Model Predictive Control of Nonlinear Interconnected Hydro-Thermal System Load Frequency Control Based Bat Inspired Algorithm

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Abstract: - Bat Inspired Algorithm (BIA) has recently been explored to develop a novel algorithm for distributed optimization and control. This paper proposes a Model Predictive Control (MPC) of Load Frequency Control (LFC) based BIA to enhance the damping of oscillations in a two-area power system. A two-area hydro-thermal system is considered to be equipped with Model Predictive Control (MPC). The proposed power system model considers generation rate constraint (GRC), dead band, and time delay imposed to the power system by governor-turbine, thermodynamic process, and communication channels. BIA is utilized to search for optimal controller parameters by minimizing a time-domain based objective function. The performance of the proposed controller has been evaluated with the performance of the conventional PI controller based integral square error technique , and PI controller tuned by GA in order to demonstrate the superior efficiency of the proposed MPC tuned by BIA. Simulation results emphasis on the better performance of the proposed BIA-based MPC compared to PI controller based on GA and conventional one over wide range of operating conditions, and system parameters variations.

Key-Words: - Bat Inspired Algorithm (BIA), Load Frequency Control (LFC), Model Predictive Control (MPC).

1 Introduction

Frequency control, during the load generation imbalance, represents a very imperative issue in large-scale power systems. Automatic generation control (AGC) plays a significant role in the power system by maintaining the scheduled system frequency and tie-line power flow during normal operating conditions and load perturbations [1-3]. Load frequency control is due to the function of AGC as mentioned by Kundur [2]. In an interconnected power system two different control loops are utilized to accomplish LFC, namely primary and supplementary speed control.

Several approaches have been made in the past about the LFC. Among various types of load frequency controllers, Proportional – Integral (PI) controllers. The PI controller is very simple for implementation and gives better dynamic response, but their performance deteriorates when the system complexity increases [4]. Modern optimal control concept for AGC designs of interconnected power system was firstly presented by Elgerd and Fosha [5-6]. The optimal control faces some difficulties to achieve good performance, such as complex mathematical equations for large systems. A robust LFC via H_∞ and H_2/H_∞ control theories has been applied in [7] with different cases for the norm between load disturbance and frequency deviation output. The main deterioration of these two methods is that they introduce a controller with the same plant order, which in turn doubles the order of the open loop system, and makes the process very complex especially for large scale interconnected power systems. In practice different conventional control strategies are being used for LFC. Yet, the limitations of conventional PI and Proportional – Integral – Derivative (PID) controllers are: slow and lack of efficiency and poor handling of system nonlinearities. Artificial Intelligence techniques like Fuzzy Logic, Artificial Neural networks, Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and ABC can be applied for LFC, which can overcome the limitations of conventional controls [8-18]. Genetic algorithms (GAs) have been extensively considered for the design of AGC. Optimal integral gains and optimal PID control parameters have been computed by GAs technique for an interconnected, equal non-reheat and reheat type two generating areas [8-9]. In [10] the Parameters of PID sliding-mode used in LFC of multi area power systems with nonlinear elements are optimized by GA. In [11], GA is used to compute the decentralized control parameters to achieve an optimum operating point for a realistic system comprising generation rate constraint (GRC), dead band, and time delays. The use of particle swarm optimization (PSO) for optimizing the parameters of AGC, where an integral controller and a proportional-plus-integral controller, is reported in [12]. In [13] the parameters of PI controller are designed by PSO with the new cost function and compared their results with [12]. In [14] Multiple Tabu Search (MTS) algorithm is used in design of a Fuzzy Logic ba sed Proportional I ntegral (FLPI) for LFC in two area interconnected power system. In [15], a robust PID controller based on Imperialist Competitive Algorithm (ICA) used for LFC application. The authors of [16, 17] have proposed bacterial foraging optimization algorithm (BFOA) for designing PI and PID-based load frequency controller for two-area power system with and without GRC. Application of BFOA to optimize several important parameters in AGC of an interconnected three unequal area thermal systems such as t he integral controller gains, governor speed regulation, and the frequency bias parameters, has been reported in [18].

Model Predictive Control (MPC) is improved considerably in the last decades in field of control. It has a lot of advantages such as fast response, and stability a gainst nonlinearities, constraints and parameters uncertainties [19]. In [20-23] some applications of MPC on LFC. In [20] the usage of MPC in multi-area power system is applied, but, only by economic viewpoint. In [21], a new state contractive constraint-based predictive control scheme was used for LFC of two-area interconnected power system. This model predictive control algorithm consists of a basic finite horizon MPC technique and an additional state contractive constraint. I n [22], feasible cooperation-based MPC method is used in distributed LFC instead of centralized MPC. The paper did not deal with the change of system's parameters and Generation Rate Constraint. A decentralized model predictive control scheme for the LFC of multi-area interconnected power system is applied in [23]. However, each local area controller is designed alone and does not consider the Generation Rate Constraint that is only imposed on the turbine in the simulation. This solution may effect in poor system wide control performance of power system with significantly interacting subsystem.

This paper proposes the BIA for optimal tuning of MPC controllers in two area interconnected power system to damp power system oscillations. The MPC control design is formulated as an optimization problem and BIA is employed to search for optimal controller parameters by minimizing a candidate time-domain based objective function. The performance of the proposed MPC-based BIA is evaluated by comparison with conventional PI controller and PI-based GA. Simulations results on a two-area test system are presented to assure the superiority of the proposed method compared with PI-based GA and conventional one.

2 Bat Inspired algorithm

Bat Algorithm has been builded based on t he echolocation behavior of bats. These bats emit a very loud sound pulse (echolocation) and listens for the effect that bounces back from the surrounding objects. Their pulse bandwidth varies depending on t he species, and increases using harmonics. Some rules building the structure of BAT algorithm and use the echolocation characteristics of bats [24–26].

Step 1 Each bat uses echolocation characteristics to classify between prey and barrier.

Step 2 Each bat flies randomly with velocity v_i at position x_i with a fixed frequency f_{min}, varying wavelength k and loudness L_0 to attach the prey. It adjust the frequency of its released pulse and adjust the rate of pulse release r in the range of [0,1], relying on the closeness of its aim.

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

Step 4 The loudness L_m^{iter} changes from a large value L_0 to a minimum constant value L_{min}.

The position x_i and velocity v_i of each bat defined and updated during the optimization process. The new solutions x_i^t and velocities v_i^t at time step t are performed by the following equations:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{1}$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_*) f_i \tag{2}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{3}$$

Where β in the range of [0,1] is a random vector drawn from a uniform distribution function. x_* is the current global best location, which is resulted after comparing all the locations among all the n bats. For implementation, every bat is randomly assigned a frequency which is change uniformly from [f_{min}, f_{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.

$$x_{new} = x_{old} + \varepsilon L^t \tag{4}$$

Where ε is a random number between [-1, 1], while L_t is the mean loudness of all bats at this time step. As the loudness usually decreases once a bat has get its prey, while the rate of pulse emission increases, the loudness can be selected as any value of convenience. Assuming $L_{min} = 0$ indicate that a bat has just found the prey and temporarily stop emitting any sound, one has:

$$L_i^{t+1} = \alpha L_i^t, r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \tag{5}$$

Where α is constant in the range of [0, 1] and γ is positive constant. As time reach infinity, the loudness tends to be zero, and γ_i^t equal to γ_i^0. The general framework of the BIA is described in Algorithm 1.

Algorithm 1: The framework of BIA

Produce Initial bat population x_i (i = 1, 2, ..., n)
while (t <Max number of iterations)
Generate new solutions by determining frequency, and updating velocities and locations/solutions [equations (1) to (3)]
if (rand > r_i)
Select a solution between the best solutions
Produce a local solution around the selected best solution
end if
Generate a new solution by flying randomly
if (rand < L_i & $f(x_i) < f(x_*)$)
Accept the new solutions
Increase r_i and reduce L_i
end if
Select the current best x_*
$t=t+1$
end while
Print result

3 Model Predictive Controller

Model Predictive Control (MPC) has been evolved as an effective control strategy to stabilize dynamical systems in the presence of nonlinearities, uncertainties and delays, especially in process control [20-23]. A general MPC scheme consists of prediction and controller unit as shown in Fig. 1. The prediction unit forecast future behavior of system depend on its current output, disturbance and control signal on a finite prediction horizon. The control unit uses the predicted output in minimizing the objective function in presence of system constraints. There are a lot of formulations of the MPC that are different either in a formulation of the objective function [19,27]. In the MPC, the measured disturbance can be compensated by the method of feed forward control. Unlike feedback controller, feed forward control rejects most of the measured disturbance before affect on the system. Feed-forward control used in association with feedback control; the feed-forward control reject most of the measured disturbance effect, and the feedback control reject the rest as well as dealing with unmeasured disturbances. More details of this control method could be found in [27, 28].

An MPC controller has been used to generate the control signal based on area control error ACE_i, change in load demand ΔP_{Di} and reference value of ACE_i as its inputs. Where reference value of ACE_i equal zero. A model predictive load frequency control scheme is shown in Fig. 2.

In this paper the MPC, toolbox in Matlab Simulink has been used to design an MPC controller. The controller design requires a Linear Time Invariant (LTI) model of the system that is to be controlled. The rate at which MPC operates is $1/NT_S$, where T_S is sampling period, N is the number of controls that are applied to the system. In most cases, N is chosen equal one. The value of T_S is important because it is the length of each prediction step. The method for selecting T_S for this problem is based on tracking performance. Selecting the prediction horizon P and control horizon M were also affected by the controller. Weights (Q and R) on system's input and output are chosen at their best quantities. The BIA is proposed in this paper to get the best value of T_S, P, M and weights on system's input and output.

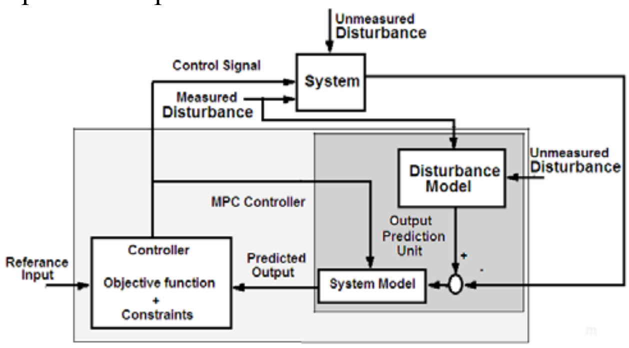

Fig. 1.A general MPC scheme

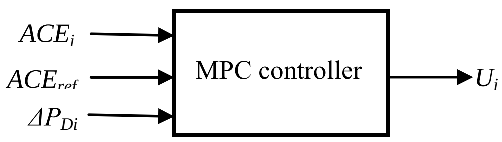

Fig. 2. A model predictive load frequency control scheme

4 Two Area hydro-thermal Power System

A model of controlled hydro-thermal plants in two-area interconnected power system with nonlinearities and boiler dynamics is shown in Fig. 3.

Where

B_i :Frequency bias parameter

B_i :Frequency bias parameter
ACE_i :Area control error
U_i :Controller output
R_i :Speed regulation in pu Hz
T_{gi} :Governor time constants in sec
T_{ti} :Turbine time constant in sec
T_{ri} :Time constant of reheater in sec
k_{ri} :Gain of reheater
T_i :Hydro governor time constant in sec
T_w :Water starting time in sec
ΔP_{Di} :Load demand change
ΔP_{tie} :Change in tie line power in p.u Mw
T_{pi} :Power system time constant in sec
K_{pi} :Power system gain
T_{12} :Synchronizing coefficient
Δf_i :System frequency deviation in Hz

The speed governor dead band has significant effect on the dynamic performance of the system. For this analysis, in this paper backlash non-linearity of about 0.05% for thermal system and the dead band non-linearity of about 0.02% for hydro system are considered. The system is provided with single reheat turbine with suitable GRC, for thermal area 0.0017MW per sec and hydro area 4.5% per sec for raising generation and 6% for lowering generation. Boiler is used to producing steam under pressure. In this study, the effect of the boiler in steam area in the power system is also considered and detailed scheme is shown in Fig. 4 given in [29].

The performance index which selected in this paper can be defined by (6).

$$J = (1 - e^{-\beta}) M_p + e^{-\beta} \times t_s \tag{6}$$

This objective function can satisfy the designer requirements using the weighting factor value (β). The factor is set larger than 0.7 to reduce the overshoot. On the other hand is set smaller than 0.7 to reduce the settling time.

This study focuses on optimal tuning of controllers for LFC using BIA. The aim of the optimization is to search for the optimum MPC parameters that improve the damping characteristics of the system under all operating conditions and various loads and finally designing a low order controller for easy implementation.

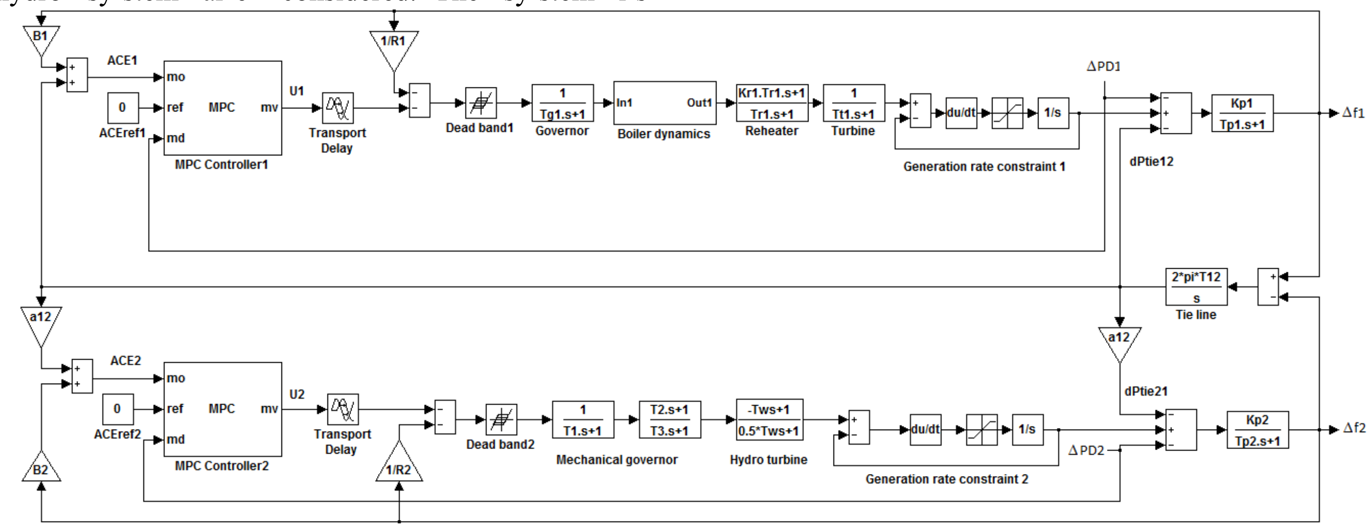

Fig. 3.Two-area interconnected power system

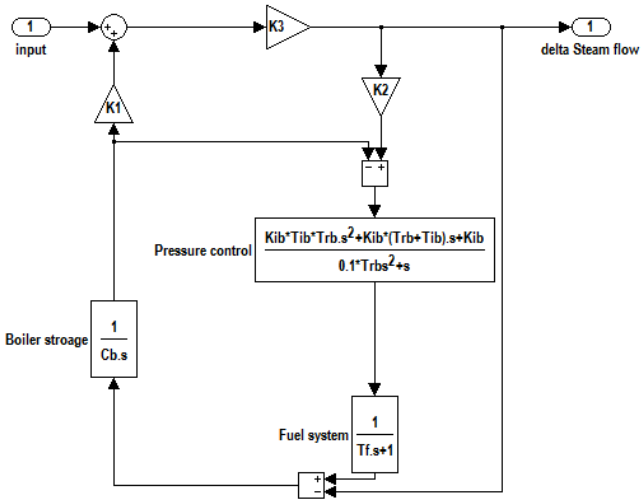

Fig. 4. Boiler dynamics

5 Simulation Results

In this section different comparative cases are examined to show the effectiveness of the proposed BIA method for optimizing controller parameters of MPC. Table 1 gives the optimum values of controller parameters for different methods. The PI controller parameters of conventional controller due to [30].

Table. 1. The Framework of BIA

	Conventional PI	***GA-PI***	***MPC***
Controller Parameters	K_{pr1}= K_{pr2}=0.3, K_{I1}= K_{I2}=0.12	K_{pr1}=0.9795, K_{I1}=0.0399, K_{pr2}=1.0719, K_{I2}=0.0440	T_{s1}=4.3123, P_1=10.000, M_1=5.8288, Q_1=0.6752, R_1=4.2568, T_{s2}=8.5418, P_2=6.8928, M_2=4.3846, Q_2=2.6881, R_2=7.0801
J	180.9325	28.753	24.6337

Case 1: a 10% step increase in demand of the first area (ΔP_{D1}), second area (ΔP_{D2}) simultaneously and time delay equal 2 second are applied (nominal test case). The change in frequency of the first area Δf_1, the change in frequency of the second area Δf_2, and change in tie-line power of the closed loop system are shown in Figs. 5–7. Remarkably, the response with conventional PI controller has high settling time and undesirable oscillations. Also compared with PI-based GA the proposed method is indeed more efficient in improving the damping characteristic of power system.

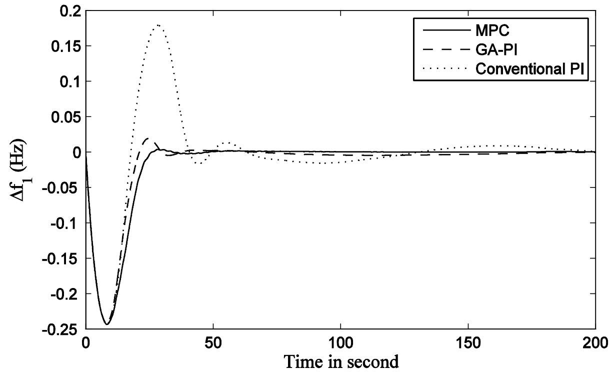

Fig. 5.Change in f_1 for case 1.

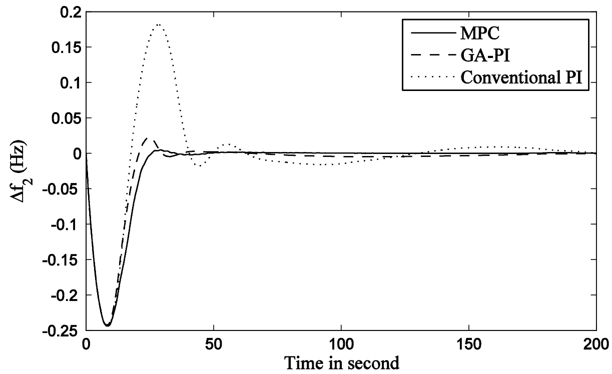

Fig. 6.Change in f_2 for case 1.

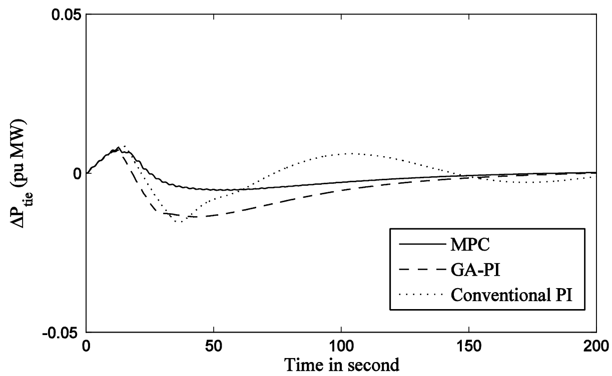

Fig. 7.Change in P_{tie} for case 1.

Case 2: a 15% step increase is applied as a change of demand in first area (ΔP_{D1}), the second area (ΔP_{D2}) simultaneously and time delay equal 2 second. The change in frequency of the first area Δf_1, the change in frequency of the second area Δf_2 and change in tie-line power of the closed loop system are shown in Figs. 8–10. From these Figures, the response with conventional controller is unstable. Moreover, the proposed method outperforms and outlasts PI-based GA in damping oscillations effectively and reducing settling time. Hence compared to the conventional controller, and PI-based GA, MPC based BIA greatly enhances the system stability and improves the damping characteristics of power system. Because of the large values of conventional PI controller response, a sub figure of this part is shown beside the main response.

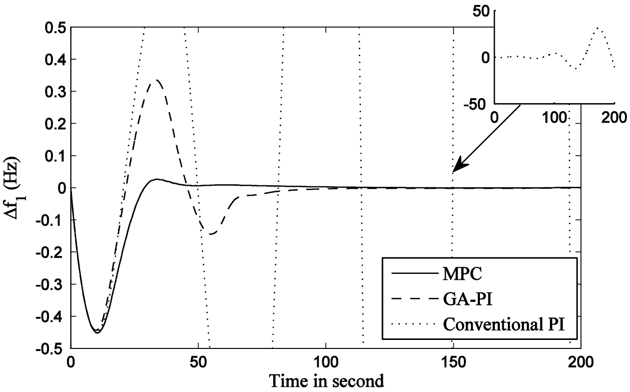

Fig. 8.Change in f_1 for case 2.

Case 3: a 10% step increase in demand of the first area (ΔP_{D1}), second area (ΔP_{D2}) simultaneously and time delay equal 15 second are applied. The change in frequency of the first area Δf_1, the change in frequency of the second area Δf_2, and change in tie-line power of the closed loop system are shown in Figs. 11–13. It is clear from these Figures that the response with PI-based GA and conventional controller are unstable. The potential and superiority of the proposed method over the conventional and PI-based GA is demonstrated.

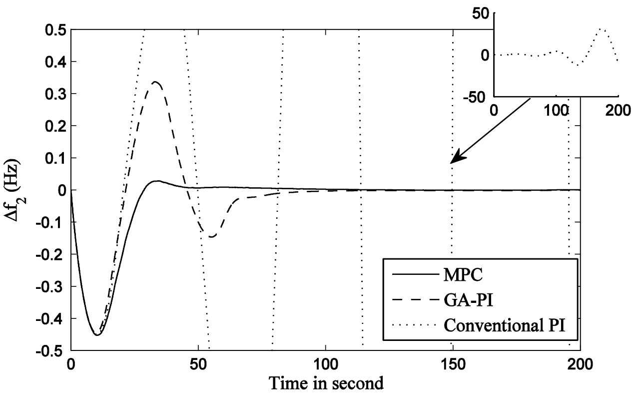

Fig. 9.Change in f_2 for case 2.

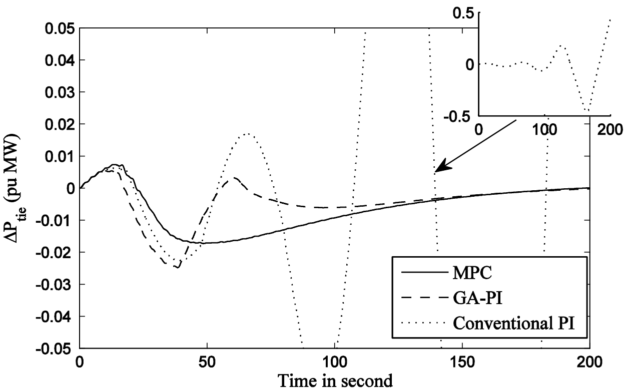

Fig. 10.Change in P_{tie} for case 2.

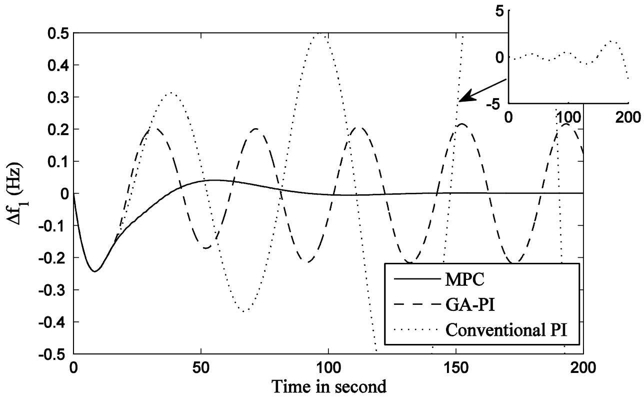

Fig. 11.Change in f_1 for case 3.

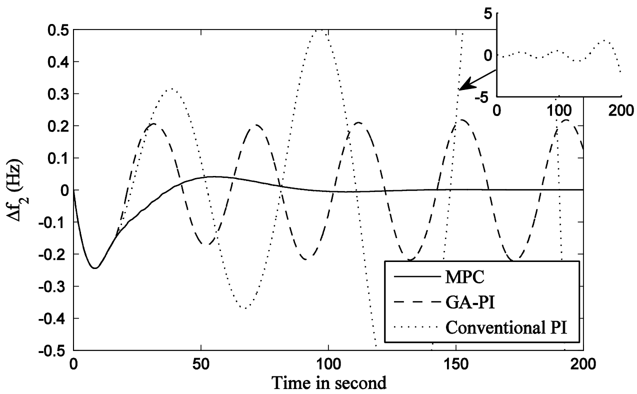

Fig. 12.Change in f_2 for case 3.

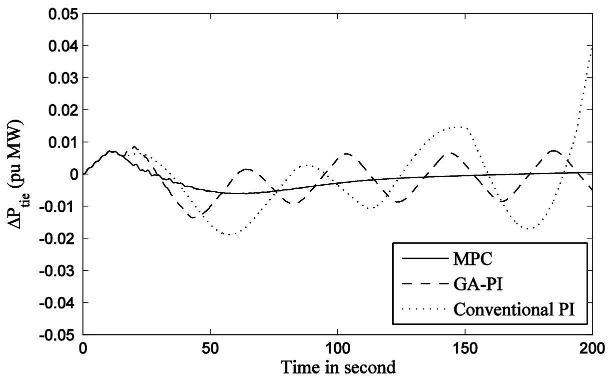

Fig. 13.Change in P_{tie} for case 3.

Case 4: a parameter variation test is also applied to validate the robustness of the proposed controller. Figs. 14–16 shows the change in frequency of the first area Δf_1, the change in frequency of the second area Δf_2, and change in tie-line power of the closed loop system with variation in T_{12}. It is clear that the system stable with the proposed controller.

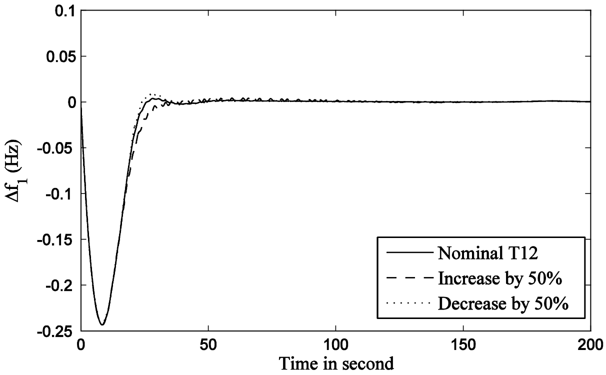

Fig. 14.Change in f_1 for case 3.

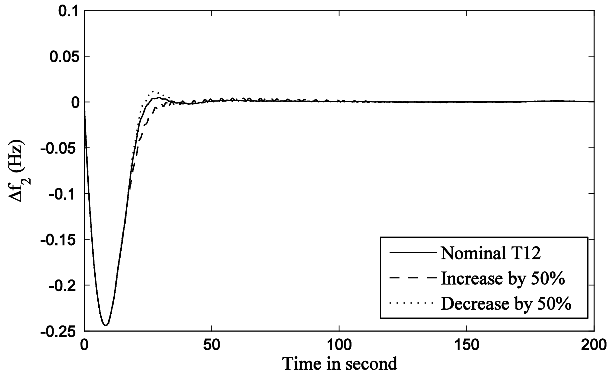

Fig. 15.Change in f_2 for case 4.

6 Conclusion

This paper presents the application of the BIA algorithm as a new artificial intelligence technique in order to optimize the AGC in a two-area interconnected power system. BIA algorithm is proposed to tune the parameters of MPC controller. A two-area power system is considered to demonstrate the proposed method. Simulation results emphasis that the designed MPC-based BIA is robust in its operation and gives a superb damping performance for frequency and tie line power deviation compared to conventional PI controller, and PI-based GA. Besides the simple architecture of the proposed controller it has the potentiality of implementation in real time environment.

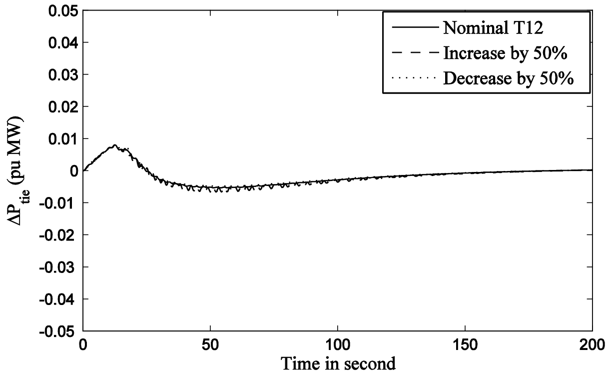

Fig. 16.Change in P_{tie} for case 4.

Appendix:

The typical values of parameters of system under study are given below: T_{t1} =0.3 s; T_{g1} =0.2 s; T_{r1} = 10 s; K_{r1} = 0.333; T_1 = 48.7 s; T_2 =0.513 s; T_3 =10 s; T_w =1 s; T_{P1} =20s; T_{P2} = 13 s; K_{P1} =120 Hz/p.u MW; K_{P2} = 80 Hz/p.u MW; T_{12} = 0.0707 MW rad^{-1}; a_{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_{rb}=69.

LTI model of the system can obtain by remove all nonlinearities. LTI_1 model of $area_1$ is obtained by remove MPC_2 of $area_2$ and open MPC_1 and click design. Export LTI_1 model of $area_1$ to workspace and save it. LTI_2 model of $area_2$ is obtained by remove MPC_1 of $area_1$ and open MPC_2 and click design. Export LTI_2 model of $area_2$ to workspace and save it.

Objective function

```
function z=Fun(x)
global Ts1 P1 M1 R1 Q1 MPC1 Ts2 P2 M2 R2 Q2
MPC2 LTI1 LTI2
Ts1=x(1) ;P1=x(2);M1=x(3); R1=x(4);Q1=x(5);
Ts2=x(6);P2=x(7);M2=x(8); R2=x(9);Q2=x(10);
w1=struct('ManipulatedVariables',0,'ManipulatedVa
riablesRate',R1,'OutputVariables',Q1,'ECR',0);
MPC1=MPC(LTI1,Ts1,P1,M1,w1);
w2=struct('ManipulatedVariables',0,'ManipulatedVa
riablesRate',R2,'OutputVariables',Q2,'ECR',0);
MPC2=MPC(LTI2,Ts2,P2,M2,w2);
sim('two_area_hydro_thermal')
c1=stepinfo(dF1,T,0);
a1=c1.SettlingTime;
b1=c1.Peak;
c2=stepinfo(dF2,T,0);
a2=c2.SettlingTime;
b2=c2.Peak;
z=(1-exp(-0.7))*b1+exp(-0.7)*a1+(1-exp(-
.7))*b2+exp(-0.7)*a2
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