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Different Particle Swarm Optimization Techniques for Optimization of PID Controller Parameters in Interconnected Power System

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Abstract

In this article, different methods of acceleration coefficients based Particle Swarm Optimization (PSO) techniques are proposed to optimize the proportional, integral and derivative gains of PID controller in two equal area interconnected power system for minimizing the frequency deviations and tie line power flow deviation to zero. First method is the acceleration coefficients are taken as fixed values that is Fixed Acceleration Coefficients (FAC). Second one is the acceleration coefficients are taken as variable one that is Time Varying Acceleration Coefficients (TVAC). The considered performance index for minimization is Integral of Time weighted Absolute value of Error (ITAE). Two different operating conditions are taken. First operating condition is taken as, the occurrence of 12.5% step load perturbation in area 1 and 5% step load perturbation in area 2. Second operating condition is taken as, the occurrence of 12.5% step load perturbation in area 1 and 20% step load perturbation in area 2. Importance of this interconnected power system is to provide reliable and efficient power to consumers. For this reason, the responses are analyzed and discussed in terms of rise time, settling time, peak overshoot, peak undershoot and peak time. Finally, it is concluded with the identification of better optimization technique which provides solution for supply of reliable and efficient power to consumers in an interconnected power system.

Keywords Interconnected power system, PID controller parameters, particle swarm optimization, time varying acceleration coefficients, fixed acceleration coefficients.

Introduction

Effective operation of interconnected power system necessitates the generation must maintain the demand and associated losses at any situation. If the demand deviates from its normal value then the interconnected power system may experience to produce the deviations of nominal frequency and scheduled power flows to other areas, which may yield harmful effects. The main objective of the interconnected power system is to maintain the system frequency as constant or within the specified limit and minimize the scheduled power flow deviations as zero. Many control strategies presented for interconnected power systems by researchers are Conventional Integral, PI and PID Controllers, State Variable Model, Adaptive Controller, Quantitative Feedback Theory, Characteristic Loci Method, Unified Tuning of PID Controllers, Optimal Feedback methods and etc. [1 to 10]. The conventional PID controllers are widely used as supplementary control in interconnected power system to maintain the constant frequency (or minimize the frequency deviations to zero) and minimize the scheduled power flow deviations to zero. Due to the complexity of interconnected power system, the PID controller parameters tuning with Ziegler Nichols may not be give efficient response. Several intelligent approaches such as Genetic Algorithm [11, 12 and 13], Particle Swarm Optimization [19, 20, 21 and 22], Bacterial Foraging Optimization Algorithm [14] and etc. have been suggested to enhance the capabilities of traditional PID parameter tuning techniques. Several researchers investigated [15 to 18] as PSO technique gives better performance than GA and other algorithms. Some advantages of PSO algorithms are derivative free algorithm, easy to implementation, limited number of parameters, simple calculation and simple concept compared from other optimization algorithms like BFO algorithm [14]. Best system response is obtained from best proportional, integral and derivative gains of PID controller, best values of PID controller gains are obtained by using suitable performance index. In interconnected power system, number of performance indices are used. Many scientists investigated ITAE gives better performance compared from ISE criterion and Ziegler-Nichols tuning [12, 23, 24 and 25].

In this paper, proportional, integral and derivative gains of PID controller parameters are optimized by using proposed TVAC and FAC Particle Swarm Optimization techniques in two equal area non reheat steam turbine interconnected power system with ITAE criterion. Two different operating conditions are taken. Step load perturbation in area 1 is considered as 12.5% for both the operating conditions. Step load perturbations in area 2 are 5% and 20% for first and second operating conditions respectively. The responses are analyzed and discussed in terms of rise time, settling time, peak overshoot, peak undershoot and peak time.

Modeling of Two Area Interconnected Power System

Frequency Deviation (ΔF_i)

The net surplus power in the area following a disturbance ΔP_D equals $\Delta P_G - \Delta P_D$ MW, and the power will be absorbed by the system in three ways:

1. By increasing the area kinetic energy W_{kin} at the rate

$$\frac{dW_{kin}}{dt} = \frac{d}{dt}\left[W^*_{kin}\left(\frac{f}{f^*}\right)^2\right] = 2\frac{W^*_{kin}}{f^*}\frac{d}{dt}(\Delta f) \qquad (1)$$

2. By increased load consumption: All typical loads (because of the dominance of motor load) experience an increase $D \triangleq \partial P_D / \partial f$ MW/Hz with speed or frequency. This D parameter can be found empirically;
3. By increasing the export of power, via tie lines, with the total amount ΔP_{tie} MW defined positive out from the area.

From the above aspects, the power equilibrium equation in i^{th} area is given in equation (2).

$$\Delta P_{Gi} - \Delta P_{Di} = 2\frac{W^*_{kin\,i}}{f^*}\frac{d}{dt}(\Delta f_i) + D_i \Delta f_i + \Delta P_{tie\,i} \quad (2)$$

From equation (2), all terms dimensions are in MW. These dimensions are converted into per unit representation by dividing the total rated area power (P_{ri}) expressed in MW in i^{th} area. Equation (3) represents the dimensions in per unit.

$$\Delta P_{Gi} - \Delta P_{Di} = 2\frac{H_i}{f^*}\frac{d}{dt}(\Delta f_i) + D_i \Delta f_i + \Delta P_{tie\,i} \quad (3)$$

Where, Inertia constant $H_i = W^*_{kin\,i}/P_{ri}$ in MW – sec. / MW or sec (* indicates the nominal values).
The equation (3) is simplified into equation (4).

$$[\Delta P_{Gi}(s) - \Delta P_{Di}(s) - \Delta P_{tie\,i}(s)]\frac{K_{pi}}{1+sT_{pi}} = \Delta F_i(s) \quad (4)$$

Where,

$$K_{pi} = \frac{1}{D_i}\,\text{Hz/puMW} \quad \text{and} \quad T_{pi} = \frac{2H_i}{f^* D_i}\,\text{sec.}$$

Block diagram model of equation (4) is shown in Figure 1.

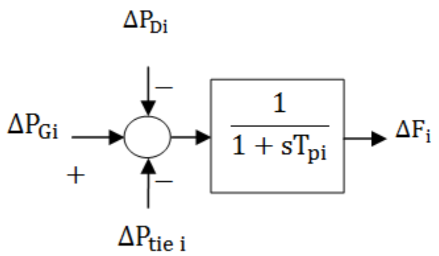

Figure 1: Block diagram model of control area.

Incremental Generated Power (ΔP_{Gi})

Real power generation in a synchronous machine is controlled by changing the prime mover torque. This change in torque is based on opening or closing the steam valve in a steam turbine. Process of opening or closing the steam valve is based on the functional diagram as shown in Figure 2. From the turbine control arrangement, the incremental generated power is obtained from change in speed changer position and speed governor. This functional diagram of Figure 2 is converted into block diagram model as shown in Figure 3. The block diagram which is shown in Figure 3 has been represented by two time constants T_{gi} and T_{ti}. The former represents the time constant of the governor, and the latter represents the time lag of the turbine in i^{th} area.

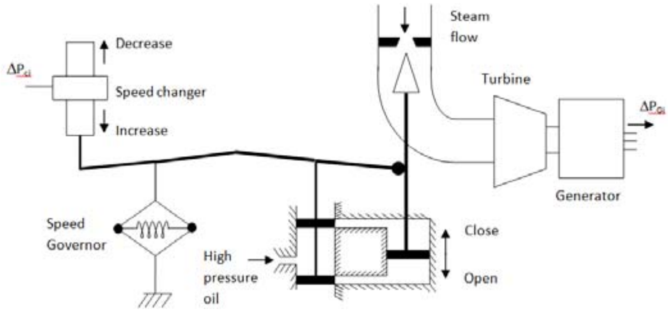

Figure 2: Functional diagram of turbine control arrangement.

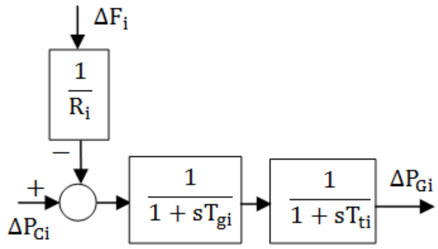

Figure 3: Block diagram model of turbine control arrangement.

Incremental Tie-Line Power ($\Delta P_{tie\,i}$)

The total real power exported from i^{th} area ($P_{tie\,i}$) is equal to sum of all out-flowing line powers ($P_{tie\,iv}$) in the lines connecting i^{th} area with v^{th} areas, i.e.,

$$P_{tie\,i} = \sum_V P_{tie\,iv} \quad (5)$$

If the tie-line losses are neglected, then the individual tie-line powers expressed in mathematical form is shown in equation (6).

$$P_{tie\,iv} = \frac{|V_i||V_v|}{X_{iv}P_{ri}}\sin(\delta_i - \delta_v) \approx P_{tie\,max\,iv}\sin(\delta_i - \delta_v) \quad (6)$$

where $V_i = |V_i|e^{j\delta_i}$, $V_v = |V_v|e^{j\delta_v}$ are the terminal bus voltages of the tie-line and X_{iv} is reactance between i^{th} area and v^{th} area. The maximum value $P_{tie\,max\,iv}$ represents the maximum real power (here expressed in per unit of the rated area power (P_{ri})) that can be transmitted via the tie-line. The tie-line is termed as "weak" because $P_{tie\,max\,iv} \ll P_{ri}$. $\Delta\delta_i$ and $\Delta\delta_v$ are phase angle deviation from their nominal values δ_i^* and δ_v^*. If the phase angles deviate from its nominal values, then the tie-line power flow is also deviated from its nominal value. Deviation of tie-line power flow is mathematically expressed in equation (7).

$$\Delta P_{tie\,iv} = \frac{\partial P_{tie\,iv}}{\partial(\delta_i - \delta_v)}(\Delta\delta_i - \Delta\delta_v) = \frac{|V_i||V_v|}{X_{iv}P_{ri}}\cos(\delta_i^* - \delta_v^*)(\Delta\delta_i - \Delta\delta_v) \quad (7)$$

The relationship between the phase angle deviation and area frequency deviation is expressed in equation (8).

$$\Delta\delta_i = 2\pi\int \Delta f_i dt \quad \text{and} \quad \Delta\delta_v = 2\pi\int \Delta f_v dt \quad (8)$$

From equations (7) and (8),

$$\Delta P_{tie\,iv} = T^*_{iv}\left(\int \Delta f_i dt - \int \Delta f_v dt\right) \quad (9)$$

Where, $T^*_{iv} = 2\pi \frac{|V_i||V_v|}{X_{iv} P_{ri}} \cos(\delta^*_i - \delta^*_v)$

Taking Laplace Transform of equation (9)

$$\Delta P_{tie\ iv}(s) = \frac{T^*_{iv}}{s}[\Delta F_i(s) - \Delta F_v(s)] \quad (10)$$

The total increment in exported power from i^{th} area is finally obtained from equation (10) and is also expressed in equation (11).

$$\Delta P_{tie\ i}(s) = \frac{1}{s}\sum_{V} T^*_{iv}[\Delta F_i(s) - \Delta F_v(s)] \quad (11)$$

The total increment in exported power from i^{th} area in two area system is obtained from equation (11) is expressed in equation (12).

$$\Delta P_{tie\ i}(s) = \frac{T^*_{iv}}{s}[\Delta F_i(s) - \Delta F_v(s)] \quad (12)$$

Diagrammatic representation of the equation (12) is shown in Figure 4.

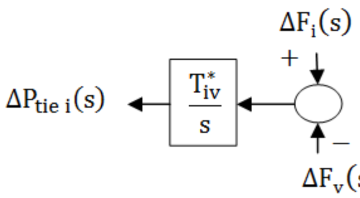

Figure 4: Block diagram model of incremental tie-line power exported from i^{th} area.

The total increment in exported power from v^{th} area in two equal area interconnected power system is obtained from total increment in exported power from i^{th} area is expressed in equation (13).

$$\Delta P_{tie\ v}(s) = -\frac{P_{ri}}{P_{rv}}\Delta P_{tie\ i}(s) = -\Delta P_{tie\ i}(s) \quad (13)$$

Because, two equal area interconnected power system, the rated area powers P_{ri} and P_{rv} are equal.

Area Control Error (ACE)

When systems are interconnected, tie-line power flows as well as frequency must be controlled. The sum of tie-line and frequency errors can be expressed as Area Control Error (ACE) in equation (14).

$$ACE_i = \Delta P_{tie\ i} + b_i \Delta F_i \quad (14)$$

Diagrammatic representation of equation (14) is shown in Figure 5.

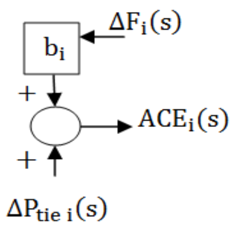

Figure 5: Block diagram model of Area Control Error.

Two area interconnected power system model is obtained from the block diagram models of Figures 1, 3, 4 and 5 is shown in Figure 6.

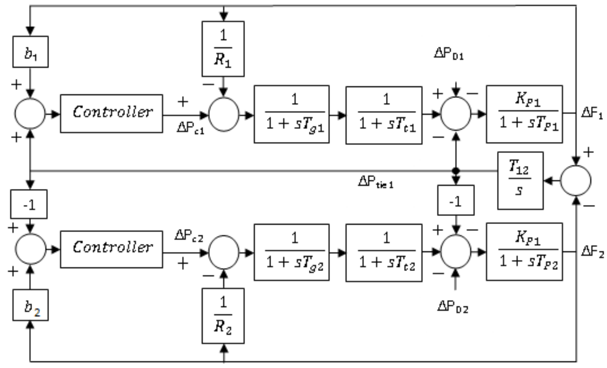

Figure 6: Block diagram representation of two area interconnected power system.

PID Controller & Performance Index

The conventional PID controllers in two area interconnected power system are given in expressions (15) and (16) respectively.

$$\Delta P_{c1}(s) = -(K_p + \frac{K_i}{s} + K_d s)(ACE_1) \quad (15)$$

$$\Delta P_{c2}(s) = -(K_p + \frac{K_i}{s} + K_d s)(ACE_2) \quad (16)$$

K_p, K_i and K_d are the proportional, integral and derivative gains, respectively.

These PID gain parameters are optimally tuned by using particle swarm optimization technique. The optimization process is based on the performance index. The performance index (or) fitness function is considered as the 'integral of the time multiplied absolute value of error' (ITAE). The performance index commonly used for optimizing the PID gain setting of the supplementary controller is based on the frequency deviations of two areas and tie line power flow deviation between two areas. The performance index (or) fitness function is given in expression (17).

$$\text{Performance Index } J = \int t(|\Delta P_{tie\ 12}| + |\Delta f_1| + |\Delta f_2|)dt \quad (17)$$

Particle Swarm Optimization

The Particle Swarm Optimization algorithm was first invented by Dr. James Kennedy and Dr. Russell Eberhart in 1995 and its elementary idea was originally inspired by mock of the social behavior of animals such as bird flocking, fish schooling and so on. It is based on the natural process of group communication to share individual knowledge when a group of birds search food in a searching space, although all birds do not know where the best position is. But from the nature of the social behavior, if any member can find out a desirable path to go, the rest of the members will follow quickly. In PSO, each member of the population is considered as particle and the population is considered as swarm.

All particles are initiated randomly and moving in randomly chosen directions, each particle goes through the searching space to find the personal best (best position of each particle) and the position yielding the lowest value amongst all the personal best that is global best (best position of particle in the entire swarm). Particles velocity is updated by using personal and global best positions, and then each particle positions are updated by the present velocity. The loop is ended with a stopping criterion predetermined in advance.

Personal best position is updated by using equation (18).

$$P_{best,i}^{itr+1} = \begin{cases} P_{best,i}^{itr} \text{ if } f\left(x_i^{itr+1}\right) > P_{best,i}^{itr} \\ x_i^{itr+1} \text{ if } f\left(x_i^{itr+1}\right) \leq P_{best,i}^{itr} \end{cases} \quad (18)$$

Global best position is updated by using equation (19).

$$G_{best}^{itr} = \min\left\{P_{best,i}^{itr}\right\} \quad (19)$$

Velocity of particle is updated by using equation (20).

$$v_i^{itr+1} = v_i^{itr} + c_1 r_1^{itr}\left[P_{best,i}^{itr} - x_i^{itr}\right] + c_2 r_2^{itr}\left[G_{best}^{itr} - x_i^{itr}\right] \quad (20)$$

Positions of particle are updated by using equation (21).

$$x_i^{itr+1} = x_i^{itr} + v_i^{itr+1} \quad (21)$$

Where,

v_i^{itr} – Velocity of particle i at iteration itr.

x_i^{itr} – Position of particle i at iteration itr.

$P_{best,i}^{itr}$ – Personal best position of particle i at iteration itr.

G_{best}^{itr} – Global best position at iteration itr.

$c_1$and c_2 – Cognitive and Social parameters respectively.

$r_1^{itr}$and r_2^{itr} – Random numbers in between 0 and 1 at iteration itr.

When $c_1 = c_2 = 0$, then the updated velocity is $v_i^{itr+1} = v_i^{itr}$. When c_1>0 and c_2 = 0, then all the particles are independent. The updated velocity is $v_i^{itr+1} = v_i^{itr} + c_1 r_1^{itr}\left[P_{best,i}^{itr} - x_i^{itr}\right]$. When c_2>0 and c_1 = 0, then all particles are attracted to single global best position in the entire swarm. The updated velocity is $v_i^{itr+1} = v_i^{itr} + c_2 r_2^{itr}\left[G_{best}^{itr} - x_i^{itr}\right]$. When $c_1 = c_2 \neq 0$, then all particles are attracted towards the average of personal best position and global best position.When$c_1 \gg c_2$, then each particle is more strongly influenced by its personal best position, resulting in excessive travelling. When $c_1 \ll c_2$, then all particles are much more influenced by the global best position, which causes all particles to run prematurely to the optima.Generally, c_1 and c_2 are stationary, with their optimized values being found empirically. Wrong initialization of c_1 and c_2 may result in divergent or cyclic behavior. From the different empirical researches it has been proposed that the two acceleration constants should be $c_1 = c_2 = 2$.

When the velocity increases to large values, then particle's positions update quickly. As a result, particles leave the boundaries of the search space and diverge. Therefore, to control this divergence, particles velocities are reduced in order to stay within boundary constraints.

Velocity clamping

Eberhart and Kennedy first introduced velocity clamping; it helps particles to stay within the boundary and to take reasonably step size in order to comb through the search space. Without this velocity clamping in the searching space the process will be prone to explode and particles positions change rapidly. Maximum velocity controls the granularity of the search space by clamping velocities and creates a better balance between global exploration and local exploitation.

Now if a particle's velocity goes beyond its specified maximum velocity, this velocity is set to the value v_{max} and then adjusted before the position update by,

$$v_i^{itr+1} = \min\left(v_i^{itr+1}, v_{max}\right) \quad (22)$$

If the maximum velocity v_{max} is too large, then the particles may move erratically and jump over the optimal solution. On the other hand, if v_{max} is too small, the particle's movement is limited and the swarm may not explore sufficiently or the swarm may become trapped in a local optimum.

This problem can be solved when the maximum velocity is calculated by a fraction of the domain of the search space on each dimension by subtracting the lower bound from the upper bound, and is defined as

$$v_{max} = \varepsilon(x_{max} - x_{min}) \quad (23)$$

where, x_{max} and x_{min} are maximum and minimum values of x and ε □ [0,1].

Finally, v_{max} was first introduced to prevent divergence. However, it has become unnecessary for convergence because of the use of inertia-weight ω and constriction factor χ.

Inertia Weight

The inertia weight, denoted by 'ω', is considered to adjusting the influence of the previous velocities. The inertia weight 'ω' will be multiplied by the velocity at the previous iteration. Therefore, the velocity equation of the particle is modified from equation (20) to

$$v_i^{itr+1} = \omega v_i^{itr} + c_1 r_1^{itr}\left[P_{best,i}^{itr} - x_i^{itr}\right] + c_2 r_2^{itr}\left[G_{best}^{itr} - x_i^{itr}\right] \quad (24)$$

The inertia weight was first introduced by Shi and Eberhart in 1999 to reduce the velocities over iterations, to control the exploration and exploitation abilities of the swarm, and to converge the swarm more accurately and efficiently.

If ω≥ 1, then the velocities increase over iteration and particles can hardly change their direction to move back towards optimum, and the swarm diverges. If ω≪ 1, then little momentum is only saved from the previous step and quick changes of direction are to set in the process. If ω = 0, then particles velocity vanishes and all particles move without knowledge of the previous velocity in each iteration.

The inertia weight is either fixed one or changeable one. Initially fixed inertia weight was used, but at present changeable inertia weight is used for velocity modifications because this parameter controls the diversification and intensification of the search space. Generally the high inertia weight is at first, which allows all particles to move freely in the search space at the initial conditions and reduces over iteration. Therefore, the process is shifting from the diversification mode to the intensification mode. This decreasing inertia weight has produced good results in many optimization problems. To control the balance between global and local diversification, to obtain quick convergence, and to reach an optimum, the inertia weight whose value decreases linearly with the iteration number is set according to the following equation.

$$\omega^{itr+1} = \omega_{max} - \left(\frac{\omega_{max}-\omega_{min}}{itr_{max}}\right) itr, \omega_{max} > \omega_{min} \quad (25)$$

Where,
ω_{max} and ω_{min} – Initial and final values of the inertia weights.
itr_{max} – Maximum iteration number.

The inertia weight technique is very useful to ensure convergence. However there is a disadvantage of this method is that once the inertia weight is decreased, it cannot increase if the swarm needs to search new areas. This method is not able to recover its diversification mode.

Constriction Coefficient

Fixed Acceleration Coefficients (FAC)

This technique introduced a new parameter 'χ', known as the constriction factor. The constriction coefficient was developed by Clerc. This coefficient is extremely important to control the exploration and exploitation tradeoff, to ensure convergence behavior, and also to exclude the inertia weight ω and the maximum velocity v_{max}. Clerc proposed velocity update equation of the particle i is calculated as follows

$$v_i^{itr+1} = \chi(v_i^{itr} + c_1 r_1^{itr}[P_{best,i}^{itr} - x_i^{itr}] + c_2 r_2^{itr}[G_{best}^{itr} - x_i^{itr}]) \quad (26)$$

Where,

$$\chi = \frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|}, \varphi = c_1 + c_2$$

If $\varphi < 4$, then all particles would slowly spiral toward and around the best solution in the searching space without convergence guarantee. If $\varphi \geq 4$, then all particles converge quickly and guaranteed. The above equation is used under the constraints that $\varphi \geq 4$. For this reason, $c_1 and\ c_2$ are taken as 2 and more than 2. This paper suggests the values for $c_1 and\ c_2$ as 2.25. For this reason, 50% updated velocity is controlled by each iteration.

Time Varying Acceleration Coefficients (TVAC)

Time (or Iteration) varying acceleration coefficients are to enhance the global search in the beginning of the optimization and to move forward the particles to converge towards the best optimum solution at the end of search. The variable accelerating coefficients are obtained from the equations (27) and (28) and discover the updated velocity using equation (26).

$$c_1 = c_{1i} + (c_{1f} - c_{1i})\frac{itr}{itr_{max}} \quad (27)$$

$$c_2 = c_{2i} + (c_{2f} - c_{2i})\frac{itr}{itr_{max}} \quad (28)$$

Where, c_{1i} and c_{1f} are initial and final values of cognitive acceleration factors, c_{2i} and c_{2f} are initial and final values of social acceleration factors, itr_{max} is the maximum number of iterations, itr is the number of current iterations.

In this paper, the suggested initial values of cognitive and social parameters 2 and final values of cognitive and social parameters are 2.5. Because at the initial stage the constriction factor is high and then gradually reduced to reach low value for final stage. This strategy controls the updated velocity.

Simulation Results and Discussion

The Simulation was carried out by using MATLAB programming and simulink toolbox. In this simulation 50 iterations are taken. Population size of particle swarm optimization is considered as 10. The system parameters are given in appendix.

TVAC PSO and FAC PSO techniques are proposed to optimize the proportional, integral and derivative gains of PID controller in equal area interconnected power system with ITAE criterion by using two operating conditions.

Operating condition – I

First operating condition is taken as, the occurrence of 12.5% of step load perturbation in area 1 and 5% step load perturbation in area 2. Figure 7 shows the fitness function (or) performance index curve for FAC PSO technique. Figure 8 shows the fitness function (or) performance index curve for TVAC PSO technique.

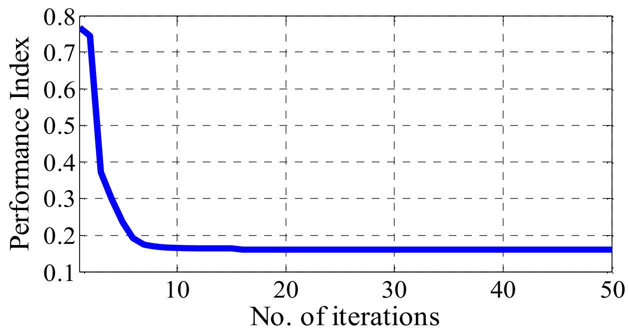

Figure 7: Fitness function (or) performance index curve for FAC PSO technique with first operating condition.

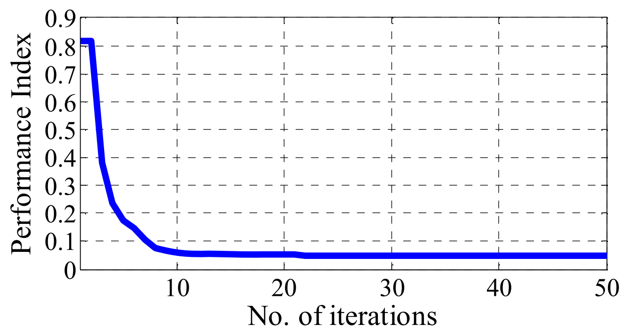

Figure 8: Fitness function (or) performance index curve for TVAC PSO technique with first operating condition.

Operating condition – II

Second operating condition is taken as, occurrence of 12.5% of step load perturbation in area 1 with 20% step load perturbation in area 2. Figure 9 shows the fitness function (or) performance index curve for FAC PSO technique. Figure 10 shows the fitness function (or) performance index curve for TVAC PSO technique.

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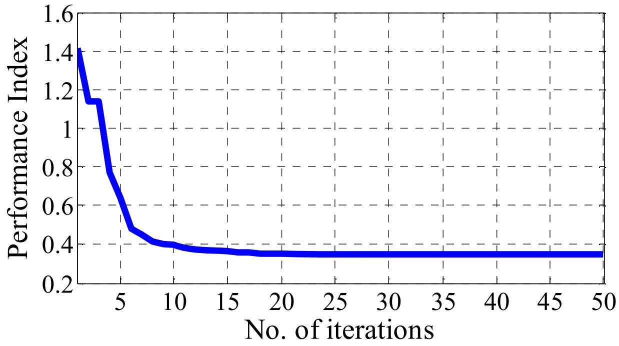

Figure 9: Fitness function (or) performance index curve for FAC PSO technique with second operating condition.

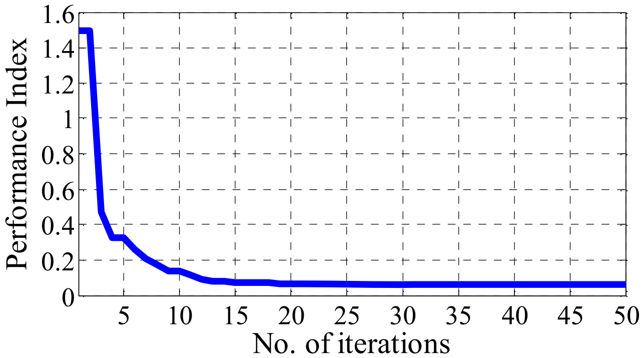

Figure 10: Fitness function (or) performance index curve for TVAC PSO technique with second operating condition.

Table 1 shows the performance index values of TVAC PSO and FAC PSO techniques for two operating conditions.

Table 1: Performance index values

	Performance Index values	
	Operating Condition-I	Operating Condition-II
TVAC PSO	0.0476	0.0604
FAC PSO	0.1601	0.3452

Fixed Acceleration Coefficients technique produces the error value of 0.1601 whereas Time Varying Acceleration Coefficients Particle Swarm Optimization technique produces the error value 0.0476. By comparing these two values it is observed that 70% of error values are eliminated in the operating condition-I. If the area 2 step load perturbation is increased by four times of operating condition – I then the error is eliminated from 70% to 82.5% is observed.

Figures 11, 12 and 13 show the performance of frequency deviations in area 1, 2 and tie line power flow deviations for first operating condition (OC – I).

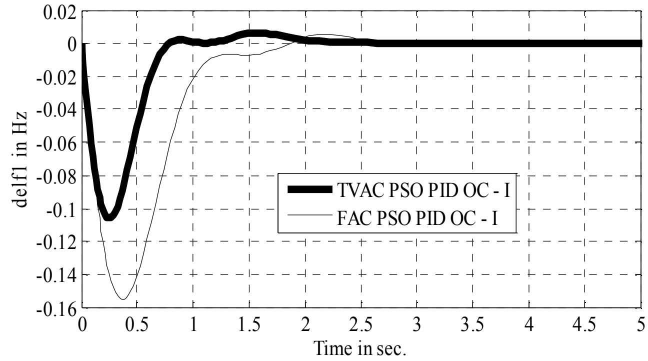

Figure 11: Frequency deviation in area 1 for first operating condition.

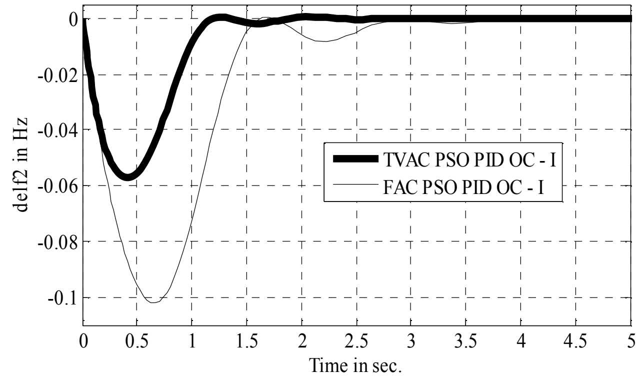

Figure 12: Frequency deviation in area 2 for first operating condition.

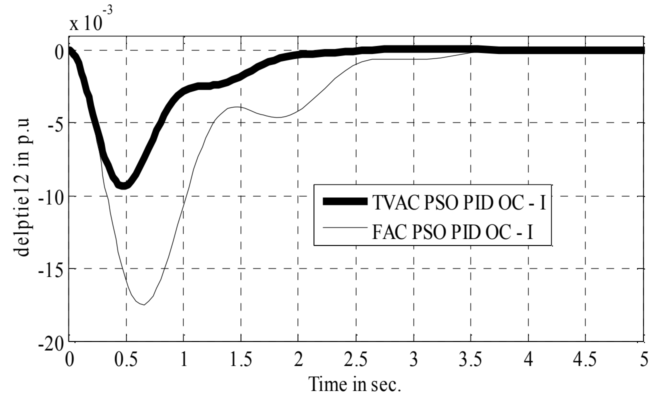

Figure 13: Tie line power flow deviation for first operating condition.

Figures 14, 15 and 16 show the performance of frequency deviations in area 1, 2 and tie line power flow deviations for second operating condition (OC – II).

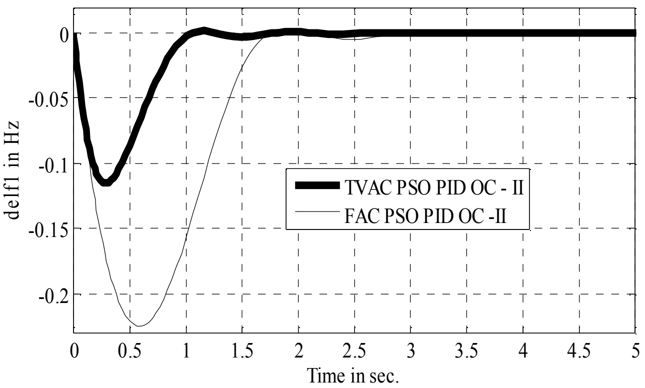

Figure 14: Frequency deviation in area 1 for second operating condition.

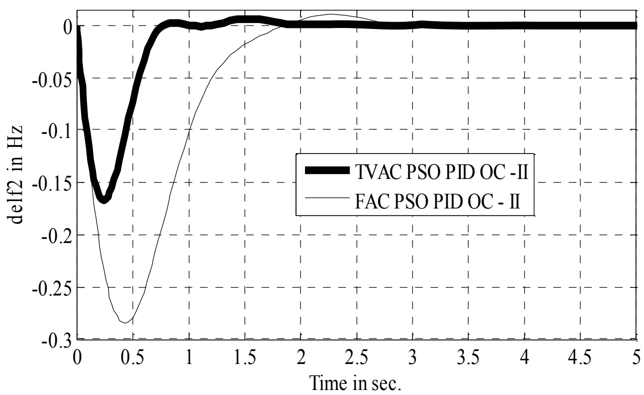

Figure 15: Frequency deviation in area 2 for second operating condition.

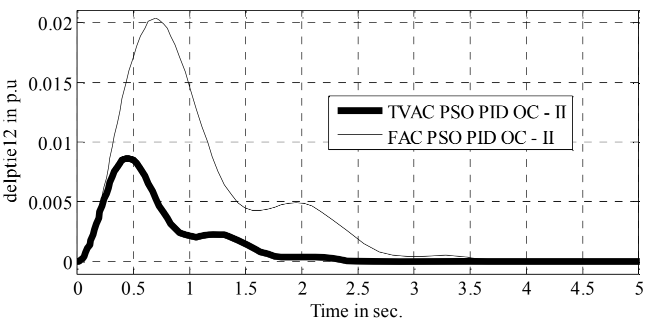

Figure 16: Tie line power flow deviation for second operating condition.

Time Varying Acceleration Coefficients Particle Swarm Optimization technique gives better performance compared from Fixed Acceleration Coefficients technique in terms of rise time, settling time, peak overshoot and peak time are shown in Figures 11 to 16.

Conclusions

Time Varying Acceleration Coefficients Particle Swarm Optimization technique gives better response than Fixed Acceleration Coefficients technique for optimization of proportional, integral and derivative gains of PID controller in interconnected power system on the occurrence of 12.5% step load perturbation of area 1 with 5% step load perturbation of area 2 and occurrence of 12.5% step load perturbation of area 1 with 20% step load perturbation of area 2.

Appendix

Two Area Interconnected Power System parameters

$P_{r1} = P_{r2} = 2000$ MW
$H_1 = H_2 = 5$ Sec.
$D_1 = D_2 = 8.33X10^{-3}$ puMW/Hz
$T_{g1} = T_{g2} = 0.08$ Sec.
$T_{t1} = T_{t2} = 0.3$ Sec.
$T_{P1} = T_{P2} = 20$ Sec.
$K_{P1} = K_{P2} = 120$ Hz/puMW
$R_1 = R_2 = 2.4$ Hz/puMW
$P_{tie\ max} = 200$ MW
$T_{12} = 0.545$ puMW/Hz
$b_1 = b_2 = 0.425$ puMW/Hz

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