International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2010	Issue 3	Volume 2	Number 2	Pages 28-36

PSO BASED NEURO-FUZZY CONTROLLER FOR LFC DESIGN INCLUDING COMMUNICATION TIME DELAYS

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Abstract- The Proportional Integral Derivative (PID) controller is the most adopted controllers for industrial plants, due to its simplicity and satisfactory performances for a wide range of processes. It should be noted that the accurate and efficient tuning of parameters such controllers is very important. On the other hand, industrial plants, such as power systems, usually have some features, such as nonlinearity, time-variability of system structure and time delay, which make controller parameter tuning more complex. Thus, the optimal tuning of PID gains is required to get the desired level of robust performance under different operation conditions. This paper presents an Adaptive Network based Fuzzy Inference System (ANFIS) to tune on-line optimal gains of a PID controller for Load Frequency Control (LFC) design in a restructured time delay power system. The problem of robustly off-line tuning of PID based LFC design is formulated as an optimization problem according to the time domain-based objective function which is solved by Particle Swarm Optimization (PSO) technique that has a strong ability to find the most optimistic results. It is used to yield optimal PID gains over a wide range of plant parameter change and different system time-delays for training the proposed ANFIS in order to adopt the gains of the PID based load frequency controller. This newly developed control strategy combines the advantage of neural networks and fuzzy inference system and has simple stricture that is easy to implement and tune. To demonstrate the effectiveness of the proposed control strategy a two-area restructured power system is considered as a test system under different operating conditions and system nonlinearities. The simulation results show that the tuned gains of the PID based load frequency controller using the ANFIS can provide better damping of frequency oscillations.

Keywords: LFC, Restructured Power System, Power System Control, PID Controller, PSO, ANFIS.

I. INTRODUCTION

Currently, the electric power industry is in transition from large, vertical utilities providing power at regulated rates to an industry that will incorporate competitive companies such as Independent Power Producers (IPPs) selling unbundled power at lower rates. Under this circumstance, any power system controls such as the Load Frequency Control (LFC) as an ancillary service acquires a principal role to maintain the electric system reliability at an adequate level and is becoming much more significant today in accordance with the complexity of interconnected power system. The main goal of the LFC is to maintain zero steady state errors for frequency deviation and good tracking load demands in a multi-area restructured power system. In addition, the power system should fulfill the requested dispatch conditions. From the mechanisms used to manage the provision this service in ancillary markets, the bilateral contracts or competitive offers stand out [1]. On the other hand, an open communication infrastructure to support control processes and the ancillary services for an effective power system is highly required in deregulated environments.

The real world power system contains different kinds of uncertainties due to system modeling errors and change of the power system structure. On the other hand, increasing size, expanding physical setups and complexity of the restructured power system introduced a set of significant uncertainties such as communication delays and plant parameter changes in power system control and operation, especially on the LFC problem solution. Thus, consideration these uncertainties in LFC synthesis/analysis are very important to design a suitable controller for good electricity trading.

Recently, some authors proposed LFC synthesis in the prescience of communication delays [2-3]. Yu and Tomosovic [2] suggested a linear matrix inequality based control strategy for a LFC system. Bevrani and Hiyama [3] used a mixed H_2/H_∞ based PI controller for a LFC system with time varying communication delays. The effects of signal delays on the LFC task have clearly investigated by these approaches. However, the effects of plant parameter changes in the presence of varying signal delays are not studied on the LFC scheme. More recently, artificial neural networks and fuzzy set techniques have been proposed to cope with system uncertainties to improve the LFC performance [4-6]. However, the parameter adjustments of these controllers need some trial and errors and also the effects of communication signal delays are not investigated on the LFC scheme. Thus, in order to have a robust controller it is required that an adaptive controller is designed using ANN and fuzzy techniques to consider plant parameter changes in the time-varying delayed LFC systems.

Despite the potential of the modern control techniques with different structure, PID type controller is still widely used for solution of the LFC problem [7-9]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions and easy to implement The PID (PI) controller parameters tuning are usually done by trial and error methods based on the conventional experiences. Hence, they are not my capable of provide good robust performance for power system faces by varied communication delays and parametric uncertainties. On the other hand, Shayeghi et al. [7] have presented a comprehensive analysis of the effects of the different PID controller parameters on the overall dynamic performance of the LFC problem. It is shown that the appropriate selection of PID controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance. Since optimal setting of PID controller gains is more complex due to nonlinearity, complexity and time-variability of the real world power systems. In this paper, an Adaptive Network based Fuzzy Inference System (ANFIS) is proposed to tune on-line optimal gains of a PID controller for LFC design in a restructured time-delayed power system. By using a hybrid learning procedure, the ANFIS can construct an input-output mapping based on human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs [10]. Takagi and Sugeno's fuzzy if-then rules are used in the ANFIS architecture [11]. In addition, the neuro-fuzzy approach combines the advantages of fuzzy logic and neural network models to design an architecture that uses a fuzzy logic to represent knowledge in an interpretable manner and the learning ability of a neural network to optimize its parameters [12].

In this study, the problem of robustly off-line tuning of PID based LFC design is formulated as an optimization problem according to the time domain based objective function which can be solved by Particle Swarm Optimization (PSO) technique. PSO is a novel population based metaheuristic, which utilize the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as a useful tool for engineering optimization. Unlike the other heuristic techniques, it has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. It has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high dimensionality [13]. It is used to obtain off-nominal optimal PID gains by minimization of the Integral of the Time multiplied Absolute value of the Error (ITAE) based performance index which considers a multiple of operating conditions is created based on different plant parameters changes and time-varied signal delays. The obtained off-nominal PID gains is used for training the proposed ANFIS in order to adopt the gains of PID based load frequency controller. The motivation for using of this control strategy are to have easy tuning and simple structure of control strategy, consider time varying signals delays and large parametric uncertainties in the LFC synthesis.

The proposed control strategy is applied to a two-area restructured power system. The simulation results show that the proposed PID-like neuro-fuzzy controller achieves good robust performance for a wide range of system parameters and multi signals delays against area load disturbances changes even in the presence of generation rate constraints (GRC).

II. TWO-AREA DEREGULATED POWER SYSTEM

In the deregulated power systems, the Vertically Integrated Utility (VIU) no longer exists. However, the common LFC goals, i.e. restoring the frequency and the net interchanges to their desired values for each control area, still remain. Generalized dynamical for the LFC scheme has been developed in Reference [14] based on the possible contracts in the deregulated environments. This section gives a brief overview on this generalized model that uses all the information required in a VIU industry plus the contract data information. In the deregulated power system, Generation Companies (GENCOs) may or may not participate in the LFC task. and Distribution Companies (DISCOs) have the liberty to contract with any available GENCOs in their own or other areas. Thus, there can be various combinations of the possible contracted scenarios between DISCOs and GENCOs. The concept of an Augmented Generation Participation Matrix (AGPM) is introduced to express these possible contracts in the generali-zed model. The rows and columns of AGPM is equal with the total number of GENCOs and DISCOs in the overall power system, respectively. For example, the AGPM structure for a large scale power system with N control area is given by:

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \quad (1)$$

where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

for i, j=1,…,N and

$$s_i = \sum_{k=1}^{i-1} n_i \,,\; z_j = \sum_{k=1}^{j-1} m_j \,,\quad s_1 = z_1 = 0$$

where, n_i and m_i are the number of GENCOs and DISCOs in area i and gpf_{ij} refer to '*generation participation factor*' and shows the participation factor GENCO i in total load following requirement of DISCO j based on the possible contract.

The sum of all entries in each column of AGPM is unity. To illustrate the effectiveness of the modeling strategy and proposed control design, a three control area power system is considered as a test system. It is assumed that each control area includes two GENCOs and a DISCO. Block diagram of the generalized LFC scheme for test power system is shown in Figure 1. The power system parameters are given in Tables 1 and 2.

The dotted and dashed lines show the demand signals based on the possible contracts between GENCOs and DISCOs which carry information as to which GENCO has to follow a load demanded by which DISCO. These new information signals were absent in the traditional LFC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the LFC task and $\sum_{j=1}^{n_i} apf_{ji} = 1$. We can write [14]:

$$d_i = \Delta P_{Loc,j} + \Delta P_{di}, \Delta P_{Loc,j} = \sum_{j=1}^{m_i} \Delta P_{Lj-i}, \quad \Delta P_{di} = \sum_{j=1}^{m_i} \Delta P_{ULj-i} \tag{2}$$

Table 1. Control area parameters

Parameter	Area - 1	Area - 2
K_P (Hz/pu)	120	120
T_P (sec)	20	20
B_i (pu/Hz)	0.4250	0.4250
T_{ij} (pu/Hz)	T_{12}= 0.545	

Table 2. GENCOs parameters

MVA$_{base}$ (1000MW) Parameter	GENCOs (k in area i) 1-1	2-1	1-2	2-2
Rate (MW)	1000	800	1100	900
T_T (sec)	0.32	0.30	0.30	0.32
T_G (sec)	0.1	0.1	0.1	0.1
R (Hz/pu)	2.4	3.3	2.5	2.4
A	0.5	0.5	0.5	0.5

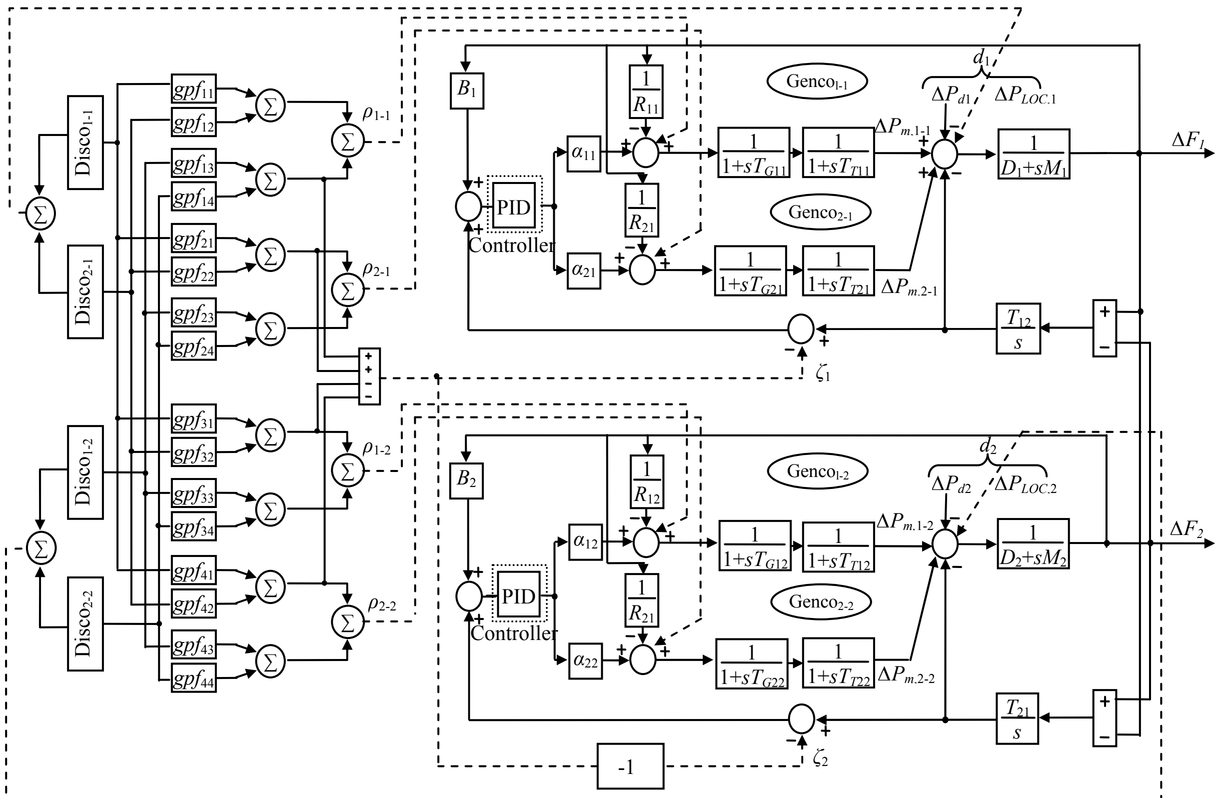

Figure 1. The generalized LFC scheme in the restructured system

$$\eta_i = \sum_{j=1\&j\neq i}^{N} T_{ij}\Delta f_j \tag{3}$$

$$\zeta_i = \Delta P_{tie,i,sch} = \sum_{k=1\&k\neq i}^{N} \Delta P_{tie,ik,sch} \tag{4}$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n_i}\sum_{i=1}^{m_k} apf_{(s_i+j)(z_k+i)}\Delta P_{L(z_k+i)-k} - \sum_{i=1}^{n_k}\sum_{j=1}^{m_i} apf_{(s_k+i)(z_i+j)}\Delta P_{L(z_i+j)-l} \tag{5}$$

$$\rho_i = [\rho_{1i} \ \cdots \ \rho_{ki} \ \cdots \ \rho_{n_i i}], \ \rho_{ki} = \sum_{j=1}^{N}[\sum_{t=1}^{m_j} gpf_{(s_i+k)(z_j+t)}\Delta P_{Lt-j}] \tag{6}$$

$$\Delta P_{m,k-i} = \rho_{ki} + apf_{ki}\Delta P_{di} \tag{7}$$

where $\Delta P_{m,ki}$ is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state.

III. TIME DELAYED LFC SCHEME

The LFC model in traditional structure with time delays is well discussed in [2-3]. This model is modified to include communication delays in the deregulated power systems. In view of this, on the control input and output in each area of the deregulated LFC scheme shown in Figure 1, the communication delays are depicted in

Figure 2. The delays on the measured frequency and tie-line power flow from remote terminal units to control center are considered on the ACE signal (the control input) and the produced rise/lower signal from the control center to individual GENCO. An exponential function $e^{-\tau s}$ is used to describe the communication delay where τ gives the communication delay time. To generate the PID based ACE signal the detected frequency and tie-line power deviations via communication line is used for achieving load following match according to contracted scenario. Via another link, the control signal is submitted to the GENCOs according to their participation factors (α_{ij}).

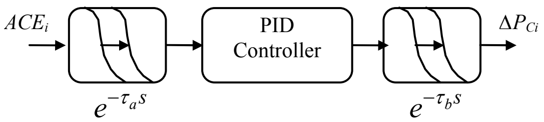

Figure 2. Signals delays Modeling

IV. PSO REVIEW AND PSO-BASED PID CONTROLLER DESIGN

This section gives a brief over view of PSO technique Also, the procedure of the PSO-based PID controller design for the solution of LFC problem is given.

A. Particle Swarm Optimization

Particle swarm optimization algorithm, which is tailored for optimizing difficult numerical functions and based on metaphor of human social interaction, is capable of mimicking the ability of human societies to process knowledge [13]. It has roots in two main component methodologies: artificial life (such as bird flocking, fish schooling and swarming); and, evolutionary computation. Its key concept is that potential solutions are flown through hyperspace and are accelerated towards better or more optimum solutions. Its paradigm can be implemented in simple form of computer codes and is computationally inexpensive in terms of both memory requirements and speed. It lies somewhere in between evolutionary programming and the genetic algorithms. As in evolutionary computation paradigms, the concept of fitness is employed and candidate solutions to the problem are termed particles or sometimes individuals, each of which adjusts its flying based on the flying experiences of both itself and its companion.

PSO keeps track of its coordinates in hyperspace which are associated with its previous best fitness solution, and also of its counterpart corresponding to the overall best value acquired thus far by any other particle in the population. Vectors are taken as presentation of particles since most optimization problems are convenient for such variable presentations. It is adaptive corresponding to the change of the best group value. The allocation of responses between the individual and group values ensures a diversity of response.

The higher dimensional space calculations of the PSO concept are performed over a series of time steps. The population is responding to the quality factors of the previous best individual values and the previous best group values. The principle of stability is adhered to since the population changes its state if and only if the best group value changes [15-16]. As it is reported in [16-17], this optimization technique can be used to solve many of the same kinds of problems as GA, and does not suffer from some of GAs difficulties. It has also been found to be robust in solving problem featuring non-linearity, non-differentiability and high-dimensionality. PSO is the search method to improve the speed of convergence and find the global optimum value of fitness function.

PSO starts with a population of random solutions "particles" in a D-dimension space. The *i*th particle is represented by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle *i* (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$.

The global version of the PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population. PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to Equation (8). The velocity of particle *i* is represented as $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest. The position of the *i*th particle is then updated according to (9) [13].

$$v_{id} = wv_{id} + c_1 rand(\,)(P_{id} - x_{id}) + c_2 rand(\,)(P_{gd} - x_{id}) \tag{8}$$

$$x_{id} = x_{id} + cv_{id} \tag{9}$$

where, P_{id} and P_{gd} are *pbest* and *gbest*. Several modifications have been proposed in the literature to improve the PSO algorithm speed and convergence toward the global minimum. One modification is to introduce a local-oriented paradigm (*lbest*) with different neighborhoods. It is concluded that *gbest* version performs best in terms of median number of iterations to converge. However, *pbest* version with neighborhoods of two is most resistant to local minima. PSO algorithm is further improved via using a time decreasing inertia weight, which leads to a reduction in the number of iterations [15]. Figure 3 shows the flowchart of the proposed PSO algorithm.

This new approach features many advantages; it is simple, fast and easy to be coded. Also, its memory storage requirement is minimal. Moreover, this approach is advantageous over evolutionary and genetic algorithms in many ways. First, PSO has memory. That is, every particle remembers its best solution (local *best*) as well as the group best solution (global *best*).

Another advantage of PSO is that the initial population of the PSO is maintained, and so there is no need for applying operators to the population, a process that is time and memory-storage-consuming. In addition, PSO is based on "constructive cooperation" between particles, in contrast with the genetic algorithms, which are based on "the survival of the fittest".

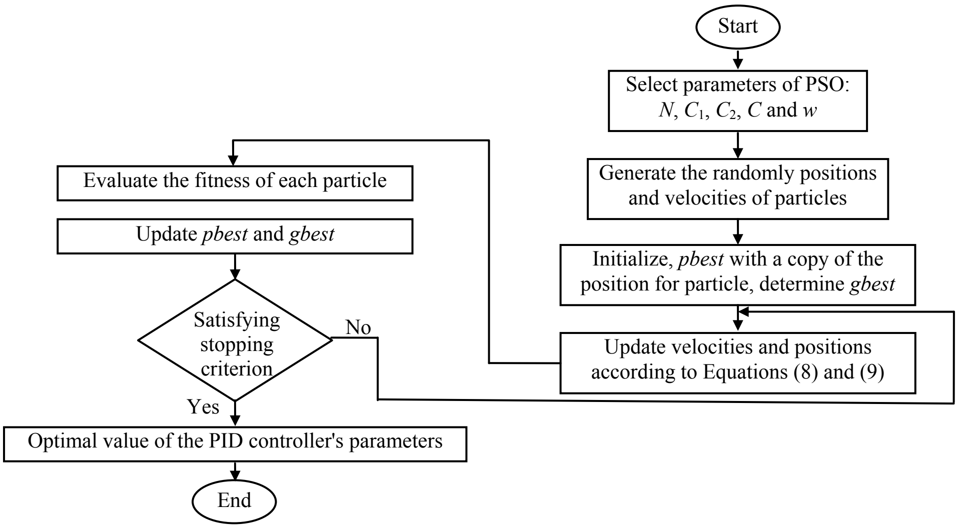

Figure 3. Flowchart of the proposed PSO technique

B. PSO-Based PID Type Load Frequency Controller

Nowadays, despite the significant developments of recent years in control theory and technology PID controllers are used in almost all sectors of industry and science such as power systems [18]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions. Furthermore, they are easy to implement using analogue or digital hardware and familiar to engineers. In this study, PID controller is used for the solution of LFC problem.

It should be noted that the transient performance of the power system with respect to the control of the frequency and tie-line power flows obviously depends on the optimal tuning of the PID controller's parameters. It is well know that the conventional methods to tune PID gains not able to locate or identify the global optimum for achieving the desired level of system robust performance due to the complexity and multi-variable conditions of the power systems and also they may be tedious and time consuming.

In order to overcome these drawbacks and provide optimal control performance, PSO algorithm is proposed to off-line optimal tune of PID gains under different operating conditions. Figure 4 shows the block diagram of PSO based tuned PID controller to solve the LFC problem for each control area (Figure 1). By taking ACE_i as the system output, the control vector for PID controller in each control area is given by:

$$u_i = K_{Pi} ACE_i + K_{Ii} \int ACE_i dt + K_{Di} A\dot{C}E_i \tag{10}$$

It is important to emphasize that the control performance can be significantly enhanced by cascading the PID controller with a lead filter, as given by:

$$G_i(s) = \frac{1 + T_{lead,1i} s}{1 + T_{lead,2i} s} \tag{11}$$

The gains K_{Pi}, K_{Ii}, K_{Di}, $T_{lead,1i}$ and $T_{lead,2i}$ are tuned using PSO technique and then, the PID controller generates the control signal that applies to the governor set point in each area. In this study, the PSO module works offline.

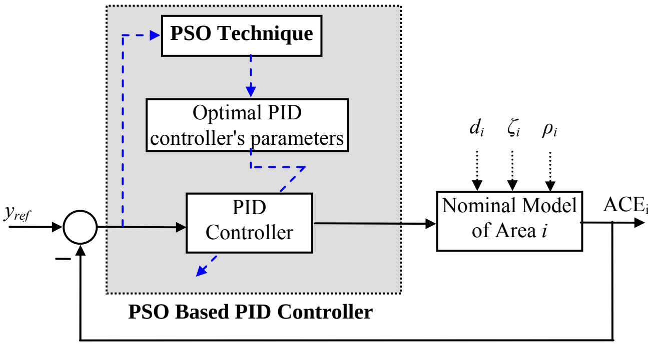

Figure 4. The proposed PSO based PID controller structure

It should be noted that choice of the properly objective function is very important in synthesis procedure for achieving the desired level of system robust performance. Because different objective functions promote different PSO behaviors, which generate fitness value providing a performance measure of the problem considered. For our optimization problem, the following objective function based on the system performance index of the: ITAE is used:

$$J = \sqrt{\sum_{i=1}^{N} \left(\int_0^{t=tsim} t \left|ACE_i\right| dt\right)^2 / N} \tag{12}$$

Where, N is the number of area control in power systems. It is worth mentioning that the lower the value of this objective function is, the better robustly the systems performance in terms of time domain characteristics. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PID controller parameter bounds.

Minimize J Subject to:

$$\begin{aligned} &K_{Pi}^{\min} \le K_{Pi} \le K_{Pi}^{\max} \\ &K_{Ii}^{\min} \le K_{Ii} \le K_{Ii}^{\max} \\ &K_{Di}^{\min} \le K_{Di} \le K_{Di}^{\max} \\ &T_{1i}^{\min} \le T_{1i} \le T_{1i}^{\max} \\ &T_{2i}^{\min} \le T_{2i} \le T_{2i}^{\max} \end{aligned} \tag{13}$$

To improve the overall system dynamical performance in a robust way and optimization synthesis, this paper employs PSO technique to solve the above optimization problem and search for optimal or near optimal set of off-nominal PID controller parameters (K_{Pi}, K_{Ii}, K_{Di}, $T_{lead,1i}$ and $T_{lead,2i}$ for i=1, 2 ,..., N) where, N is the number of control areas.

V. PID-LIKE NEURO-FUZZY CONTROLLER

PID controller has the advantage of simple structure, good stability and high reliability. The key issue for PID controller design is to settle the gains so that the controller works well under every condition. On the other hand, nonlinearity, structure variability and multi time delayed of LFC scheme makes very difficult to suit a wide range of working conditions with only a set of fixed PID gains. In order to overcome these drawbacks and to have a robust PID controller an adaptive technique based neuro-fuzzy approach is required for LFC task. For this reason, an adaptive network based fuzzy inference system is proposed to on-line tune of PID gains for the solution of LFC problem under different operating conditions and signals time-delays. The ANFIS is trained to adopt gain-setting of PID controller for a wide range of plant parameter changes and multi time-delayed LFC systems. When the ANFIS has been trained, it will yield the optimal PID gains for any operating conditions and time delays even if they are not in the train data. The proposed ANFIS based LFC scheme is shown in Figure 5.

A. Neuro-Fuzzy Network Model

The neuro-fuzzy method combines the advantages of neural networks and fuzzy theory to design a model that uses a fuzzy theory to represent knowledge in an interpretable manner and the learning ability of a neural network to optimize its parameters [19]. ANFIS is a specific approach in neuro-fuzzy development which was first introduced by Jang [10].

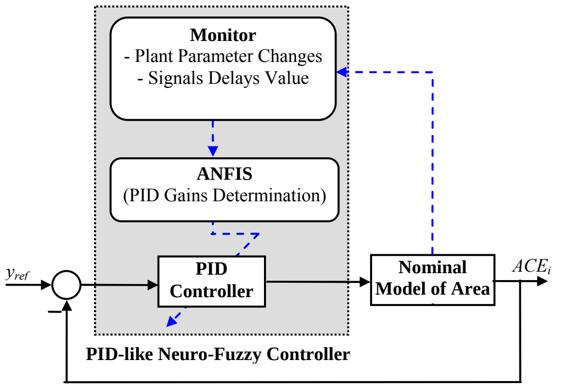

Figure 5. Architecture of the proposed ANFIS based load frequency controller

The model considered here is based on Takagi-Sugeno inference model. ANFIS uses a hybrid learning algorithm to identify consequent parameters of Sugeno-type fuzzy inference systems. It applies a combination of the least squares method and backpropagation gradient descent method for training fuzzy inference system membership function parameters to emulate a given training data set. The neuro-fuzzy system owes much from the feedforward neural network with supervised learning capability. The fuzzy inference system under consideration has three inputs (value of system parameter change percent (PCP) than the nominal value, communications delays τ_a or τ_b) and produce the values of K_{Pi}, K_{Ii}, K_{Di}, T_{1i} and T_{2i} (PID and lead-lag filter parameters) separately. The whole process can be summarized at the three steps as follows [20]:

i) Input operating conditions fuzzification: Fuzzify the input operating conditions; PCP and τ_a in terms of fuzzy subsets. Each row of Sugeno Fuzzy Kogic (SFL) rule base table composed of two nominal input and corresponding nominal optimal PID and lead-lag filter parameters as output obtained by the PSO algorithm. The nominal control values of the input subsets for PCP (0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3) and those of τ_a (1, 2, 3), respectively, at which membership values are unity. They are nominal input conditions, too. Sugeno fuzzy rule base table consists of 21 (=7×3) logical operating conditions or sets. Each input set corresponds to nominal optimal PID gains as output.

ii) Fuzzy inference system: This is firstly done for on-line imprecise values of operating conditions. From SFL table for each valid logical set corresponding input sets and minimum μ and nominal proposed controller parameters are obtained.

iii) Sugeno defuzzification: This is done to obtain crisp output for each parameters of controllers as follows:

$$\text{Final crisp output, } G_{crisp} = \frac{\sum_i W_{\min}^{(i)}.G_i}{\sum_i W_{\min}^{(i)}} \quad (14)$$

where, i correspond to input sets satisfied among 21 input sets and G_i is any of the PID gains. $W_{\min}^{(i)}$ is the minimum membership value corresponding to ith input set being satisfied.

VI. APPLICATION TO THE TWO-AREA POWER SYSTEM

A two-area restructured power system, shown in Figure 1 is considered as a test system to illustrate the effectiveness of the proposed control strategy. It is assumed that each control area includes two GENCOs and DISCOs. In the study, the linear model of turbine $\Delta PV_{ki}/\Delta PT_{ki}$ in Figure 1 is replaced by a nonlinear model of Figure 6 (with ±0.05 limit). This is to take GRC into account, i.e. the practical limit on the rate of the change in the generating power of each GENCO. The results in Reference [4, 21] indicated that GRC would influence the dynamic responses of the system significantly and lead to larger overshot and longer settling time. Moreover, affirmative effect of signals delays on LFC problem is also taken into account.

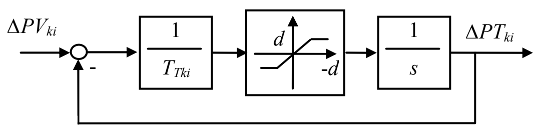

Figure 6. Nonlinear turbine model with GRC

Simulation results and eigenvalue analysis show that the open loop system performance is affected more significantly by changing in the K_{pi}, T_{pi}, B_i and T_{ij} than changes of other parameters [21-22]. On the other hand, in the deregulated environment LFC system is subjected to the multi communication time-delays which would influence the dynamic responses of the system significantly and lead to larger overshot, longer settling time and even instability. Thus, to illustrate the capability of the proposed strategy in this example, in the view point of uncertainty our focus will be concentrated on variation of K_{pi}, T_{pi}, B_i and T_{ij} parameters and signal delays. Hence, for the given power system, we have set our objectives to area frequency regulation and assuring robust stability and performance in the presence of specified uncertainties, load changes and system nonlinearities as follows:

1. Holding dynamical robust performance for the overall power system in the presence of 30% uncertainty for the K_{pi}, T_{pi}, B_i and T_{ij} in each control area and varied signals time delays in range $\tau_a \in [1 \quad 3]$ and $\tau_b \in [1.5 \quad 3.5]$.
1. Minimizing the effects of new introduced disturbances on the output signals according to the possible contracts.
2. Getting zero steady state error and good tracking for load demands and disturbances.
3. Maintaining acceptable overshoot and settling time on the frequency deviation signal in each control area.

In the proposed method, we must firstly tune the PID controller and lead-lag filter parameters optimally in each control area on the given power system to achieve the above control objectives. The optimization of off-nominal PID controller parameters is carried out by evaluating the objective cost function as given in Equation (12). Consider that all DISCOs contract with available GENCOs for power as per the following AGPM. All GENCOs participate in the LFC task.

$$AGPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

It is assume that a large step load 0.1 pu(MW) is demanded by each DISCOs in all areas. Moreover, consider that DISCOs of area 1 and 2 demands 0.05 and 0.03 pu(MW) of excess power, respectively, which is reflected as a local load perturbation of the areas. Under this contracted scenario, the nominal operating conditions are obtained with multi signal time delays τ_a = (1, 2 and 3) and variation system parameters of K_{pi}, T_{pi}, B_i and T_{ij} from -30% to 30% of the nominal values by 10% step (i.e. 21 operating conditions).

In order to acquire better performance, number of particle, particle size, number of iteration, C_1, C_2 , and C is chosen as 30, 10, 60, 2, 1.73 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.2. It should be noted that PSO algorithm is run several times and then off-nominal optimal set of controller parameters is selected.

VII. SIMULATION RESULTS

The proposed PID-like neuro-fuzzy controller is applied for each control area of the restructured multi time-delayed power system. To illustrate robustness of the proposed control strategy against parametric uncertainties and system time delays, simulations are carried out for four number of operating conditions is considered as follows:

- PCP=0.75, τ_a=1 and τ_b=1.5
- PCP=0.85, τ_a=3 and τ_b=3.5
- PCP=1.15, τ_a=2 and τ_b=2.5
- PCP=1.25, τ_a=3 and τ_b=3.5

under large load demands in the presence of GRC. Sugeno fuzzy rule based off-nominal, online optimal gains for off-nominal parameters in the above cases are shown in Table 3.

A. Scenario 1

In this scenario, the closed loop performance is tested in the presence of both step contracted load demands and uncertainties. A case of combined Poolco and bilateral based contracts between DISCOs and available GENCOs is considered based on the AGPM as given in pervious section. In this case, DISCOs have the freedom to have a contract with any GENCO in their or other areas. Power system responses in case 1 are depicted in Figure 7.

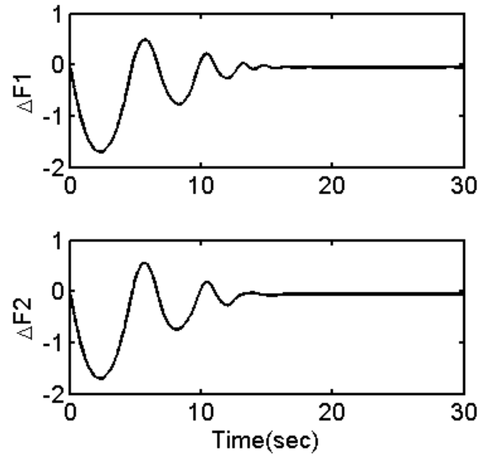

Figure 7. Power system response for scenario 1

B. Scenario 2

The purpose of this scenario is to test the effectiveness of the proposed controller against large parametric uncertainties and large signals time delays. Consider scenario 1 again. The power system responses in this case with 15% decrease in system uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} for large time delays τ_a=3 and τ_b=3.5 are shown in Figure 8.

C. Scenario 3

The purpose of this scenario is to test the effectiveness of the proposed controller against medium parametric uncertainties and signals time delays. Consider scenario 1 again. The power system responses in this case with 15% increase in system uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} for τ_a=2 and τ_b=2.5 are shown in Figure 9.

Table 3. Sugeno fuzzy based off-nominal, on-line optimal gains

Case No.	Off-Line Parameters (τ_a, τ_b, PCP)	K_{P1}	K_{I1}	K_{D1}	$T_{lead,11}$	$T_{lead,12}$	K_{P2}	K_{I2}	K_{D2}	$T_{lead,21}$	$T_{lead,22}$
1	1, 1.5, 0.75	0.369	0.585	0.026	1.559	20.0	0	0.740	0.727	1.559	6.487
2	3, 3.5, 0.85	0.22	0.360	0.15	1.830	19.38	0	0.410	0.720	0.81	8.34
3	2, 2.5, 1.15	0.441	0.319	0.525	1.550	19.08	0.393	0.530	0.202	2.07	5.778
4	3,3.5, 1.25	0.123	0.707	0.230	4.401	19.49	0	0.491	0.161	0.267	11.76

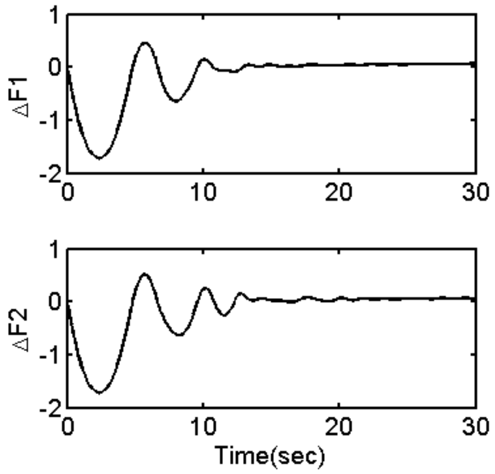

Figure 8. Power system response for scenario 2

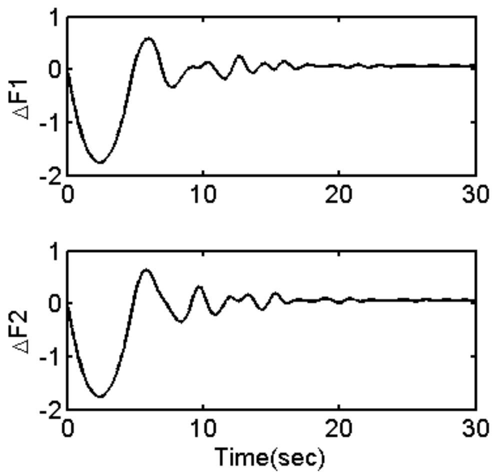

Figure 9. Power system response for scenario 3

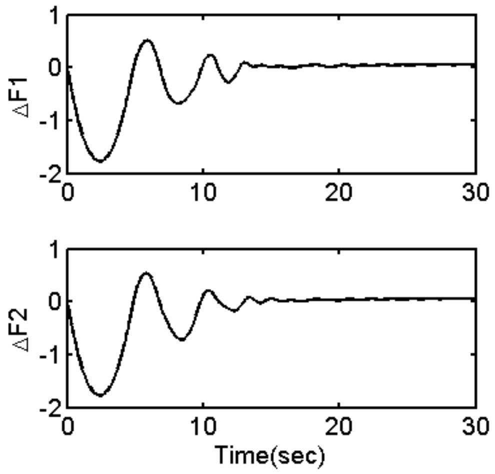

Figure 10. Power system response for scenario 4

D. Scenario 4

The purpose of this scenario is to test the effectiveness of the proposed controller against large parametric uncertainties and large signals time delays. Consider scenario 1 again. The power system responses in this case with 25% increase in system uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} for large time delays τ_a=3 and τ_b=3.5 are shown in Figure 10.

The simulation results demonstrate that the proposed control strategy track the load fluctuations and meet robustness for a wide range of plant parameter changes and time delays.

VIII. CONCLUSIONS

One of the important problems in LFC task is designing a suitable controller to get a desire level of robust performance against parametric uncertainties and multi-time delays. In this paper, to consider system uncertainties and multi communication time delays in synthesis procedure an ANFIS based PID controllers is proposed for solution of LFC problem in a restructured time delayed power system. It should be noted that the accurate and efficient tuning of parameters PID is very important. For this reason off-nominal optimal PID gains for training ANFIS is obtained using PSO algorithm by minimization of the time domain based performance index. The ANFIS is trained to adopt gain-setting of PID controller for a wide range of plant parameter changes and multi time-delayed LFC systems. The salient feature of this control strategy is combination of the advantage of neural networks and fuzzy inference system and to have simple stricture that is easy to implement and tune. The proposed control strategy was applied to a two-area restructured power system. The simulation results show that the proposed PID-like neuro-fuzzy controller achieves good robust performance for a wide range of system parameters and multi time delays LFC system. Thus, it is recommended to generate good quality and reliable electric energy in the restructured power systems.

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