that a bat has just found a prey and temporarily stop emitting any sound. This is governed by the following equations:

$$L_i^{t+1} = \beta L_i^t, \quad 0 < \beta < 1, \quad v_i^{t+1} = v_i^0(1 - e^{-\gamma}), \quad \gamma > 0$$

As time approaches infinity, zero loudness is achieved, and $v_i^t = v_i^0$. The flowchart of the BIA is shown in Fig. 1 while the corresponding pseudo code is given in the Appendix.

**Candidate objective function**

As suggested previously, the proposed design has to cope with the system nonlinearities resulting from the inclusion of GRC and GDB. Further, incorporating time delays results in a quasi-polynomial rather than linear characteristic polynomial for the closed loop system. Consequently, eigenvalue-based objective functions as that described in [27] are not suitable, and a time domain-based objective function becomes a good candidate. Although the specifications of a time-domain response are various, maximum overshooting ($M_p$) and the settling time ($T_s$) are of greatest interest while designing convenient controllers. Generally, it is required to minimize both peak response and settling time as possible so as to enhance the stability margins of a power system. Accordingly, the following performance index is proposed to carry out the design.

$$J = (1 - e^{-\mu})M_p + e^{-\mu}T_s, \quad 0 < \mu < 1$$

Such objective function can satisfy both design requirements using an appropriate value for the weighting factor ($\mu$). If this factor is set as $\mu > 0.7$, the overshooting decreases significantly and settling time increases remarkably. The situation is reversed, if it is set as $\mu < 0.7$. Hence, a good compromise between $M_p$ and $T_s$ is achieved at the limiting value, i.e. $\mu = 0.7$.

**Model predictive control**

Model predictive control (MPC) has been evolved as an effective control strategy to stabilize nonlinear dynamical systems having uncertainties and time delays, mainly in process control [29,30]. A general scheme of an MPC comprises two basic units, namely prediction unit and controller unit as depicted in Fig. 2a. Prediction unit forecasts future behavior of the system based on its current output, disturbance and control signal over a finite prediction horizon. Control unit utilizes the predicted output in minimizing the objective function subject to system constraints. Various formulations of the objective function may be considered while carrying out the design as those described in [21,29]. In an MPC, the measured disturbance is compensated using feed-forward control. Unlike feedback controller, feed-forward control can reject most of the measured disturbance before affect the system. Comprising both feed-forward and feedback controls represents the most powerful feature of the MPC, because the first can reject most of the measured disturbance, while the second rejects the remainder. Unmeasured disturbances are dealt with similarly. For further readings on MPC, Refs. [29,30] and the references therein are recommended. The suggested MPC controllers will receive the area control error $ACE_i$, load perturbation $\Delta P_i$, and reference value of $ACE_i$ as inputs, to generate the control signal output. Reference values of $ACE_i$ are all set to zero. An MPLFC scheme is suggested as shown in Fig. 2b. It should be emphasized that each local controller will manipulate only local signals, i.e. data exchange between different areas is not necessary.

The proposed design is carried out in Matlab Simulink using MPC toolbox. The design is initiated by deriving the linear time invariant (LTI) model of the system to be controlled. The LTI model considered in the MPC unit of certain area is computed after removing the MPC unit of the other area and vice versa. The disturbance model, which is an LTI model, explores the disturbance changes when the system is subjected to unmeasured disturbance. These LTI models are all formed as discrete state-space models. If a

$$v_i^t = v_i^{t-1} + (x_i^t - x^*) f_i$$

$$x_i^t = x_i^{t-1} + v_i^t$$

\[ (1) \]
sampling period ($T_s$) and a number of injected control signals ($N$) are considered, then the MPC controller is operated at a rate of $1/NT_s$. The number of control signals are often set to $N = 1$. Selecting an appropriate sampling interval is vital because it determines the length of each prediction step. Such value is basically selected to achieve good tracking performance. Moreover, the performance of an MPC controller is affected deterministically by the selection of prediction horizon ($P$) and control horizon ($M$). Finally, two weighting factors $Q$ and $R$ have to be carefully imposed on the system input and output respectively. Finally, BAT algorithm is applied to get the optimistic values of $T_s$, $P$, $M$, $Q$, and $R$. 

![Diagram of Model Predictive Controller](image1)

**Fig. 2.** Model predictive controller: (a) general scheme, (b) proposed MPC-based LFC unit.

![Diagram of Two-Area Interconnected Power System](image2)

**Fig. 3.** Two-area interconnected power system.

![Diagram of Boiler Dynamics](image3)

**Fig. 4.** Boiler dynamics.
Two area hydro-thermal power system

A model of controlled nonlinear hydro-thermal power system is shown in Fig. 3. Remarkably, the suggested Simulink-based model can clearly account for governor dead bands (GDBs), generation rate constraints (GRCs) and the transport delays $e^{-Tds}$. In the thermal area, the boiler dynamics, as shown in Fig. 4, are considered as well. Dead bands are imposed in the model using backlash nonlinearities where 0.05% and 0.02% are considered for the thermal system and hydro system respectively. As only one reheat stage is considered, the GRC of the thermal area is set to 0.0017 MW/s, while that of the hydro is set to 0.045 MW/s for increasing generation and set to 0.06 MW/s for decreasing generation. The parameters of the considered system are given in the Appendix.

Simulation results

In this section, BAT search algorithm is devoted to getting the optimistic parameters of the proposed MPLFCs. The resulting controllers are tested under various disturbance scenarios subject to system nonlinearities and time delays. Systematically, nonlinearities are considered unaltered while various values of time delays are studied. Load perturbations in one or both areas may be considered to initiate system disturbance. Comparing the performance of the BIA-based MPLFCs to that of conventional and GA-based PI controllers is carried out to confirm the effectiveness of the first. The parameters of the conventional PI controllers designed for the same system are given in [31–32]. Both BIA and GAs are considered to look for the optimal controllers parameters when the system undergoes 10% simultaneous step increment in both areas while 2 s transport delays are considered. The optimal parameters of conventional PI, GA-based PI and BIA-based MPLFCs are listed in Table 1 where the corresponding objective functions are computed. These parameters are considered while testing different controllers under different disturbance scenarios. These scenarios are sufficiently characterized by the magnitude of simultaneous step load perturbations (SSLPs) and the amount of transport time delays. Obviously, BIA-based MPC designed for the thermal system operates at a rate of $0.232 \text{s}^{-1}$ which is greater than that of the hydro system given by $0.117 \text{s}^{-1}$.

Scenario I: The system undergoes 0.01 p.u. SSLPs and it is subjected to 2 s transport time delays.

The frequency changes in both areas and the change in tie-line power, subject to disturbance Scenario I, are shown in Fig. 5. All controllers undershoot likewise due to the inclusion of GRCs as depicted in Fig. 5a and b. Remarkably, conventional PI controller results in greater overshooting, poor settling time and undesirable oscillations. Moreover, the proposed MPLFCs outperforms GA-based PI controller because it has less settling time and smaller overshooting.

Scenario II: The system undergoes 0.015 p.u. SSLP and it is subjected to 2 s transport delays.

<table>
<thead>
<tr>
<th>Controller parameters and the objective function ($J$)</th>
<th>Conventional PI</th>
<th>GA-based PI</th>
<th>BIA-based MPLFCs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area #1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{p1} = 0.3$, $K_{i1} = 0.12$</td>
<td>$K_{p1} = 0.9795$, $K_{i1} = 0.0399$</td>
<td>$T_{s1} = 4.3123$, $P_1 = 10$, $M_1 = 5.8288$, $Q_1 = 0.6752$, $R_1 = 4.2568$</td>
<td></td>
</tr>
<tr>
<td><strong>Area #2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{p2} = 0.3$, $K_{i2} = 0.12$</td>
<td>$K_{p2} = 1.0719$, $K_{i2} = 0.044$</td>
<td>$T_{s2} = 8.5418$, $P_2 = 6.8928$, $M_2 = 4.3846$, $Q_2 = 2.6881$, $R_2 = 7.6801$</td>
<td></td>
</tr>
<tr>
<td><strong>Objective function ($J$)</strong></td>
<td>$J = 180.9325$</td>
<td>$J = 28.753$</td>
<td>$J = 24.6337$</td>
</tr>
</tbody>
</table>

Fig. 5. System response subject to Scenario I: (a) frequency deviation in Area #1 ($\Delta f_1$), (b) frequency deviation in Area #2 ($\Delta f_2$), (c) tie-line power deviation ($\Delta P_{tie}$).

When Scenario II takes place, conventional PI controllers fail to maintain system stability under increased load demands as shown in Fig. 6. Further, GA-based PI controllers result increased
overshooting and settle down after 75 s while the proposed BIA-based MPLFCs need less than 50 s to do so. Noticeably, the performance of BIA-based MPLFCs can strongly outperform that of GA-based PI controllers.

**Scenario III:** The system undergoes 0.01 p.u. SSLP and it is subjected to increased transport time delays of 15 s.

Simulating the nonlinear model subject to Scenario III, frequency deviations and tie-line power are depicted in Fig. 7. Obviously, conventional and GA-based PI controllers fail to guarantee system stability under increased time delays. Even under increased time delays, the proposed controllers succeed to preserve system stability with better damping characteristic. Accordingly, the proposed design becomes a good choice to cope with nonlinearities and tolerate excessive time delays.

**Robustness study**

Robustness of the proposed design against system parameter uncertainties, is investigated for further testing. To carry out this test, the synchronizing torque coefficient is assumed to be uncertain and vary around its nominal value ($T_{12}^o$) by ±50%, i.e. $T_{12} \in [0.5T_{12}^o, 1.5T_{12}^o]$. This wide range of $T_{12}$ can sufficiently account for strong and poor coupling between the two areas. The nonlinear model of the system is stimulated at the nominal, upper and lower
the superiority of our design in capturing system nonlinearities and transport delays. Consequently, the suggested design can guarantee system stability under increased load perturbations and excessive time delays. Simulation results have been carried out to emphasize on the robustness of the proposed design against system parameters uncertainties.

Appendix A

Pseudo-code of the BIA algorithm:

```
while (t < Max number of iterations)
Generate new solutions by determining frequency, and updating velocities and locations/solutions (Eqs. (1)–(3))
if (rand > ri)
Select a solution between the best solutions
Generate a new solution by flying randomly if (rand < Li & f(xi) < f(x*))
Accept the new solutions
Increase ri and reduce Li
if Select the current best x*
t = t+1
end while
Print result
```

Typical values of the system parameters are given as follows:

- Typical values of the system parameters are given as follows:
- $T_{11} = 0.3$ s; $T_{12} = 0.2$ s; $T_{13} = 10$ s; $K_{11} = 0.333$; $T_{1} = 48.7$ s; $T_{2} = 0.513$ s; $T_{3} = 10$ s; $T_{4} = 1$ s; $T_{5} = 20$ s; $T_{23} = 13$ s; $K_{1} = 120$ Hz/p.u. MW; $K_{2} = 80$ Hz/p.u. MW; $T_{12} = 0.0707$ MW/rad; $\alpha_{12} = -1$; $R_{1} = R_{2} = 2.4$ Hz/p.u. MW; $B_{1} = B_{2} = 0.425$ p.u. MW/Hz.
- Boiler (oil fired) data: $K_{1} = 0.85$; $K_{2} = 0.095$; $K_{3} = 0.92$; $C_{b} = 200$; $T_{f} = 10$; $K_{ib} = 0.03$; $T_{ib} = 26$; $T_{ib} = 69$.

References


Conclusion

The parameters of model predictive load frequency controller by BAT search algorithm design is carried out to cope with system nonlinearities comprising generation rate constraints (GRCs) and governor dead bands (GDBs). Further, incorporated transport time delays are considered. A candidate time-domain based objective function has been considered to minimize both maximum overshoot and settling time. Comparing the proposed BIA-based MPLFCs to conventional and GA-based PI controllers has proved

limits of $T_{12}$ to confirm the robustness of the proposed design as shown in Fig. 8.

Fig. 8. System response subject to robustness study: (a) frequency deviation in Area #1 ($\Delta f_1$), (b) frequency deviation in Area #2 ($\Delta f_2$), (c) tie-line power deviation ($\Delta P_{tie}$).

Fig. 8. System response subject to robustness study: (a) frequency deviation in Area #1 ($\Delta f_1$), (b) frequency deviation in Area #2 ($\Delta f_2$), (c) tie-line power deviation ($\Delta P_{tie}$).

Fig. 8. System response subject to robustness study: (a) frequency deviation in Area #1 ($\Delta f_1$), (b) frequency deviation in Area #2 ($\Delta f_2$), (c) tie-line power deviation ($\Delta P_{tie}$).


