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Particle Swarm Optimization Based Interconnected Hydro-Thermal AGC System Considering GRC and TCPS

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***Abstract*—**This paper represents performance of particle swarm optimisation (PSO) algorithm based integral (I) controller and proportional-integral controller (PI) for interconnected hydro-thermal automatic generation control (AGC) with generation rate constraint (GRC) and Thyristor controlled phase shifter (TCPS) in series with tie line. The control strategy of TCPS provides active control of system frequency. Conventional objective function integral square error (ISE) and another objective function considering square of derivative of change in frequencies of both areas and change in tie line power are considered. The aim of designing the objective function is to suppress oscillation in frequency deviations and change in tie line power oscillation. The controller parameters are searched by PSO algorithm by minimising the objective functions. The dynamic performance of the controllers I and PI, for both the objective functions, are compared with conventionally optimized I controller.

***Keywords*—**Automatic generation control (AGC), Generation rate constraint (GRC), Thyristor control phase shifter (TCPS), Particle swarm optimization (PSO).

I. Introduction

AREAS or regions of coherent generators groups always exist in large-scale power systems. These various areas are interconnected through tie lines. The tie lines are used to exchange energy between areas and to provide inter-area support in case of abnormal conditions. Any change in load in the system with high capacity and close interconnection among generation areas, large tie-line power fluctuations and frequency oscillations occur. So load frequency control is a very important issue in power system operation and control for supplying sufficient and reliable power with good quality. The main goal of load frequency control of a power system is to maintain the frequency of each area and tie line power flow within the specified tolerance. Generation and distribution of electric energy with good reliability and quality in power system operation and control is achieved by Automatic Generation Control (AGC). The objective of AGC is to minimize the transient deviations in frequency deviation and tie line power interchange and to ensure to reach their steady state values.

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Considerable work [1]–[6] has been carried out for the AGC of interconnected power systems as reported in the literature. Various controllers are designed to minimize frequency and tie line power deviations based on classical control theory and modern control theory [7]-[9]. Different established classical controllers are integral, proportional-integral and proportional-integral-derivative types. To overcome the drawbacks of classical controllers and to solve the load frequency control problem effectively, new artificial intelligence-based approaches have been proposed recently to design a controller. Considerable research work attempting to propose better AGC systems based on optimal control theory [10], [11], neural network [12], [13], and fuzzy system theory [14], [15].

Recently, the concept of utilizing power electronics devices for power system control has been accepted as Flexible AC Transmission Systems (FACTS). FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system. Among of them, a solid-state phase shifter is expected as an effective apparatus with a high ability of power flow control. A Thyristor Controlled Phase Shifter (TCPS) is expected to be an effective apparatus for the tie-line power flow control of an interconnected power system [16]. TCPS installed in series with the tie-line in between two areas of an interconnected power system, so as to positively control the system frequency and considered as a new ancillary service. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; damping the power oscillation; and enhancing transient stability. In the present study, the design problem of a TCPS-based controller is considered to compare the performance of PSO optimization algorithm.

A traditional and easy way of trying to improve the PSO method is by manually changing its behavioral meters. Various studies have been reported in the literature, regarding the use of velocity boundaries for the movement of the particles and the choice of the so-called inertia weight which is believed to influence the degree of exploration versus exploitation of the PSO particles. A comprehensive survey of such studies is on everything from the selection of behavioral parameters to the neighborhood topology determining how particles influence each other, as well as other algorithmic details [19], [20].

Although new methods are proposed for tuning the PI controller, their usage is limited due to complexities arising at the time of implementation. Since, Particle Swarm Optimization (PSO) algorithm is an optimization method that finds the best parameters for controller in the uncertainty area of control. It has been used in almost all sectors of industry and science. In view of the above, an attempt has been made in this paper for the optimal design of PSO based I/PI controller for AGC in two area interconnected power system. The design problem of the proposed controller is formulated as an optimization problem and PSO is employed to search for optimal controller parameters. By minimizing the two objective functions dynamic performance of the system is improved. First objective function is conventional ISE and second is proposed objective functions, in which the square of derivative of frequency deviations and tie line power deviations are involved. Further, the superiority of the proposed design approach is illustrated by comparing the proposed approach with published paper [16] for the AGC system. Simulation results revels that the proposed controller with proposed objective function suppresses the power system oscillations and improved performance criteria such as such as integral of square error (ISE), integral, Integral of Time multiplied by Square Error (ITSE), Integral of Time multiplied by Absolute Error (ITAE), Integral of Absolute Error (IAE).

II. System Modeling

The system under investigation consists of two area interconnected power system of hydro-thermal plant as shown in Fig. 1. The system is widely used in literature is for the design and analysis of automatic load frequency control of interconnected areas.

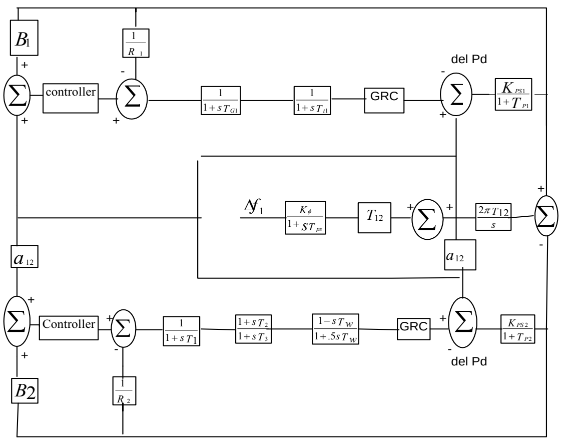

Fig. 1 Two area interconnected hydro-thermal system considering TCPS in series with tie line

In Fig. 1, B_1 and B_2 are the frequency bias parameters; ACE_1 and ACE_2 are area control errors; u_1 and u_2 are the control outputs form the controller; R_1 and R_2 are the governor speed regulation parameters in pu Hz; T_{G1} and T_{G2} are the speed governor time constants in sec; ΔP_{G1} and ΔP_{G2} are the change in governor valve positions (pu); T_{T1} and T_{T2} are the turbine time constant in sec; ΔP_{T1} and ΔP_{T2} are the change in turbine output powers; ΔP_{D1} and ΔP_{D2} are the load demand changes; ΔP_{tie} is the incremental change in tie line power (p.u); K_{P1} and K_{P2} are the power system gains; T_{P1} and T_{P2} are the power system time constant in sec; T_{12} is the synchronizing coefficient and Δf_1 and Δf_2 are the system frequency deviations in Hz,. The relevant parameters are given in appendix.

Linearized Model of TCPS

The schematic of an interconnected two-area hydro–hydro system considering a TCPS in series with the tie-line is shown in Fig. 1. Resistance of the tie-line is neglected. Without TCPS, the incremental tie-line power flow from Area 1 to Area 2 can be expressed as

$$\Delta P_{tie12}{}^{\circ} = \frac{2\pi T_{12}}{s}[\Delta f_1(s) - \Delta f_2(s)] \tag{1}$$

When a TCPS is placed in series with the tie-line, the current the current flowing from Area 1 to Area 2 can be written as

$$I_{12} = \frac{|V_1| < (\delta_1 + \varphi) - V_2 < \delta_2}{jX_{12}} \tag{2}$$

$$P_{tie12} - jQ_{tie12} = V_1^* I_{12} |V_1| \angle \delta_1 + \varphi \left[\frac{V_1 \angle(\delta_1 + \varphi) - V_2 \angle \delta_2}{jX_{12}}\right] \tag{3}$$

Separating the real parts of (3), we get

$$P_{tie12} = \frac{|V_1|\,|V_2|}{X_{12}} \sin(\delta_1 - \delta_2 + \varphi) \tag{4}$$

In (4), perturbing δ_1,δ_2 and φ from their nominal values δ_1°, δ_2° and φ° respectively, we get

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^o - \delta_2^o + \phi^o) \sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\phi) \tag{5}$$

But$(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi)$ is very small and hence

$$\sin(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \approx (\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi).$$

Therefore

$$\Delta P_{tie12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^o - \delta_2^o + \phi^o)(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \tag{6}$$

Let

$$T_{12} = \frac{|V_1|\,|V_2|}{X_{12}} \cos(\delta_1^{\circ} - \delta_2^{\circ} + \varphi^{\circ}) \tag{7}$$

Thus (6) reduces to

$$\Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2 + \Delta\varphi) \tag{8}$$

Therefore

$$\Delta P_{tie12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) + T_{12}\Delta\varphi \tag{9}$$

We know that

$$\Delta\delta_1 = 2\pi \int \Delta f_1\, dt \text{ and } \Delta\delta_2 = 2\pi \int \Delta f_2\, dt \tag{10}$$

From (9) and (10), we get

$$\Delta P_{tie12} = 2\Pi T_{12}\left(\int \Delta f_1 dt - \int \Delta f_2 dt\right) + T_{12}\Delta\phi \quad (11)$$

$$\Delta P_{tie12}(s) = \frac{2\Pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) + T_{12}\Delta\phi(s) \quad (12)$$

As per (12), tie-line power flow can be controlled by controlling the phase shifter angle $\Delta\varphi$. The phase shifter angle $\Delta\varphi$ (s) can be represented as [12]-[14]:

$$\Delta\varphi(s) = \frac{K_\varphi}{1+sT_p}\Delta Error_1(s) \quad (13)$$

where K_φ and TPS are the gain and time constants of the TCPS.

$$\Delta Error_1 = \Delta f_1 \quad (14)$$

Thus, (13) can be rewritten as

$$\Delta P_{tie12}(s) = \frac{2\Pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) + T_{12}\frac{k_\phi}{1+sT_p} \quad (15)$$

The AGC system considered is two interconnected hydro-thermal system, where area1 comprises reheat thermal system and area2 comprises a hydro system. Typical generation rate constraints of 10%/min. for thermal area and 4.5%/sec. (270%/min.) for raising generation and 6%/sec. (360%/min.) for lowering generation in the hydro area are considered as in the IEEE Committee Report on power plant response [17], [18]. The detailed of transfer function block diagram model along with TCPS in series with tie line power is given in Fig. 1.

III. The Proposed Approach

An integral (I) control has the effect of eliminating the steady-state error, but it may make the transient response worse. A proportional controller has the effect of reducing the rise time, but never eliminates the steady-state error. Proportional integral (PI) controllers are the most often type used today in industry. In view to the above, both I and PI controller are considered in the present paper. For I and PI controller different controllers parameters are considered for both areas. For PI controller, parameters are to be determined KP_1, KP_2 and KI_1, KI_2

For I controller, parameters to be determined are KI_1 and KI_2.

The error inputs to the controllers are the respective area control errors (ACE) are given by:

$$e_1(t) = ACE_1 = B_1\Delta f_1 + \Delta P_{Tie} \quad (17)$$

$$e_2(t) = ACE_2 = B_2\Delta f_2 - \Delta P_{Tie} \quad (18)$$

The control inputs of the power system u_1 and u_2 are the outputs of the controllers. With I structure the control inputs are obtained as:

$$u_1 = K_{I1}\int ACE_1 \quad (19)$$

$$u_2 = K_{I2}\int ACE_2 \quad (20)$$

The control inputs of the power system u_1 and u_2 with PI structure are obtained as:

$$u_1 = K_{P1}ACE_1 + K_{I1}\int ACE_1 \quad (21)$$

$$u_2 = K_{P2}ACE_2 + K_{I2}\int ACE_2 \quad (22)$$

In the design of I/PI controller, the objective function is first defined based on the desired specifications and constraints. The design of objective function to tune the controller is generally based on a figures and tables performance index that considers the entire closed loop response. In control design four types of errors are considered ITAE, ISE, ITSE and IAE. The object of obtaining the optimal solution of controller gain is considered as optimization problem, and PSO algorithm is used to tune the gains of controllers. In order to convergence to optimal solution, two different objective functions are considered. First objective function considered is conventional ISE given in (23). Second objective function is derived as the rate changes of frequency deviations of control areas and change in tie line power with time given in (24).

$$J_1 = ISE = \int_0^{t_{sim}} (\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{Tie})^2 \cdot dt \quad (23)$$

$$J_2 = \int_0^{t_{sim}} t\left(\frac{d\Delta f_1}{dt}\right)^2 + \left(\frac{d\Delta f_2}{dt}\right)^2 + \left(\frac{d\Delta P_{Tie}}{dt}\right)^2 \cdot dt \quad (24)$$

where, Δf_1 and Δf_2 are the system frequency deviations; ΔP_{Tie} is the incremental change in tie line power; t_{sim} is the time range of simulation.

Minimize J

Subject to

$K_{P\min} \leq K_P \leq K_{P\max}$ *and* $K_{I\min} \leq K_I \leq K_{I\max}$

IV. Particle Swarm Optimization Algorithm

The PSO method is a member of wide category of Swarm Intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers. Further, each particle has a memory and hence it is capable of remembering the best position in the search space ever visited by it. The position corresponding to the best fitness is known as pbest and the overall best out of all the particles in the population is called gbest. The modified velocity and position of each particle can be calculated using the current velocity and the distance from the pbest j,g to gbestg as shown in the following formulas :

$$v_{f,g}^{(t+1)} = w * v_{j,g}^{(t)} + c_1 * r_1() * (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 * r_2() * (gbest_g - x_{j,g}^{(t)}) \quad (25)$$

$$x_{f,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad (26)$$

With j = 1, 2... n and g = 1,2...m
Where
n =number of particles in a group;
m = number of members in a particle;
t = number of iterations (generations);
$v_{j,g}^{(t)}$ = velocity of particle j at iteration t,
With $v_g^{\min} \le v_{j,g}^{(t)} \le v_g^{\max}$
c1, c2 = cognitive and social acceleration factors respectively;
r1, r2 = random numbers uniformly distributed in the range (0, 1);
$x_{j,g}^{(t)}$ = Current position of j at iteration t;
Pbest j = pbest of particle j;gbest = gbest of the group;

The j-th particle in the swarm is represented by a g-dimensional vector xj = (xj,1, xj,2, ……,xj,g) and its rate of position change (velocity) is denoted by another g-dimensional vector vj = (vj,1, vj,2, ……, vj,g). The best previous position of the j-th particle is represented as pbestj = (pbestj, 1, pbestj, 2… pbestj, g). The index of best particle among all of the particles in the group is represented by the gbestg.

In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters c1 & c2 determine the relative pull of pbest and gbest and the parameters r1 & r2 help in stochastically varying these pulls. In the above equations, superscripts denote the iteration number. The computational flow chart of PSO algorithm is shown in Fig. 2.

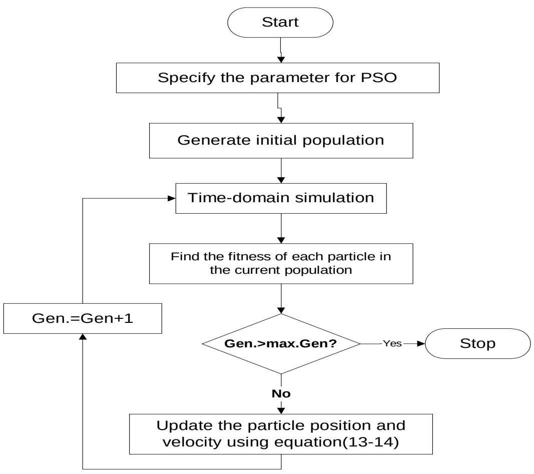

Fig. 2 Flowcharts of particle swarm optimization algorithm

V. Results and Discussion

The model of the system under study has been developed in MATLAB/SIMULINK environment and PSO program has been written (in .mfile). The developed model is simulated considering a 1% step load change in hydro area. The objective function is calculated in the .m file and used in the optimization algorithm. The process is repeated for each individual in the population.

In this paper the following PSO parameters are considered to verify the performance of the PSO optimized I /PI controller.

Population size: 50; ω =0.9;
c1=0.12; c2=0.12;Iteration: 30;

Simulations were conducted on MATLAB 7 environment. The optimization was repeated 20 times and the best final solution among the 20 runs is chosen as proposed controller parameters. The best final solutions obtained in the 20 runs are shown in Table I.

TABLE I
Tuned Controller Parameters for Different Objective Functions

Objective function/ controller parameters			J_1 (ISE)	J_2 (Proposed)
I controller	Integral gain	K_{I1}	0.0896	0.083
		K_{I2}	0.3492	0.3706
PI controller	Proportional gain	K_{P1}	0.6552	1.0083
		K_{P2}	0.7925	1.2913
	Integral gain	K_{I1}	0.1324	0.1540
		K_{I2}	0.1918	0.4453

A time domain simulations are performed for a step load change of 1% given in area1 at t=0. Frequency deviation of area1 and area 2 Vs time is plotted in Figs. 3 and 4 with ISE as objective function. As seen from the figure overshoot of PSO tuned PI controller is improved by 52.33% to conventional I controller for frequency deviation in area1 and area2. Settling time of both PSO tuned I and PI controllers are less compared to conventionally optimized I controller.

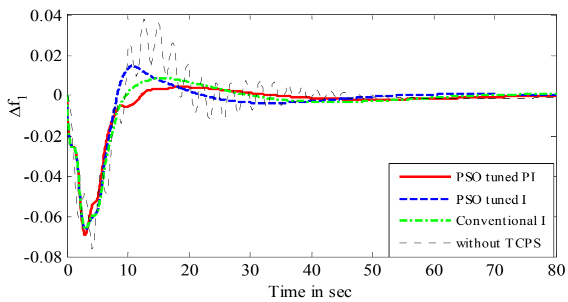

Fig. 3 Change in frequency of area-1 for 1 % load change in area-1 with ISE objective function

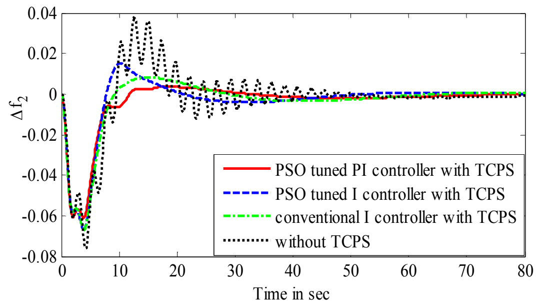

Fig. 4 Change in tie line power for 1 % load change in area-1 with ISE as objective function

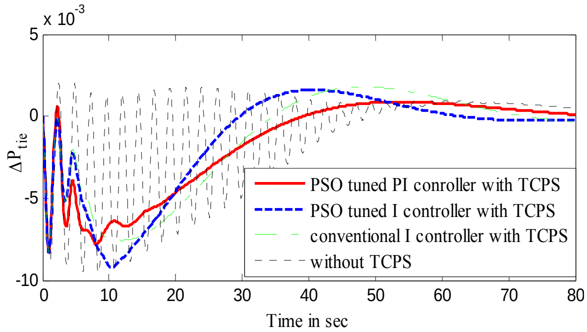

Fig. 5 Change in tie line power for 1 % load change in area-1 with ISE as objective function

Fig. 5 shows the change in tie line power deviation with time for without TCPS, with TCPS conventionally optimized I controller, PSO tuned I and PI controllers. It is observed from Fig. 5 overshoot of PSO tuned PI controller is improved by 51.36% compared tuned conventionally optimized I controller. Also PSO tuned PI and I controllers settled earlier than conventionally optimized I controller.

TABLE II
ERROR CRITERIA AND SETTLING TIMES WITH ISE AS OBJECTIVE FUNCTION J_1

Parameters		PSO optimized I controller		PSO optimized PI controller		Conventionally optimized I controller [16]
		Value	%Improved value	Value	%Improved value	
ISE		0.0349	1.13%	0 .0297	15.86%	0.0353
ITSE		0.1675	4.64%	0.1236	30.13%	0.1769
ITAE		9.9511	6.41%	7.9202	25.51%	10.632
T_S (sec)	Δf_1	17.8	22.27%	11	53.28%	22.9
	Δf_2	16.7	22.69%	10.9	50.0%	21.6
	ΔP_{tie}	19.5	11.36%	19.2	12.73%	22.0

Table II shows all the error values and settling times (5% of final value) when the controller parameters are optimized using ISE error criteria. To show the effectiveness of the proposed PSO method results are compared with a recently published classical technique for the same interconnected power system and for the same ISE objective function [16]. As seen from results for PSO tuned I/PI controllers, errors are reduced and also settling time for Δf_1, Δf_2 and ΔP_{Tie} are reduced, percentage improvement are also shown in Table-II. A large improvement is seen in case of PSO optimized PI controller.

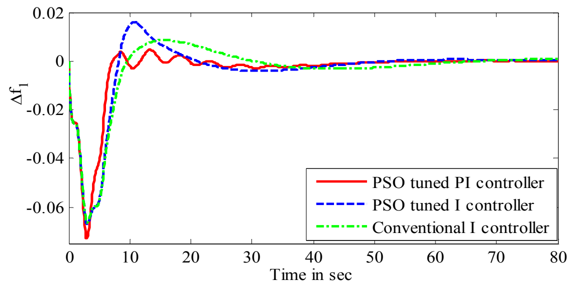

Fig. 6 Change in frequency of area-1 for 1 % change in area-1 with proposed objective function

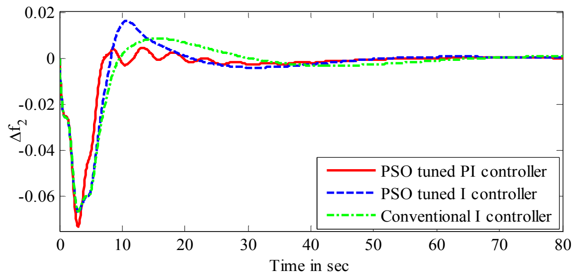

Fig. 7 Change in frequency of area-2 for 1 % change in area-1 with proposed objective function

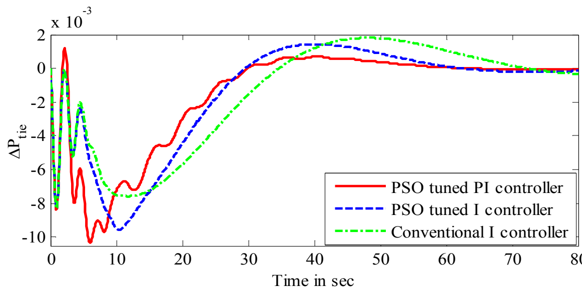

Fig. 8 Change in tie line power for 1 % load change in area-1 with proposed objective function

The results show that proposed approach achieves good dynamic performance than conventionally optimised I controller. To show the superiority of proposed approach, simulation results of frequency deviations of control areas and change in tie line power are provided in Figs. 6-8. As seen from Fig. 6, though the overshoot of PSO tuned I controller is higher value, but compared to settling time, it settles quickly as compared conventionally optimised I controller.PSO tuned PI controller has 46.51% improvement in overshoot for frequency deviation in area1 and area 2 from conventionally optimised I controller. Similarly Fig. 7 shows the frequency deviation of area 2 with time for PSO tuned PI/I controller and conventionally optimised I controller. Fig. 8 shows change in tie line power which depicts that overshoot of PSO tuned PI controller is improved by 33.33% from conventionally optimised I controller.

TABLE III
ERROR CRITERIA AND SETTLING TIMES WITH PROPOSED OBJECTIVE FUNCTION J_2

Parameters		PSO optimized I controller		PSO optimized PI controller		Conventionally optimized I controller [16]
		Value	%improved value	Value	%Improved value	
ISE		0.0352	0.28%	0.0279	20.96%	0.0353
ITSE		0.1694	4.24%	0.1078	39.06%	0.1769
ITAE		10.233	3.75%	7.0166	34.01%	10.6323
T_S (sec)	Δf_1	16.7	27.07%	6.9	69.87%	22.9
	Δf_2	15.7	25.76%	6.9	64.19%	21.6
	ΔP_{tie}	19.3	12.27%	15.6	29.09%	22

Table III shows the error criteria ISE, ITAE, IAE and settling time of Δf_1, Δf_2 and ΔP_{Tie} for proposed objective function and compared with conventionally optimised integral controller. As seen from the table settling time of PSO optimised PI controller is improved by 69.87%, 64.19% and 29.09% for Δf_1, Δf_2 and ΔP_{Tie} from conventionally optimized integral controller. Main purpose of designing the objective function is to reduce oscillations in power system, which is important issue in power system operation.

VI. CONCLUSION

In this paper interconnected hydro-thermal power system with TCPS in series with tie line power is considered. PI and I controllers are optimised with PSO algorithm for two different objective functions; ISE and proposed objective function ;to improve system response in terms of settling time. Conventional objective function ISE is used for comparison with the published paper reference [16]. Simulation results reveal that frequencies and tie-power oscillations following sudden load disturbance in either of the areas can be suppressed by considering TCPS in series with tie line. The results obtained conforms that the proposed control strategy optimized with new objective function achieves better dynamic performances than the standard objective functions. With proposed objective function settling time of Δf_1, Δf_2 and ΔP_{Tie} are improved for both integral and PI controllers, compared to the published result. It is observed that the proposed PSO optimised integral controller performs better than conventionally optimised integral controller and best performance is obtained with PSO optimised PI controller.

APPENDIX

All the notations carry the usual meanings

(a) System Data:

$P_{R1} = P_{R2}$ = 1200 MW, T_{P1}=T_{p2}=20 s,
K_{P1}= K_{P2} = 120 Hz/p.u. MW, T_t= 0.3 s, T_1= 41.6 s,
T_2 = 0.513 s,T_R = 5 s, T_W = 1 s, T_{12} = 0.0866 s,
T_G = 0.08 s, R_1= R_2= 2.4 Hz/p.u. MW,
B_1 = B_2= 0.4249 p.u. MW/Hz
D_1=D_2 =8.33× 10^{-3} p.u.MW/Hz,

(b) TCPS Data:

T_{ps} = 0.1 s, $K_\emptyset$ = 1.5 rad/Hz,$\emptyset_{max}$= 100, $\emptyset_{min}$= - 100

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