

# LFC Design of a Deregulated Power System with TCPS Using PSO

H. Shayeghi , H.A. Shayanfar, A. Jalili

**Abstract**—In the LFC problem, the interconnections among some areas are the input of disturbances, and therefore, it is important to suppress the disturbances by the coordination of governor systems. In contrast, tie-line power flow control by TCPS located between two areas makes it possible to stabilize the system frequency oscillations positively through interconnection, which is also expected to provide a new ancillary service for the further power systems. Thus, a control strategy using controlling the phase angle of TCPS is proposed for provide active control facility of system frequency in this paper. Also, the optimum adjustment of PID controller's parameters in a robust way under bilateral contracted scenario following the large step load demands and disturbances with and without TCPS are investigated by Particle Swarm Optimization (PSO), that has a strong ability to find the most optimistic results. This newly developed control strategy combines the advantage of PSO and TCPS and has simple structure that is easy to implement and tune. To demonstrate the effectiveness of the proposed control strategy a three-area restructured power system is considered as a test system under different operating conditions and system nonlinearities. Analysis reveals that the TCPS is quite capable of suppressing the frequency and tie-line power oscillations effectively as compared to that obtained without TCPS for a wide range of plant parameter changes, area load demands and disturbances even in the presence of system nonlinearities.

**Keywords**—LFC, TCPS, Deregulated Power System, Power System Control, PSO.

## 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. In the case that many IPPs which lack sufficient abilities of frequency control, but have been connected in any power systems. Furthermore, various kinds of apparatus with large capacity and fast power consumption such as testing plants for nuclear fusion, steel factories etc increase significantly. When these loads are connected in power systems, they may cause a serious problem of frequency oscillations. Due to the above

H. Shayeghi is with the Department of technical Eng., University of Mohaghegh Ardabili, Ardabil, Iran (corresponding author to provide phone: 98-551-2910; fax: 98-551-2904; e-mail: hshayeghi@gmail.com).

H.A. Shayanfar with the Center of Excellence for Power System Automation and Operation, Electrical Eng. Department, Iran University of Science and Technology, Tehran, Iran.

A. Jalili with the Electrical Engineering Department, Islamic Azad University, Ardabil Branch, Ardabil, Iran (e-mail: arefjalili@gmail.com).

discussion, it is very important to consider how the control services of system frequency should be implemented. Thus, solution and stabilization of Load Frequency Control (LFC) task in an interconnected power system becomes challenging when implemented in the further competitive environment. A new frequency stabilization service which emphasis not only efficiency, reliability and economics, but also, advanced and improved controls for satisfying the requirements of power system operation, is much in demand. The most common methods used to accomplish frequency control are generator governor response (primary frequency regulation) and LFC. The goal of LFC is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighboring control areas. From the mechanisms used to manage the provision this service in ancillary markets, the bilateral contracts or competitive offers stand out [1].

In recent years, the fast progress in the field of power electronics has opened new opportunities for the application of the FACTS devices as one of the most effective ways to improve power system operation controllability and power transfer limits [2-3]. This extra flexibility permits the independent adjustment of certain system variables such as power flows, which are not normally controllable. A Thyristor Controlled Phase Shifter (TCPS) is regarded as one of the versatile devices in the FACTS device family which is expected to be an effective apparatus for the tie-line power flow control of an interconnected power system. It is a device that injects a variable series voltage to affect the power flow by modifying the phase angle [4-5]. Thus, the TCPS is essentially an equipment to modulate active power flow in power systems and the its high speed makes the TCPS attractive to be used for improvement system operation and control. In this paper, a new control method using a TCPS to provide an active control facility for the solution of LFC problem in the deregulated power system is proposed.

In the analysis of an interconnected power system, some areas considered as the channels of disturbances. Literature survey shows that, in most of the works concerned with LFC problem [6-12] of interconnected power systems the supplementary controllers are designed to regulate the area control errors to zero effectively. However, the power frequency and the tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response [9]. On the other hand, tie-line power flow control by a TCPS installed in series with tie-line between two areas has the possibility to control the system frequency positively through interconnection. Thus, to suppress of the

transmission of disturbances an active power source with fast response such as a TCPS is expected to be the most effective countermeasure. The proposed TCPS can utilize the frequency control capabilities of other interconnected areas to stabilize the frequency oscillation of an area which lacks sufficient control capability. The proposed control will be a new ancillary service for the solution of LFC problem in the restructured power systems.

Also, literature survey shows sample applications of TCPS for the improvement of dynamic and transient stability of power systems [4-5, 14-17]. However, no attempt has been carried out for the solution of LFC problem in a deregulated power system considering TCPS. In view of the above, TCPS is used to demonstrate technical and economic feasibility of them in deregulated power system applications. The active power transmission requirement to damp the frequency oscillations caused by small load perturbations is much smaller. In such cases, the real power transfer takes place in a very short time. Thus, addition of a TCPS to the system significantly improves transients of frequency and tie-line power deviations against to small load disturbances.

Despite the potential of modern control techniques with different structure, PID type controller is still widely used for solution of the LFC problem [18-20]. 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. On the other hand, Shayeghi et al. [18] 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. The controller parameter tuning can often be done by trial and error or by using the conventional optimization technique. It is well known that the conventional method for tuning of PID controller parameters may be tedious and time consuming. In order to overcome this drawback, a particle swarm optimization (PSO) based algorithm is used for tuning of PID controller's parameters to improve optimization synthesis and LFC performance without and with considering TCPS under possible contracted scenario and area load changes. 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-linear, non-differentiability and high dimensionality [21-23]. In this study, the problem of robust PID controllers design with and without considering TCPS is formulated as an optimization problem based on a system performance index the integral of the time multiplied absolute value of the error (ITAE) which considers a multiple of operating conditions and PSO is used to solve this problem.

The proposed control strategy is tested on a three-area restructured power system. To damp out the oscillations due to load demands and instantaneous load perturbations as fast as possible, LFC including PSO based tuned PID (PSOPID)

controllers with considering two TCPS installed in series with system tie-lines is used. To illustrate effectiveness of the proposed method three scenarios of possible contracts under different operating conditions are simulated through some performance indices in the presence of large parametric uncertainties and system nonlinearities under various area load changes. The performance indices are chosen as the ITAE and figure of demerit (FD). The simulation results show that the proposed controller achieves good robust performance for a wide range of system parameters and area load disturbances changes even in the presence of generation rate constraints (GRC). Moreover, analysis of controller resulting show that with considering TCPS dynamical performances of system such as frequency oscillation and settling time significantly is improved due to any large load changes.

## II. TCPS MODEL

The TCPS is superior to the governor system in terms of high-speed performances. When a sudden load perturbation occurs in a power system, the TCPS quickly starts control to suppress the peak value of the transient frequency deviation. Subsequently, governor systems responsively compensate for the steady-state error of frequency deviation. Figure 1 shows the schematic diagram of a tie-line between a two-area interconnected power system. TCPS is placed near area *i*. Although, there are a variety of TCPS configurations, their basic characteristics for power flow control are the same. Thus, here, the mathematical model of a TCPS for stabilization of frequency oscillations is derived from the power flow control characteristics of The TCPS.

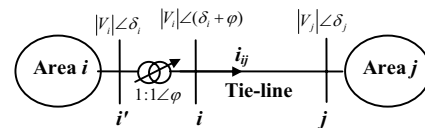


Fig. 1. Interconnected two-area system with TCPS in series with tie-line.

In Fig. 1, the current  $i_{ij}$  can be expressed as

$$i_{ij} = \frac{|V_i| \angle(\delta_i + \varphi) - |V_j| \angle \delta_j}{jX_{ij}} \quad (1)$$

Where,  $X_{ij}$  is the tie-line reactance;  $V_i$  and  $V_j$  are the terminal bus voltages. The active and reactive power flows at bus *i* are:

$$P_{ij} + jQ_{ij} = V_i I_{ij}^* \quad (2)$$

Where,  $I_{ij}^*$  is the complex conjugate of  $I_{ij}$ . Substituting Eq. (1) into Eq. (2) yields

$$P_{ij} - jQ_{ij} = |V_i| \angle(\delta_i + \varphi) \left( \frac{|V_i| \angle(\delta_i + \varphi) - |V_j| \angle \delta_j}{jX_{ij}} \right) \quad (3)$$

As a result, the relation in the real part of Eq. (3) gives

$$P_{ij} = \frac{|V_i| |V_j|}{X_{ij}} \sin(\delta_i - \delta_j + \varphi) \quad (4)$$

Here, it is assumed that  $V_i$  and  $V_j$  are constant. By linearizing this equation about an operating point, we have:

$$\Delta P_{ij} = \frac{|V_i||V_j|}{X_{ij}} \cos(\delta_i^0 - \delta_j^0 + \varphi^0) \sin(\Delta\delta_i - \Delta\delta_j + \Delta\varphi) \quad (5)$$

Where, superscript 0 denotes the value at operating point. But,  $(\Delta\delta_i - \Delta\delta_j + \Delta\varphi)$  is very small and hence,  $\sin(\Delta\delta_i - \Delta\delta_j + \Delta\varphi) \approx \Delta\delta_i - \Delta\delta_j + \Delta\varphi$ . Also, let  $T_{ij} = |V_i||V_j| \cos(\delta_i^0 - \delta_j^0 + \varphi^0) / X_{ij}$ .

Thus, Eq. (5) can be written as

$$\Delta P_{ij} = T_{ij} (\Delta\delta_i - \Delta\delta_j + \Delta\varphi) \quad (6)$$

We also known that  $\Delta\delta_i = \int \Delta\omega_i dt$  and  $\Delta\delta_j = \int \Delta\omega_j dt$ . Thus, from Eq. (6) we have:

$$\Delta P_{ij} = T_{ij} (\int \Delta\omega_i dt - \int \Delta\omega_j dt) + T_{ij} \Delta\varphi \quad (7)$$

Tacking the Laplace transform of Eq. (7), it can be written as

$$\Delta P_{ij} = \frac{T_{ij}}{s} (\Delta\omega_i(s) - \Delta\omega_j(s)) + T_{ij} \Delta\varphi(s) \quad (8)$$

From Eq. (8), it can be seen that the tie-line power flow can be controlled by controlling the phase shifter angle  $\Delta\varphi$ . The phase shifter angle can be described as follows:

$$\Delta\varphi(s) = \frac{K_{TCPS}}{1 + sT_{TCPS}} U_{TCPS}(s) \quad (9)$$

Where,  $K_{TCPS}$  and  $T_{TCPS}$  are the gain and time constants of TCPS. In this study, the input signal to the TCPS control logic is considered the frequency deviation of area  $i$  ( $\Delta\omega_i$ ). Thus, the tie-line power flow perturbation becomes

$$\Delta P_{ij} = \frac{T_{ij}}{s} (\Delta\omega_i(s) - \Delta\omega_j(s)) + T_{ij} \frac{K_{TCPS}}{1 + sT_{TCPS}} \Delta\omega_i(s) \quad (10)$$

But, in the deregulated power systems the actual tie-line power flow also includes the demand from DISCOs in one area to GENCOs in another areas (see Eq. (15) for more details).

### III. GENERALIZED LFC MODEL

In the deregulated power systems, the vertically Integrated Utility (VIU) structure, which supplies power to the customers at regulated rates no longer exists, however, the common LFC objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area still remain. Generalized dynamical model for the LFC scheme has been developed in our pervious paper [24] based on the possible contracts in the deregulated environment. 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 are can be various combinations of possible contract scenarios between DISCOs and GENCOs. The concept of an 'Augmented Generation Participation Matrix' (AGPM) is introduced to express these possible contracts in the generalized model. The rows and columns of AGPM matrix is equal with total number of GENCOs and DISCOs in the overall power system, respectively. The

AGPM structure for a large scale power system with  $N$  control area is given by:

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

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  $i, j = 1, \dots, N$  and

$$s_i = \sum_{k=1}^{i-1} n_k, z_j = \sum_{k=1}^{j-1} m_k, \quad \& \quad s_1 = z_1 = 0$$

In the above,  $n_i$  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 contracts. The sum of all entries in each column of AGPM is unity.

Block diagram of a generalized LFC scheme for control area  $i$  in a deregulated power system with considering TCPS is shown in Fig. 2. The nomenclature used is given in Appendix A. The Dashed dot-lines show the connections between each area with the rest of the system and the demand signals based on the possible contracts. These new information signals are considered as disturbance channels for the decentralized LFC design. 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 [24]:

$$d_i = \Delta P_{Loc,j} + \Delta P_{di}, \Delta P_{Loc,j} = \sum_{j=1}^{m_i} \Delta P_{Lj-i}, \Delta P_{di} = \sum_{j=1}^{m_i} \Delta P_{ULj-i} \quad (12)$$

$$\eta_i = \sum_{j=1, j \neq i}^N T_{ij} \Delta f_j \quad (13)$$

$$\zeta_i = \Delta P_{ie,i,sch} \sum_{k=1 \& k \neq i}^N \Delta P_{ie,ik,sch} \quad (14)$$

$$\Delta P_{ie,ik,sch} = \sum_{j=1}^{n_i} \sum_{l=1}^{m_k} apf_{(s_i+j)(z_k+l)} \Delta P_{L(z_k+l)-k} - \sum_{l=1}^{n_i} \sum_{j=1}^{m_k} apf_{(s_k+l)(z_i+j)} \Delta P_{L(z_i+j)-l} \quad (15)$$

$$\rho_i = [\rho_{i1} \quad \cdots \quad \rho_{ki} \quad \cdots \quad \rho_{nj}] \quad (16)$$

$$\rho_{ki} = \sum_{j=1}^{n_i} [\sum_{l=1}^{m_j} gpf_{(s_i+k)(z_j+l)} \Delta P_{Ll-j}] \Delta P_{m,k-i} = \rho_{ki} + apf_{ki} \Delta P_{di}, \quad k = 1, 2, \dots, n_i \quad (17)$$

$\Delta P_{m,ki}$  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.

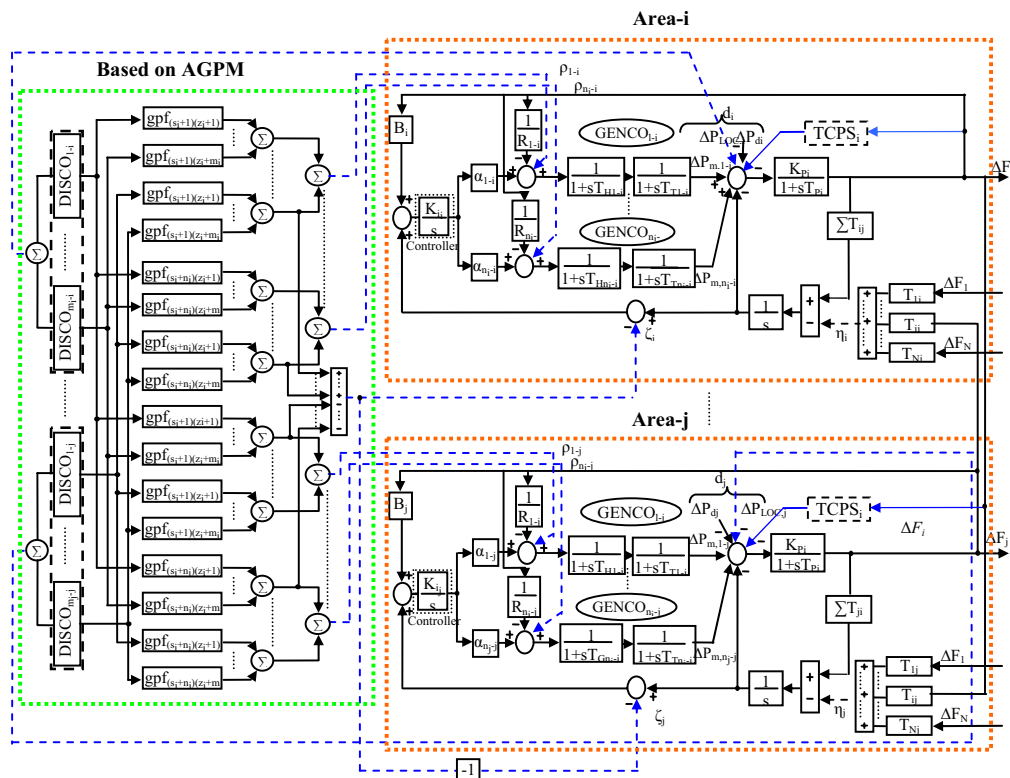


Fig. 2. The generalized LFC scheme in the restructured system including TCPS in series with tie- line between area  $i$  and  $j$ .

#### IV. PSO TECHNIQUE AND PSO-BASED PID CONTROLLER DESIGN

This section gives a brief overview of PSO technique [21]. 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 [21]. 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. In fact, the fundamental principles of swarm intelligence are adaptability, diverse response, proximity, quality, and stability. 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 [21-22]. As it is reported in [23-24], 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-linear, 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. It starts with a population of random solutions “particles” in a D-dimension space. The  $i$ th particle is represented by  $X_i = (x_{i1}, x_{i2}, \dots, x_{iD})$ . 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  $P_i = (p_{i1}, p_{i2}, \dots, p_{iD})$ . 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 Eq. (18). The velocity of particle  $i$  is represented as  $V_i = (v_{i1}, v_{i2}, \dots, v_{iD})$ . 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 Eq. (19) [21].

$$v_{id} = w \times v_{id} + c_1 \times rand() \times (P_{id} - x_{id}) + c_2 \times rand() \times (P_{gd} - x_{id}) \quad (18)$$

$$x_{id} = x_{id} + cv_{id} \quad (19)$$

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 [22]. 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”.

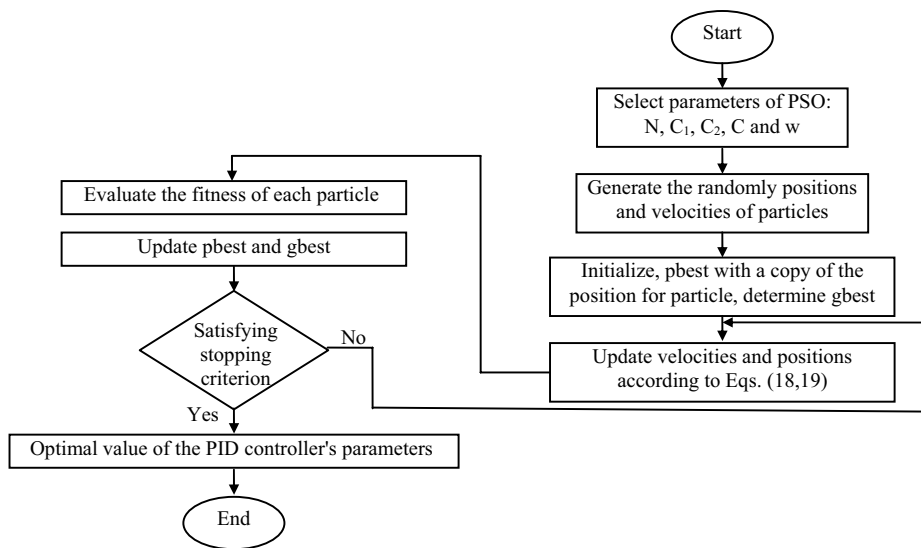


Fig. 3. Flowchart of the proposed PSO technique.

### 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. 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 known that the conventional methods to tune PID controller parameters 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 optimal tune of PID controllers parameters 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 (Fig. 2).

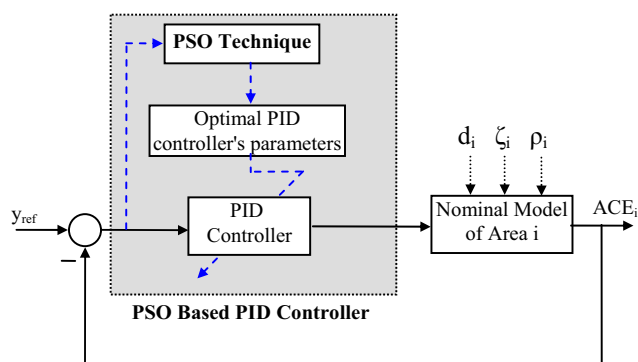


Fig. 4. The proposed PSO based PID controller structure.

By taking  $ACE_i$  as the system output, the control vector for PID controller is given by

$$u_i = K_{p_i} ACE_i + K_{i_i} \int ACE_i dt + K_{d_i} \dot{ACE}_i \quad (20)$$

The gains  $K_{P_i}$ ,  $K_{I_i}$  and  $K_{D_i}$  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. 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 [24]. For our optimization problem, the following objective function based on the system performance index of the: ITAE is used:

$$J = \left( \sum_{j=1}^{NP} RME_j \right) / NP \quad (21)$$

Where,

$$RME_i = \sqrt{\sum_{j=1}^N (ITAE_i) / N} \quad , \quad ITAE_i = 100 \int_0^{t_{sim}} |ACE_i| dt \cdot$$

$NP$  and  $N$  is the total number of operating conditions and area control in power systems, respectively. 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 :

$$\begin{aligned} K_{P_i}^{\min} &\leq K_{P_i} \leq K_{P_i}^{\max} \\ K_{I_i}^{\min} &\leq K_{I_i} \leq K_{I_i}^{\max} \\ K_{D_i}^{\min} &\leq K_{D_i} \leq K_{D_i}^{\max} \end{aligned} \quad (22)$$

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 PID controller parameters ( $K_{P_i}$ ,  $K_{I_i}$  and  $K_{D_i}$  for  $i=1, 2, \dots, N$ ) where,  $N$  is the number of control areas.

## V. CASE STUDY

A three-area restructured power system considering TCPS in series with tie-lines, shown in Fig. 5 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. The power system parameters are the same as [20, 24] and given in Tables 1 and 2. TCPS data are given in Appendix B.

In the study, the linear model of turbine  $\Delta PV_{ki} / \Delta PT_{ki}$  in Fig. 2 is replaced by a nonlinear model of Fig. 6 (with  $\pm 0.05$  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 Ref. [25-26] indicated that GRC would influence the dynamic responses of the system significantly and lead to larger overshoot and longer settling time. Moreover, affirmative effect of TCPS on LFC problem is also taken into account.

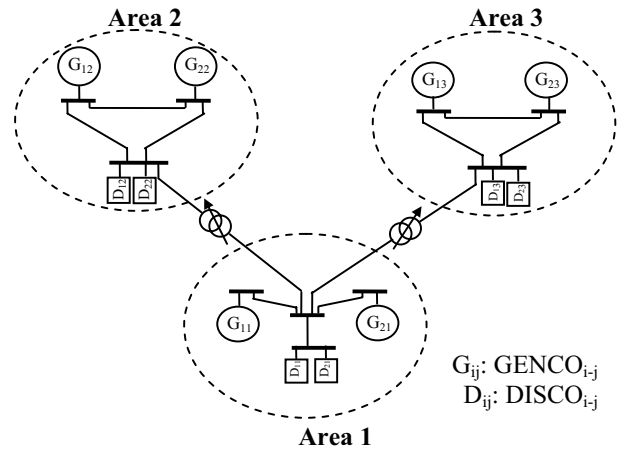


Fig. 5. A three-area restructured power system.

TABLE I  
CONTROL AREA PARAMETERS

Parameter	Area -1	Area -2	Area -3
$K_P$ (Hz/pu)	120	72	91
$T_P$ (sec)	20	14.3	10.6
$B$ (pu/Hz)	0.8675	0.785	0.87
$T_{ij}$ (pu/Hz)	$T_{12} = T_{13} = T_{23} = 0.545$		

TABLE II  
GENCOs PARAMETER

MVA <sub>base</sub> (1000MW) Parameter	GENCOs ( $k$ in area $i$ )					
	1-1	2-1	1-2	2-2	1-3	2-3
Rate (MW)	1000	800	1100	900	1000	1020
$T_T$ (sec)	0.36	0.42	0.44	0.4	0.36	0.4
$T_H$ (sec)	0.06	0.07	0.06	0.08	0.07	0.08
$R$ (Hz/pu)	2.4	3.3	2.5	2.4	2.4	3.3
$\alpha$	0.5	0.5	0.5	0.5	0.5	0.5

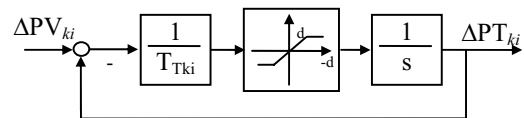


Fig. 6. Nonlinear turbine model with GRC.

Simulation results and eigenvalue analysis show that the open loop system performance is affected more significantly by changing in the  $K_{P_i}$ ,  $T_{P_i}$ ,  $B_i$  and  $T_{ij}$  than changes of other parameters [25]. 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 these parameters. 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 25% uncertainty for the  $K_{P_i}$ ,  $T_{P_i}$ ,  $B_i$  and  $T_{ij}$  in each control area.

2. Minimizing the effects of new introduced disturbances on the output signals according to the possible contracts.
3. Getting zero steady state error and good tracking for load demands and disturbances.
4. Maintaining acceptable overshoot and settling time on the frequency deviation signal in each control area.

In the proposed method, we must tune the PID controller parameters optimally in each control area on the given power system to achieve the above control objectives. The optimization of PID controller parameters is carried out by evaluating the objective cost function as given in Eq. (21), which considers a multiple of operating conditions. Consider that all DISCOs contract with available GENCOs for power as per the following AGPM. All GENCOs participate in the LFC task.

$$AGPM = \begin{bmatrix} 0.25 & 0 & 0.25 & 0 & 0.5 & 0 \\ 0.5 & 0.25 & 0 & 0.25 & 0 & 0 \\ 0 & 0.5 & 0.25 & 0 & 0 & 0 \\ 0.25 & 0 & 0.5 & 0.75 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

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, 2 and 3 demands 0.07, 0.04 and 0.02 puMW of excess power, respectively, which is reflected as a local load perturbation of the areas. Under this contracted scenario, the operating conditions are obtained with variation system of  $K_{pis}$ ,  $T_{pi}$ ,  $B_i$  and  $T_{ij}$  from -25% to 25% of the nominal values by 5% step (i.e. 11 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 25, 9, 300, 2, 2 and 1, respectively. Also, the inertia weight,  $w$ , is linearly decreasing from 0.9 to 0.4. It should be noted that PSO algorithm is run several times and then optimal set of controller parameters is selected. Results of controller parameter set values without and with considering TCPS are listed in Table 3. Also, Fig. 7 shows the minimum fitness value evaluating process with considering TCPS.

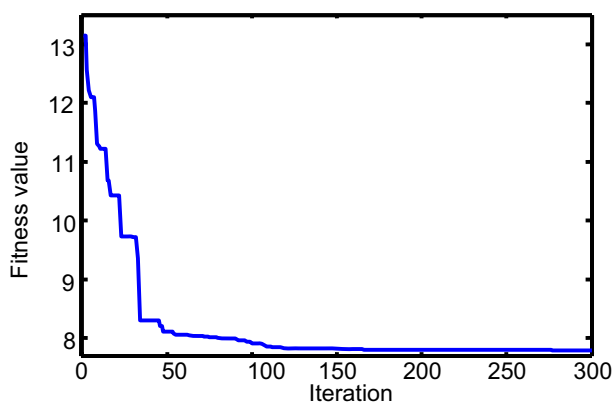


Fig. 7. Minimum fitness value convergence with considering TCPS.

TABLE III  
 OPTIMAL PID CONTROLLER PARAMETERS USING PSO

AREA	With TCPS			Without TCPS		
	$K_P$	$K_I$	$K_D$	$K_P$	$K_I$	$K_D$
Area 1	1.0	0.076	0.418	0.01	0.039	0.999
Area 2	0.999	0.05	0.967	0.203	0.03	1.0
Area 3	0.999	0.038	0.630	0.996	0.03	1.0

## X. SIMULATION RESULT

The proposed PSO based tuned PID controller is applied for each control area of the restructured power system without and with considering TCPS. To illustrate robustness of the proposed control strategy against parametric uncertainties and contract variations, simulations are carried out for two scenarios of possible contracts under various operating conditions and large load demands in the presence of GRC.

### 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 another areas. It is assumed that a large step load 0.1 pu MW is demanded by all DISCOs. Based on the given AGPM all GENCOs participate in the LFC task. The one GENCO in area 2 and GENCO 2 in area 3 only participate for performing the LFC in their areas, while other GENCOs track the load demand in their areas and/or others. Power system responses with 25% decrease in uncertain parameters  $K_{pis}$ ,  $T_{pi}$ ,  $B_i$  and  $T_{ij}$  are depicted in Fig. 8 without and with TCPS. Using the proposed method and considering TCPS, the frequency deviation of all areas is quickly driven back to zero and the tie-line power flows properly converges to the specified values of Eq. (15) in the steady state. i.e.:  $\Delta P_{tie, 12, sch} = 0$  and  $\Delta P_{tie, 13, sch} = 0.025$  pu MW.

### B. Scenario 2

In this case, it may happen that a DISCO violates a contract by demanding more power than that specified in the contract. This excess power must be reflected as a local load of the area (un-contracted load) but not as the contracted demand. It is assumed that in addition to specified contracted load demands and 25% increase in uncertain parameters, the one DISCO from areas 1, 2 and DISCO 2 in area 3 demands 0.07, 0.04 and 0.02 puMW as a large un-contracted load, respectively. Using the Eq. (1) the total local load in areas is computed as:

$$\begin{aligned} d_1 &= 0.1 + 0.1 + 0.07 = 0.27, \\ d_2 &= 0.1 + 0.1 + 0.04 = 0.24, \\ d_3 &= 0.1 + 0.1 + 0.02 = 0.22 \text{ pu MW} \end{aligned}$$

The purpose of this scenario is to test the effectiveness of the proposed controller against uncertainties and large load disturbances in the presence of GRC. The power system responses are shown in Fig. 9 without and with TCPS. Using the proposed method and considering TCPS, the frequency oscillation is quickly damped and the tie-line power flows properly converge to the specified value of Eq. (15) in the steady state. As AGPM is the same as in scenario 1 and the un-

contracted load of areas is taken up by the GENCOs in the same areas, the tie-line power is the same as in scenario 1 in the steady state. The un-contracted load of DISCOs in area

1 and 3 is taken up by the GENCOs in these areas according to ACE participation factors in the steady state. .

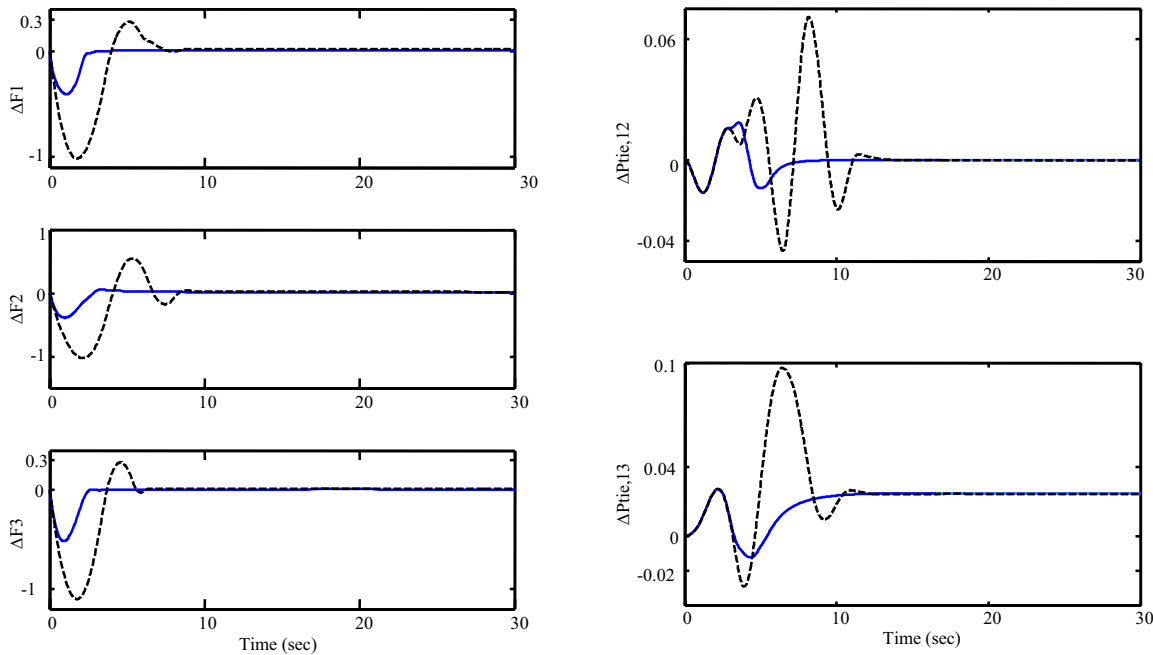


Fig. 8. Deviation of frequency and tie lines power flows; Solid (with TCPS) and Dashed (without TCPS).

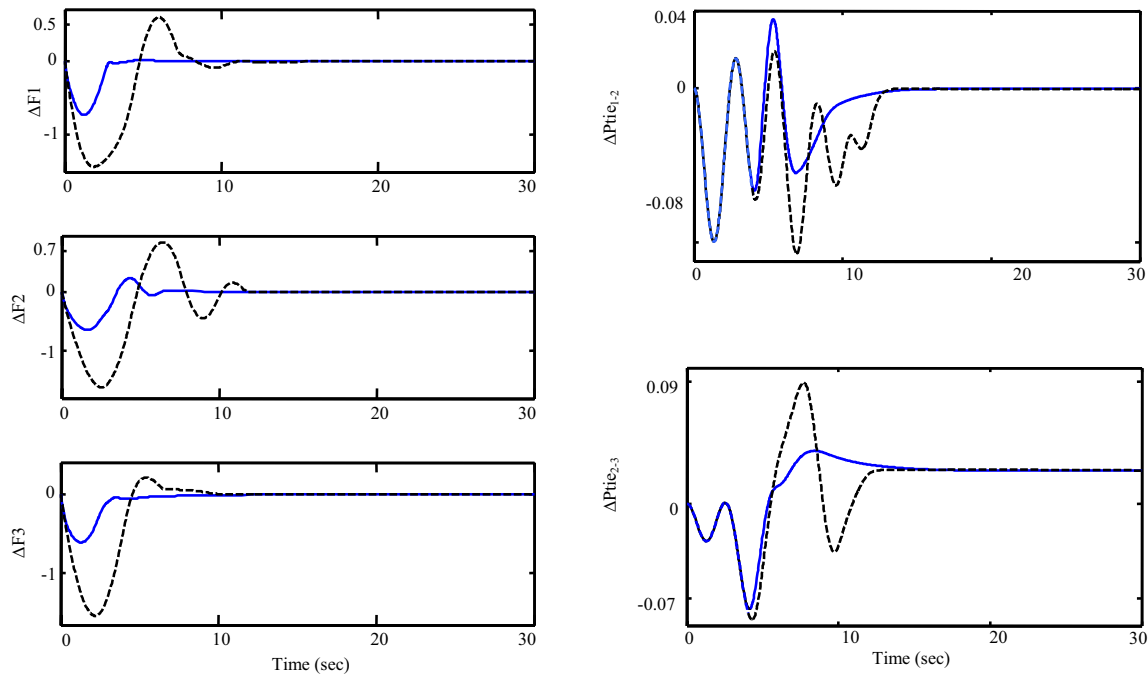


Fig. 9. Deviation of frequency and tile lines power flows; Solid (with TCPS) and Dashed (without TCPS).

The simulation results in the above scenarios represent the positive effect of TCPS on the improvement of the oscillation of frequency due to any load demands and disturbances. It can be seen that the proposed control strategy with considering TCPS can be ensure the robust performance such for possible contracted scenarios under modeling uncertainties in the presence of GRC.

## XI. CONCLUSIONS

A robust load frequency controller with considering TCPS in the competitive electricity environment using the generalized LFC scheme model is proposed. To improve the overall dynamical performance in the presences of plant parameters changes and system nonlinearities the PID controller based



LFC problem has been formulated as an optimization problem based on a system performance index ITAE for multiple of operating conditions and solved by PSO technique to obtain optimal parameters. The PSO algorithm proposed in this paper is easy to implement without additional computational complexity. Thereby experiments this algorithm gives quite promising results. The ability to jump out the local optima, the convergence precision and speed are remarkably enhanced and thus the high precision and efficiency are achieved. Moreover, all PID controllers are designed simultaneously, taking into consideration the interaction among them. Also, they have simply and decentralized nature since only local measurements are employed as the controller inputs. This makes the proposed PSO based PID controller easy to implement and tune.

The effectiveness of the proposed strategy by TCPS was tested on a three-area power system under possible contracts with various load changes in the presence of modeling uncertainties and GRC. The simulation results show that the proposed method is superior and the dynamic performance of system such as frequency and tie-lines power flows oscillations is significantly suppressed by controlling the phase angle of TCPS for a wide range of plant parameter and area load changes. Also,

#### APPENDIX A: NOMENCLATURE

$F$	area frequency
$P_{Tie}$	net tie-line power flow
$P_T$	turbine power
$P_V$	governor valve position
$P_C$	governor set point
$ACE$	area control error
$apf$	ACE participation factor
$\Delta$	deviation from nominal value
$K_P$	subsystem equivalent gain
$T_P$	subsystem equivalent time constant
$T_T$	turbine time constant
$T_H$	governor time constant
$R$	droop characteristic
$B$	frequency bias
$T_{ij}$	tie line synchronizing coefficient between area $i$ and $j$
$P_d$	area load disturbance
$P_{Lj-i}$	contracted demand of Disco $j$ in area $i$
$P_{ULj-i}$	un-contracted demand of Disco $j$ in area $i$
$P_{m,j-i}$	power generation of GENCO $j$ in area $i$
$P_{Loc}$	total local demand
$\eta$	area interface
$\zeta$	scheduled power tie line power flow deviation

#### APPENDIX B: TCPS DATA

$T_{TCPS}=0.1$  s;  $K_{TCPS}=1.5$  rad/Hz;  $\varphi_{max}=10^\circ$ ;  $\varphi_{min}=-10^\circ$ .

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