Application of Some Modern Techniques in Load Frequency Control in Power Systems

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Abstract The main objective of Load Frequency Control (LFC) is to regulate the power output of the electric generator within an area in response to changes in system frequency and tie-line loading. Thus the LFC helps in maintaining the scheduled system frequency and tie-line power interchange with the other areas within the prescribed limits. Most LFCs are primarily composed of an integral controller. The integrator gain is set to a level that compromises between fast transient recovery and low overshoot in the dynamic response of the overall system. This type of controller is slow and does not allow the controller designer to take into account possible changes in operating conditions and non-linearities in the generator unit. Moreover, it lacks robustness. This chapter studies LFC in two areas power system using PID controller. In this chapter, PID parameters are tuned using different tuning techniques. The overshoots and settling times with the proposed controllers are better than the outputs of the conventional PID controllers. This chapter uses MATLAB/SIMULINK software. Simulations are done by using the same PID parameters for the two different areas because it gives a better performance for the system frequency response than the case of using two different sets of PID parameters for the two areas. The used methods in this chapter are: (a) Particle

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Swarm Optimization,(b) Adaptive Weight Particle Swarm Optimization, (c) Adaptive Acceleration Coefficients based PSO (AACPSO) and (d) Adaptive Neuro Fuzzy Inference System (ANFIS). The comparison has been carried out for these different controllers for two areas power system, the study presents advanced techniques for Load Frequency Control. These proposed techniques are based on Artificial Intelligence. It gives promising results.

Keywords Adaptive acceleration coefficients based particle swarm optimization · Adaptive fuzzy · Adaptive weight particle swarm optimization · ANFIS · Load frequency control · Particle swarm optimization technique

1 Introduction

Frequency is an explanation of stability criterion in power systems [17, 18, 27, 35]. To provide the stability, active power balance and steady frequency are required. Frequency depends on active power balance. If any change occurs in active power demand/generation in power systems, frequency cannot be hold in its rated value. So oscillations increase in both power and frequency. Thus, system subjects to a serious instability problem. In electric power generation, system disturbances caused by load fluctuations result in changes to the desired frequency value. Automatic Generation Control (AGC) or Load Frequency Control (LFC) is an important issue in power system operation and control for supplying stable and reliable electric power with good quality [28, 33]. The principle aspect of Automatic Load Frequency Control is to maintain the generator power output and frequency within the prescribed limits.

In order to keep the power system in normal operating state, a number of controllers are used in practice. The PID controller will be used for the stabilization of the frequency in the load frequency control problems [17, 18, 27, 28, 35]. Each control area is responsible for individual load changes and scheduled interchanges with neighboring areas [31]. Area load changes and abnormal conditions leads to mismatches in frequency and tie line power interchanges which are to be maintained in the permissible limits, for the robust operation of the power system. For simplicity, the effects of governor dead band are neglected in the Load Frequency Control studies. To study the realistic analysis of the system performance, the governor dead band effect is to be incorporated. To improve the stability of the power networks, it is necessary to design LFC system that controls the power generation and active power at tie lines.

Many studies have been carried out in the past on this important issue in power systems, which is the load frequency control. As stated in some literature [11, 16, 25], its objective is to minimize the transient deviations in these variables (area frequency and tie-line power interchange) and to ensure their steady state errors to be zeros. In this chapter, different intelligent techniques such that Particle Swarm Optimization

(PSO), Adaptive Weighted Particle Swarm Optimization techniques (AWPSO), Adaptive Acceleration Coefficients based PSO (AACPSO) and Adaptive Neuro Fuzzy Inference System (ANFIS) will be used to determine the parameters of a PID controller according to the system dynamics. Using the same parameters of PID controller for the two different areas because it gives a better performance for the system frequency response than in case of using two different PID parameters for each different area [25]. In the integral controller, if the integral gain is very high, undesirable and unacceptable large overshoots will be occurred. However, adjusting the maximum and minimum values of proportional (K_p), integral (K_i) and integral (K_d) gains respectively, the outputs of the system (voltage, frequency) could be improved. The main objectives of LFC, is to regulate the power output of the electric generator within a prescribed area in response to changes in system frequency, tie line loading so as to maintain the scheduled system frequency and interchange with the other areas within the prescribed limits.

In this simulation study, two area power systems parameters are chosen and load frequency control of this system is made based on PID controller by using Particle Swarm Optimization and Adaptive Weight Particle Swarm Optimization Techniques (PSO) and (AWPSO) to choose best parameters of PID Controller [13, 23, 26] and Also using Adaptive Neuro Fuzzy Inference System (ANFIS) to control LFC in power system [6–8, 24]. This chapter is organized as follow: Section one introduces the chapter. The second section presents literature review of the study. Section three introduces PSO, AWPSO and the Adaptive Acceleration Coefficients based PSO (AACPSO). Section four introduces ANFIS. Section five displays the case study. Section six presents a comparative study between the above methods according to the three types of performance Indices (IAE, ISE and ITAE) and Genetic Algorithm (GA), ordinary PI controller, Ziegler Nichols tuned PID (ZN), Bacteria Foraging Optimization (BFO) tuned PID controller and the results using Particle Swarm Optimization (PSO), Adaptive Weighted Particle Swarm (AWPSO), Adaptive Acceleration Coefficients based PSO (AACPSO), and Adaptive Neuro Fuzzy Inference System (ANFIS) in order to assess the results.

Therefore. Section seven concludes the study. Finally a list of references and Appendix of this chapter are given at the end of the chapter.

2 Literature Review

The PID controller is considered to be a key component of industrial control system. It was first described by Minorsky [4]. During the Second World War a great interest was developed in the classical control theory and particularly the PID control of processes. Its simplicity and general good performance made its operation very widespread in industry. It has been stated that in process control applications more than 95 % of the controllers are PID type. Also, they state that 30 % of the PID loops operate in the manual mode and 25 % of PID loops actually operate under default factory settings. The choice of appropriate PID parameters can be achieved manually by trial and error, using as guidelines the transient and steady response characteristic of each of the three terms. However, this procedure is very time consuming and requires certain skills [5].

Many investigations have been carried out to design a controller for minimizing the mismatches in frequency and power transfer within the neighboring areas. The controller should provide some degree of strength under various operating conditions. Conventional PD, PI, PID controllers does not provide sufficient control performance with the effect of governor dead band [17, 18, 27, 28, 35]. To tune the controller there are many methods used since 1890s till now, some of the historical methods discussed in the References of the chapter. First method is the manual tuning which used if the system remains online. This tuning method is to first set K_I and K_d values to zero, increase the K_P until the output of the loop oscillates, then K_P should be set to approximately half of that value for a "quarter amplitude decay". Second method is an automatic method called Ziegler–Nichols method which introduced by John G. Ziegler and Nathaniel B. Nichols in the 1940s [28, 35]. It is recognized that the step response of most process control systems has an S-shaped curve called the process reaction curve and can be generated experimentally or from dynamic simulation of the plant. The shape of the curve is characteristic of high order systems, and the plant behavior may be approximated by the following transfer function [34]:

$$\frac{Y(S)}{U(S)} = \frac{K \cdot e^{-t_d \cdot s}}{\tau \cdot S + 1} \tag{1}$$

Which is simply; a first order system plus a transportation lag. The constants in the above equation can be determined from the unit step response of the process. Ziegler and Nichols applied the PID controller to plants without integrator or dominant complex-conjugate poles, whose unit-step response resemble an S shaped curve with no overshoot. This S-shaped curve is called the reaction curve as shown in Fig. 1.

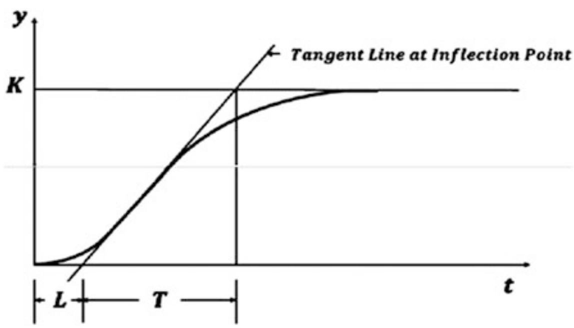

Fig. 1 Reaction curve used by Ziegler and Nichols

The following PID controller parameters were suggested:

$$K_P = {}^{1.2T}/_{L} \quad (2)$$

$$K_i = {}^{K_P}/_{2L} \quad (3)$$

$$K_d = 0.5 \cdot L \cdot K_P \quad (4)$$

Although the method provides a first approximation the response produced is under damped and needs further manual retuning. Some disadvantages of these control techniques for tuning PID controllers are:

a. Excessive number of rules to set the gains.
b. Inadequate dynamics of closed loop responses.
c. Difficulty to deal with nonlinear processes.
d. Mathematical complexity of the control design.

Therefore, it is interesting for academic and industrial communities the aspect of tuning for PID controllers, especially with a reduced number of parameters to be selected and a good performance to be achieved when dealing with complex processes.

Most modern industrial facilities no longer tune loops using the manual calculation methods. Instead, PID tuning and loop optimization software are used to guarantee dependable results [16, 20, 31]. These software packages will gather the data, develop process models, and suggest optimal tuning.

Some software packages can even develop tuning by gathering data from reference changes, such as PSO, AWPSO [23, 24, 26], AACPSO [1] and ANFIS methods ([3, 6–10, 12, 19, 21, 22, 32]). This chapter will discuss the design of the PID controller by using modern method PSO, AWPSO, AACPSO and ANFIS. These methods depend on a computer software program written on MATLAB. These programs had loops and run many times until reach to a solution of the transfer function to have a value of PID parameters which will be described below. These parameters lead to have the smallest value of settling time and over shoot. Therefore, these values of PID parameters (with this used method) are the best values to reach to the best controller parameters.

3 Overview on Practical Swarm Optimization Technique

A Particle Swarm Optimization (PSO) is an optimization algorithm modeled. It's one of Artificial Intelligence (AI) Techniques. It is an intelligent control system combines the techniques. From the fields of AI with those of control engineering to design independent systems that can sense, reason, learn and act in an intelligent method. PSO depends on the simulation of the social behavior of bird and fish school [26]. PSO is developed through the simulation of a bird flocking in two-dimension

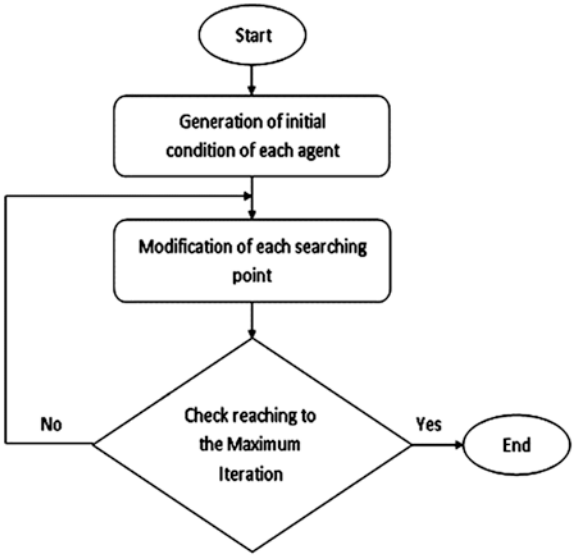

Fig. 2 General flow chart of PSO

space by X-Y axis position where Vx and Vy express the velocity in X direction and Y direction. The flow chart described in Fig. 2, presented the steps of PSO. Modification of the agent position is realized by the position and velocity information [13, 23, 24, 26]. This information is analogy of personal experiences of each agent. Each agent knows its best value so far (Pbest) and its XY position; each agent knows the best value so far in the group (gbest) among Pbests. This information is analogy of knowledge of how the other agents around them have performed. Namely, each agent tries to modify its position using the following information:

Let the particle of the swarm is represented by the N dimensional vector ith

$$X_i = (X_1, X_2, X_3, \ldots X_N) \tag{5}$$

The previous best position of the Nth particles is recorded and represented as follows:

$$\mathrm{Pbest\,i} = (\mathrm{Pbest\,1},\ \mathrm{Pbest\,2}, \ldots, \mathrm{Pbest\,N}) \tag{6}$$

where Pbest is Particle best position (m), N is the total number of iterations.

The best position of the particle among all particles in the swarm is represented by gbest the velocity of the particle is represented as follows:

$$\mathrm{Vi} = (\mathrm{V1},\ \mathrm{V2}, \ldots \mathrm{VN}) \tag{7}$$

where

V_i is the velocity of each i particle.

The modified velocity and position of each particle can be calculated from the current velocity and the distance from particle current position to particle best position P_{best} and to global best position g_{best} as shown in the following equations:

$$V_i(t) = W \cdot V_i(t-1) + C_1 \cdot rand(0,1) \cdot (P_{best} - X_i(t-1)) + C_2 \cdot rand(0,1) \cdot (g_{best} - X_i(t-1)) \quad (8)$$

$$X_i(t) = X_i(t-1) + V_i(t) \quad (9)$$

$$i = 1, 2, 3 \ldots N \quad (10)$$

$$j = 1, 2, 3 \ldots D \quad (11)$$

where

$V_i(t)$	Velocity of the particle i at iteration t (m/s)
$X_i(t)$	The Current position of particle i at iteration t (m)
D	The Dimension
C1	The cognitive acceleration coefficient and it is a positive number
C2	Social acceleration coefficient and it is a positive number
rand [0, 1]	A random number obtained from a uniform random distribution function in the interval [0, 1]
gbest	The Global best position (m)
W	The Inertia weight

3.1 Adaptive Weighted Particle Swarm Optimization

Adaptive Weighted Particle Swarm Optimization (AWPSO) technique has been proposed for improving the performance of PSO in multi-objective optimization problems [23, 24]. AWPSO is achieved by two terms [26]: inertia weigh (W) and Acceleration factor (A). The inertia weight function is to balance global exploration and local exploration. It controls previous velocities effect on the new velocity. Larger the inertia weight, larger exploration of search space while smaller the inertia weights, the search will be limited and focused on a small region in the search space. The inertia weight formula is as follows which makes W value changes randomly from W_o to 1 [6–8].

$$W = W_o + rand\,(0,1)\,(1 - W_o) \quad (12)$$

where

Wo The initial positive constant in the interval chosen from [0, 1]

Particle velocity at ith iteration as follows:

$$V_i(t) = W \cdot V_i(t-1) + AC_1 \cdot rand(0,1) \cdot (P_{best} - X_i(t-1)) + AC_2 \cdot rand(0,1) \cdot (g_{best} - X_i(t-1)) \tag{13}$$

Additional term denoted by A called acceleration factor is added in the original velocity equation to improve the swarm search.

The acceleration factor formula is given as follows [26]:

$$A = A_o + \frac{i}{n} \tag{14}$$

where

A_o	Is the initial positive constant in the interval [0.5, 1].
n	is the number of iteration.
C_1 and C_2	Are the constant representing the weighing of the stochastic acceleration terms that pull each particle towards P_{best} and g_{best} positions.

As shown in acceleration factor formula, that the acceleration term will increase as the number of iterations increases. This will enhance the global search ability at the end of the run and help the algorithm to get far from the local optimum region. In this article, the term A_O is set at 0.5. Low values of $C_1$and C_2 allow particles to roam far from the target region before being tugged back. However, high values result in abrupt movement toward, or past, target regions.

3.2 Adaptive Acceleration Coefficients Based PSO

The Time Varying Inertia Weight (TVIW) W in Sect. (3.1) can locate a good solution at a significantly faster rate but its ability to fine tune the optimum solution is weak, due to the lack of diversity at the end of the search. It has been observed by most researchers that in PSO, problem based tuning of parameters is a key factor to find the optimum solution accurately and efficiently [35]. New researches have emerged to improve PSO Algorithms, as Time-Varying Acceleration Coefficients (TVAC), where C_1 and C_2 in [15] change linearly with time, in the way that the cognitive component is reduced while the social component is increased as the search proceeds.

In this section, a new approach called Adaptive Acceleration Coefficients based PSO (AACPSO) to implement the PSO algorithm will be described as illustrated in [1]. A suggestion will be given on how to deal with inertia weight and acceleration factors. The new approach is confident to change acceleration coefficients exponentially (with inertia weight) in the time, with respect to their minimal and maximal values. The choice of the exponential function is justified by the increasing or decreasing speed of such a function to accelerate the convergence process of the algorithm and to get better search in the exploration s pace. Furthermore, C_1 and C_2 vary adaptively according to the fitness value of G_{best} and P_{best}, [15] becomes:

$$V_i^{(t+1)} = w^{(t)} V_i^{(t)} + C_1^{(t)} r_1 * \left(Pbest_i^{(t)} - X_i^{(t)} \right) + C_2^{(t)} r_2 * \left(Gbest^{(t)} - X_i^{(t)} \right) \quad (15)$$

$$w^{(t)} = w_o * \exp(-\propto_w *t) \quad (16)$$

$$C_1^{(t)} = C_{1o} * \exp\left(-\propto_c *t * k_c^{(t)}\right) \quad (17)$$

$$C_2^{(t)} = C_{2o} * \exp\left(-\propto_c *t * k_c^{(t)}\right) \quad (18)$$

$$\propto_c = \frac{-1}{t_{\max}} \ln\left(\frac{C_{2o}}{C_{1o}}\right) \quad (19)$$

$$k_c^{(t)} = \frac{\left(F_m^{(t)} - Gbest^{(t)}\right)}{F_m^{(t)}} \quad (20)$$

where

$w^{(t)}$	The inertia weight factor
$C_1^{(t)}$	Acceleration coefficient at iteration t
i	Equal 1 or 2
t	The iteration number
ln	The neperian logarithm
α_w	Is determined with respect to initial and final values of ω with the same manner as αc described in [4]
$k_c^{(t)}$	Determined based on the fitness value of Gbest and Pbest at iteration t
$\omega_{o,}$ c_{io}	initial values of inertia weight factor and acceleration coefficients respectively with i = 1 or 2
$F_m^{(t)}$	The mean value of the best positions related to all particles at iteration t

4 Preface to Fuzzy Logic

The word "fuzzy" is defined as unclear, indefinite, fuzzy systems are systems to be precisely defined and fuzzy *control* is a special kind of nonlinear control. The description of the Fuzzy system specified in many references these references describe the Fuzzification and Defuzzification process and the equations of each case [6, 8, 21, 22, 32]. There are two kinds of explanation for fuzzy systems theory:

a. The real world is too complicated for precise descriptions to be obtained Therefore approximation (or fuzziness) must be introduced in order to obtain a practical, accurate model.
b. As the world moving into the information period, human knowledge becomes increasingly important. A theory is needed to formulate human knowledge in a systematic method and put it into engineering system, together with other information like mathematical models and sensor measurements.

Fuzzy Logic (FL) requires some numerical parameters in order to operate such as what is considered significant error and significant rate-of-change-of-error, but exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them. Fuzzy logic has many several unique features that make it a particularly good choice for many control problems. In the following there are some of these advantages [33]:

1. It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.
2. Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
3. FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.
4. Because of the rule-based operation, any reasonable number of inputs can be processed (1–8 or more) and numerous outputs (1–4 or more) generated, although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system, each with more limited responsibilities.
5. Fuzzy Logic can control nonlinear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.
6. Fuzzy Logic doesn't need any system parameter estimation or identification.
7. Fuzzy Logic can deal with nonlinear systems (there is no need for Linearization).

4.1 Adaptive Neuro Fuzzy Inference System

The acronym ANFIS derives its name from Adaptive Neuro Fuzzy Inference System (ANFIS). In the field of artificial intelligence, Neuro-Fuzzy refers to combinations of artificial neural networks and fuzzy logic.

Neuro-fuzzy was proposed by J. S. R. Jang. Neuro-fuzzy hybridization results in a hybrid intelligent system that synergizes these two techniques by combining the human-like reasoning style of fuzzy systems with the learning and connectionist structure of neural networks.

Neuro-fuzzy hybridization is widely termed as Fuzzy Neural Network (FNN) or Neuro-Fuzzy System (NFS) in the literature. Neuro-fuzzy system (the more popular term is used in imminent) incorporates the human-like reasoning style of fuzzy systems through the use of fuzzy sets and a linguistic model consisting of a set of IF-THEN fuzzy rules.

The main strength of neuro-fuzzy systems is that they are universal approximates with the ability to solicit interpretable IF-THEN rules [7]. The strength of neuro-fuzzy systems involves two contradictory requirements in fuzzy modeling: interpretability versus accuracy. In practice, one of the two properties prevails. The neuro-fuzzy in fuzzy modeling research field is divided into two areas: linguistic fuzzy modeling that is focused on interpretability; and precise fuzzy modeling that is focused on accuracy.

Using a given input and output data set, the toolbox function ANFIS constructs a fuzzy inference system (FIS) whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone or in combination with a least squares type of method. This adjustment allows the fuzzy systems to learn from the modeling data [14, 29, 30]. Moreover, ANFIS is used in many applications of power system [3, 9, 10, 17–19].

This chapter proposed two inputs-three outputs self tuning of a PID controller. The controller design used the error and change of error as inputs to the self tuning, and the gains (K_P, K_I, K_d) as outputs. The FLC is adding to the conventional PID controller to adjust the parameters of the PID controller on-line according to the change of the signals error and change of the error. The fuzzy logic model presented SIMULINK in MATLAB program is used.

5 Cases Study

Simulations are done by using MATLAB/SIMULINK for the case of two power system areas connected with each other's by tie transmission line as shown in Figs. 4 and 5 [32]. The parameters of area 1 and area 2 are shown in the Appendix. Basically, electric power system components are non-linear; therefore a linearization around a nominal operating point is usually performed to get a linearized system model which is used in the controller design process.

The operating conditions of power systems are continuously changing. Accordingly, the real plant usually differs from the assumed one. Therefore, classical algorithms to design an automatic generation controller using an assumed plant may not ensure the stability of the overall real system [33]. The load frequency controller function is to minimize the transient deviation of the frequency and maintains their values to steady state values and to restore the scheduled interchanges between different areas.

MATLAB programs are used for PSO, AWPSO and AACPSO to make tuning of the PID controller's parameters. These parameters adjusted to have minimum integrated error value with shorted settling time. The objective function is defined as follows [31]:

For Integral of Absolute Error (IAE):

$$IAE = \int_{0}^{\infty} |e(t)| dt \tag{21}$$

$$f = IAE_1 + IAE_2 + IAE_{Ptie} \tag{22}$$

Integral of Squared Error (ISE)

$$ISE = \int_{0}^{\infty} e^2(t) dt \tag{23}$$

$$f = ISE_1 + ISE_2 + ISE_{Ptie} \tag{24}$$

Integral of Time Weighted Absolute Error (ITAE)

$$ITAE = \int_{0}^{\infty} t|e(t)| \mathrm{dt} \tag{25}$$

$$f = ITAE_1 + ITAE_2 + ITAE_{Ptie} \tag{26}$$

where

e	Is the error
f	Is the objective function
$IAE_1, IAE_2, IAE_{Ptie\,1}$	The Integral of Absolute Error of area 1, area 2 and the tie line of the System
$ISE_1, ISE_2, ISE_{Ptie1}$	The Integral of Squared Error of area 1, area 2 and the tie line of the System
$ITAE_1, ITAE_2, ITAE_{Ptie\,1}$	Integral of Time Weighted Absolute Error of area 1, area 2 and the tie line of the System

For the two power system areas, step loading disturbance has been applied for each area, 0.07 p.u load throw has been withdrawn from the first area and 0.05 p.u loading added for the second area. The control objective is to control the frequency deviation for each area. Figure 4 presents the diagram shows the steps of this study. The study the performance of the PID controller was compared in case of each intelligent technique (PSO, AWPSO, AACPSO and finally using ANFIS algorithms).

The performance index selected by the user in the beginning of the program. Based on this performance index (*f*) optimization problem can be stated as: Minimize *f* the nominal system description and parameters are describing in the following.

5.1 Model Description and Parameters

The block diagram of the two areas power system model using PID controller presented at Fig. 3 as presented in [33]. The description for the system parameters is displayed in Table 1 and the parameters values of the system is presented in Table 2.

So the transfer function of governors, turbine, mass and load becomes as given in [33]:

$$G_{h1}(S) = G_{h2}(S) = \frac{1}{0.08s + 1} \tag{27}$$

$$G_{t1}(S) = G_{t2}(S) = \frac{1}{0.3s + 1} \tag{28}$$

$$G_{y1}(S) = G_{y2}(S) = \frac{120}{20s + 1} \tag{29}$$

5.2 Steps of the Study

The flow chart presents in Fig. 4 explains the steps of the study.

To optimize the performance of a PID controlled system, the PID gains K_P, K_i, and K_d of the two-area electric power system shown in Fig. 3 are adjusted to minimize a certain performance index. The performance index is calculated over a time interval; T, normally in the region of $0 < T < ts$ where t_s is the settling time of the system. By using different techniques in conjunction with Eqs: 21–29 the optimal controller parameters under various performance indices were obtained as shown in Tables 1, 2 and 3 show the results of the different methods used based PID controller.

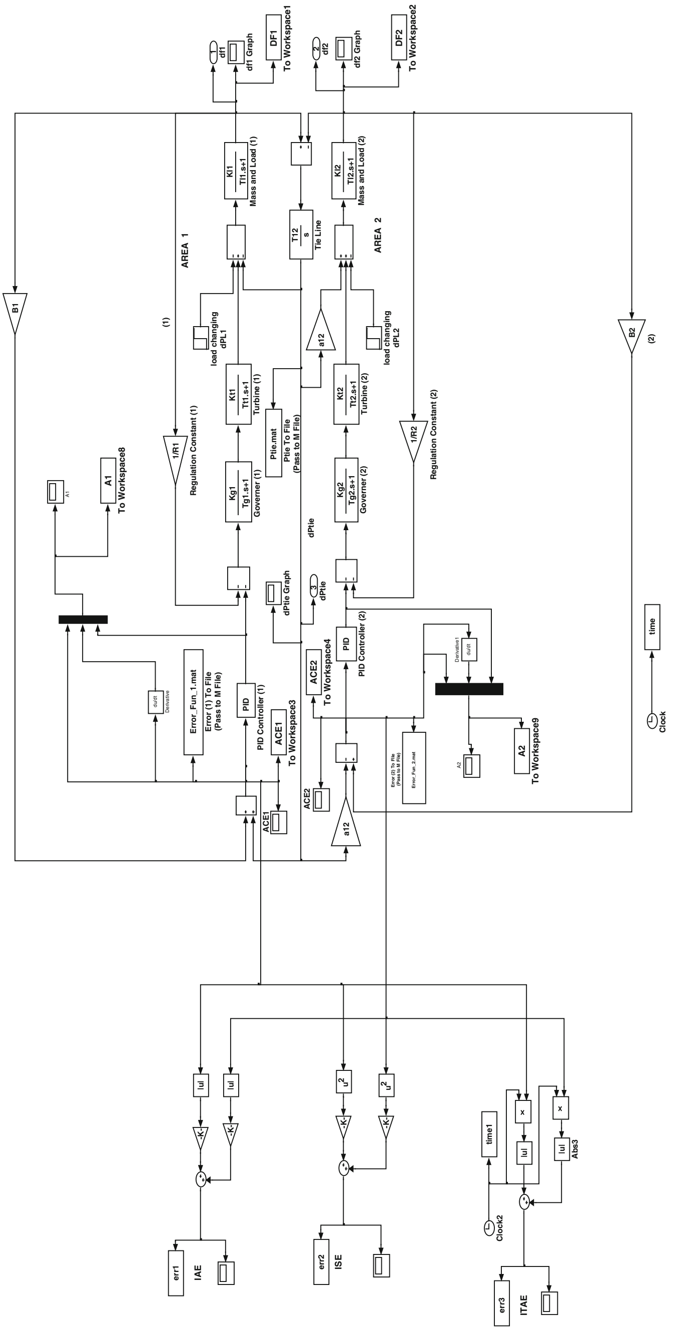

Fig. 3 Two-area power system SIMULINK model using PID controller

Table 1 Parameter description

Parameter	Description
Tg1, Tg2	Time constant for area 1 governor and area 2 governor in (seconds)
Tt1, Tt2	Turbine time delay between switching the valve and output turbine torque (seconds)
Tl1, Tl2	Generator 1 and generator 2 inertia constant
Kl1, Kl2	Power system gain constant (HZ/MW p.u)
R1, R2	Speed regulation constant of the governor (HZ/MW p.u)
B1, B2	Frequency bias p.u. MW/HZ
T12	Tie line synchronizing coefficient with area 2 MW p.u/HZ
a12	Gain
Δf_1 or df_1	Area 1 frequency deviation
Δf_2 or df_2	Area 2 frequency deviation
dPL1, dPL2	Frequency sensitive load change for area 1 and area 2
ΔPtie or dPtie	Net tie line power flow
Vi	Area interface
ACE1	Area 1 control error
ACE2	Area 2 control error

Table 2 Parameters values

System parameters	Value
Tg1, Tg2	0.08 s
Tt1, Tt2	0.3 s
Tl1, Tl2	20 s
Kl1, Kl2	100 HZ/MW p.u
R1, R2	2.4 HZ/MW p.u
B1, B2	0.425 MW p.u/HZ
T12	0.05 MW p.u/HZ
a12	1

5.3 *Results in Case of IAE Error*

Figures 5 and 6 presents the frequency deviation of area 1 and area 2 without using PID controller.

In the following sections discuss the impact the way the AI techniques used on the Tie Line and area control error ACE of the system.

5.3.1 Tie Line Power

Figure 7 displays the frequency change of the tie line power with using PSO, AWPSO And AAPSO Based PID Controller,

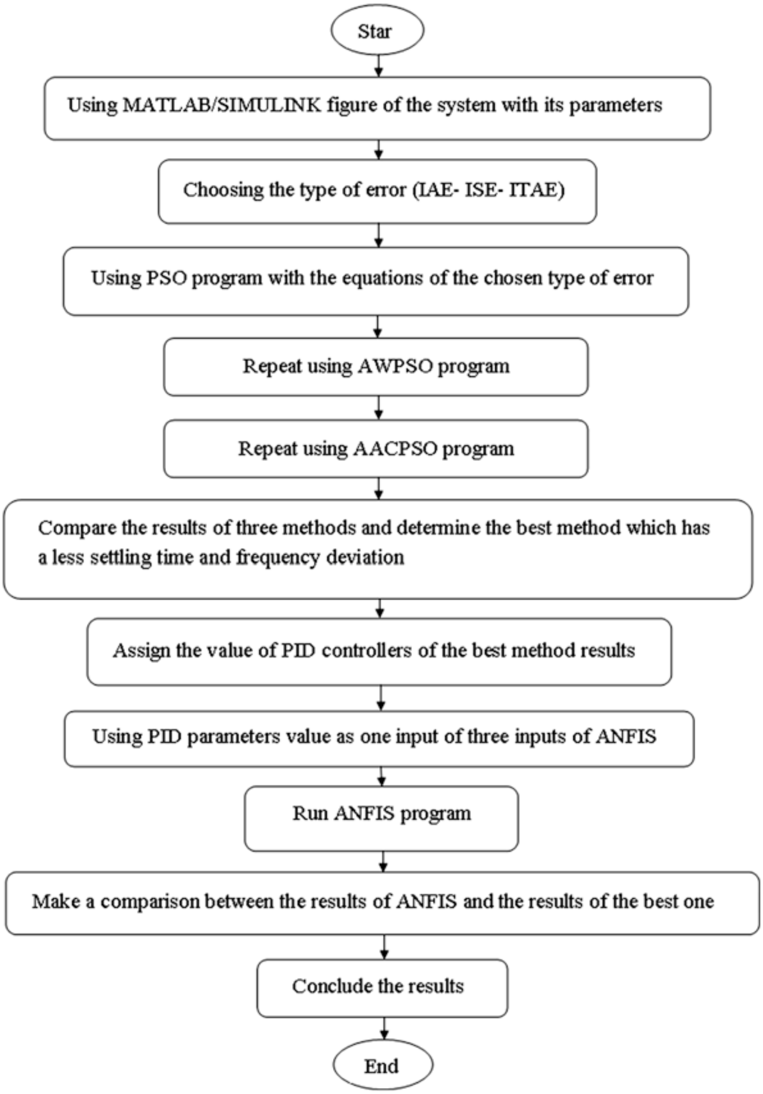

Fig. 4 The steps of the study

The results display in Table 4, Fig. 7 show that:

1. Tables 3 and 4 indicate that on the Tie line power, the value of settling time in case of using AACPSO is the best results and has a smaller value comparing with the other methods used (PSO, AWPSO).
2. The settling time of Tie line in case of using AC is less than its value in case of using AWPSO by about 0.6 s, and less than its value when using PSO by about 4.1 s.
3. Settling time by AWPSO is smaller than using PSO by 0.0359 s.

Table 3 The results of the program using PSO, AWPSO and AACPSO

Items of comparison	PSO	AWPSO	AACPSO
Number of iterations	500	500	500
Error IAE (integrated error)	0.0611	0.0252	0.0149
Settling time _Area 1 (s)	5.4281	1.9323	1.6514
Settling time _Area 2 (s)	7.6946	4.1854	3.569
Settling time _Tie line (s)	7.7624	4.2082	3.6553
Kp1	2.4283	8.1472	9.1995
Ki1	1.5555	7.5774	9.4936
Kd1	1.3753	2.7603	3.2393
Kp2	2.9522	3.4998	4.7149
Ki2	9.2078	1.6218	0.876
Kd2	5.7955	8.6869	2.1397

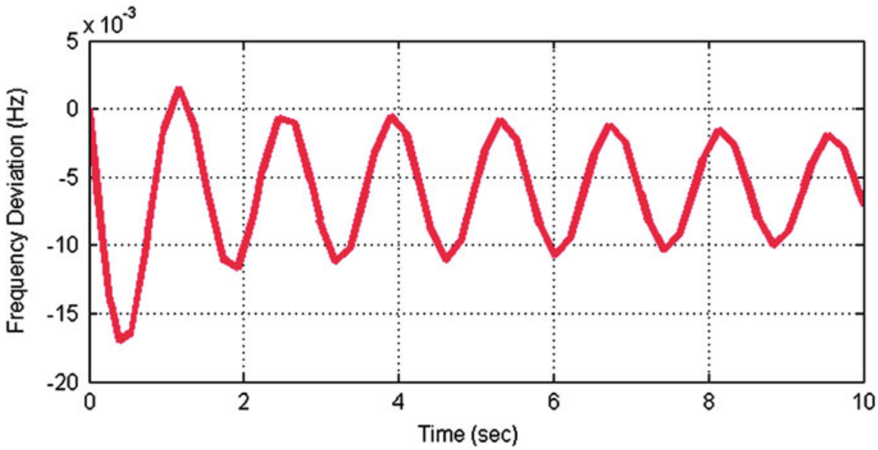

Fig. 5 The frequency deviation of area 1 without controller

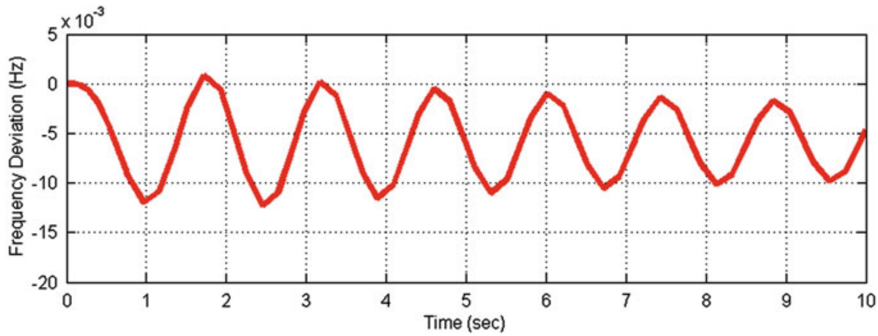

Fig. 6 The frequency deviation of area 2 without controller

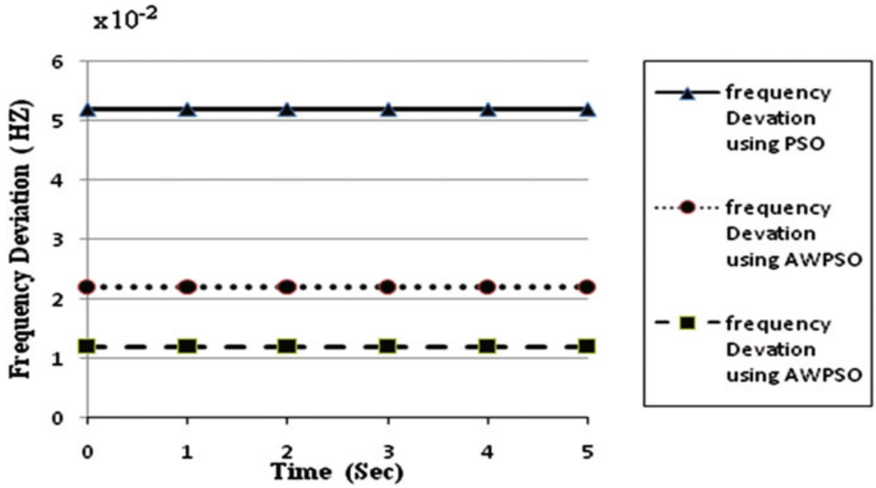

Fig. 7 Tie line power changes using PSO, AWPSO and AAPSO based PID controller in case of using IAE error

Table 4 Tie line behavior at different typed of control

Items of comparison	PSO	AWPSO	AACPSO
Settling time _Tie line (s)	7.7624	4.2082	3.6553
Maximum frequency of tie line power (Hz)	3.00E−07	4.24E−07	1.06E−06
Time at maximum frequency of tie line power (s)	20.502	22.2727	4.8003
Minimum frequency of tie line power (Hz)	−0.0011	−3.66E−04	−3.20E−04
Time at minimum frequency of tie line power (s)	1.0319	0.612	0.5743

4. The maximum frequency of Tie line power in case of using AWPSO is less than its value of the other methods of controller used by a very small value.
5. In general the maximum frequency of Tie line power is construed to be zero.
6. Time at maximum power in case of using AACPSO is less than the other values of PSO and AWPSO. This value is less than the time of maximum power in case of using PSO by about 23.4 % and less than its value in case of using AWPSO by about 21.5 %.
7. The minimum Tie line power in case of using AWPSO and AACPSO are almost equal and less than its value in case of using PSO.
8. Time at minimum power in case of using AACPSO is less than the other values of PSO and AWPSO.

5.3.2 Integral of Absolute Error of Area 1 and Area 2

The first choice of the MATLAB program used in this study is IAE as described above. In the following there are the Figures describe the output of the system after controlling the error on area 1 and area 2. Figure 8 presents the frequency deviation of area 1 with PSO based PID Controller, Fig. 9 presents the frequency deviation of area 1 with AWPSO based PID controller and Fig. 10 illustrates the frequency deviation of area 1 with AACPSO based PID controller.

From the results shown in Table 3 and also the above Figs. 8, 9 and 10 all these show that:

1. The settling time of area 1 to reach to the steady state in case of using AWPSO is less than the value of settling time using PSO by about 3.5 s.

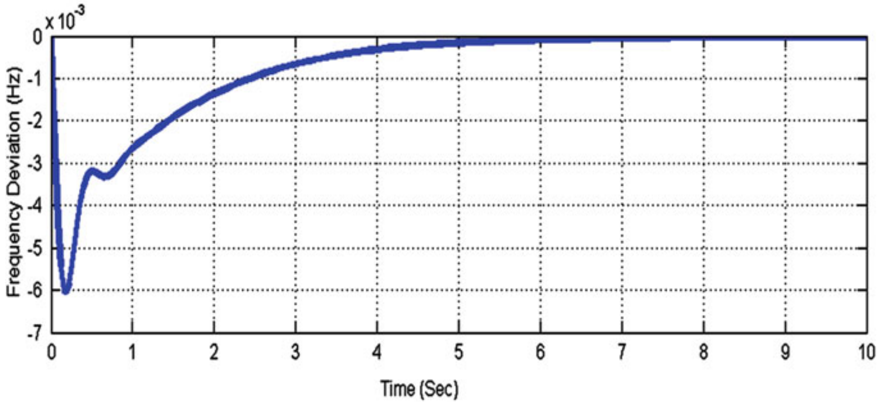

Fig. 8 The frequency deviation of area 1 with PSO based PID controller using IAE performance indices

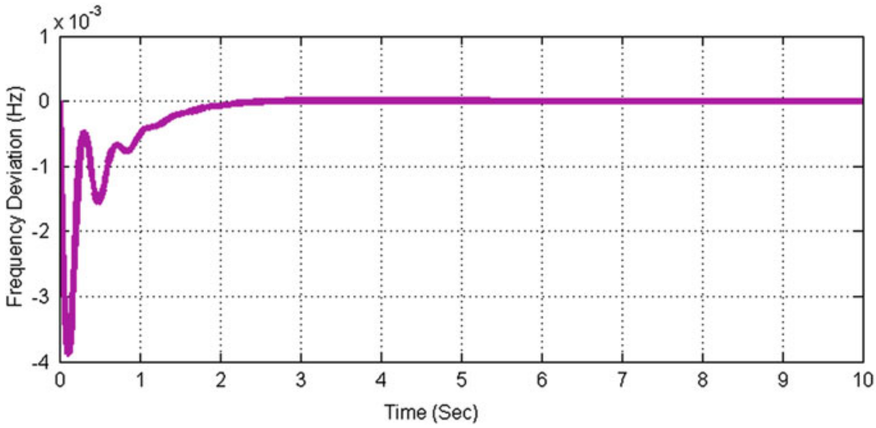

Fig. 9 The frequency deviation of area 1 with AWPSO based PID controller using IAE performance indices

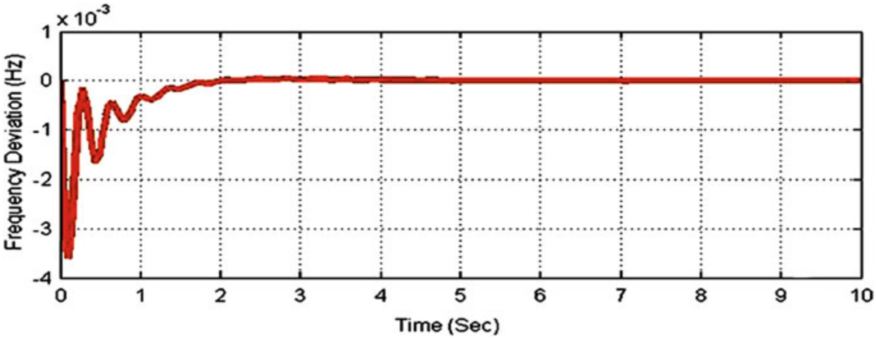

Fig. 10 The frequency deviation of area 1 with AACPSO based PID controller using IAE performance indices

2. The settling time by using AACPSO in the program is less than that value by using AWPSO by about 0.3 s.
3. All these results present that: the best method used to reach the minimum value of settling time in area 1 is AACPSO.

The next Figures present the behavior of area 2 in different cases of Artificial Intelligence techniques.

Figure 11 shows the frequency deviation of area 2 with PSO based PID controller using IAE performance indices; Fig. 12 presents the behavior of the frequency deviation of area 2 in case of using AWPSO, while; Fig. 13 displays The frequency deviation of area 2 with AACPSO based PID controller.

From the results shown in Table 3 and also the Figs. 11, 12 and 13 all these show that:

1. The settling time of area 2 by using AWPAO is less than its value by using PSO by 3.5092 s. While; the settling time becomes smaller if using AACPSO.

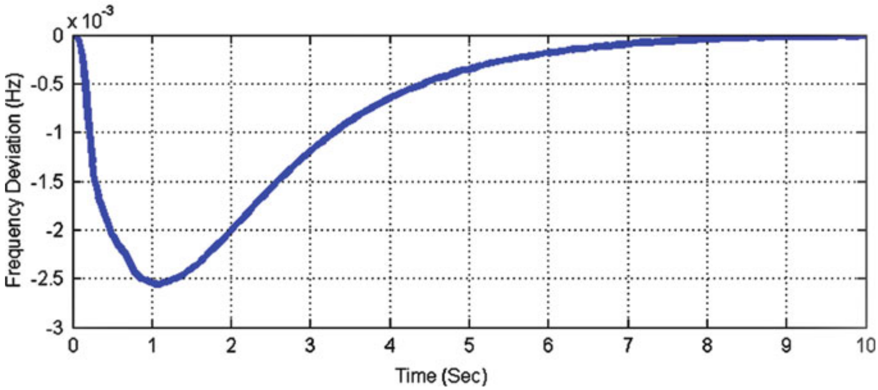

Fig. 11 The frequency deviation of area 2 with PSO based PID controller using IAE performance indices

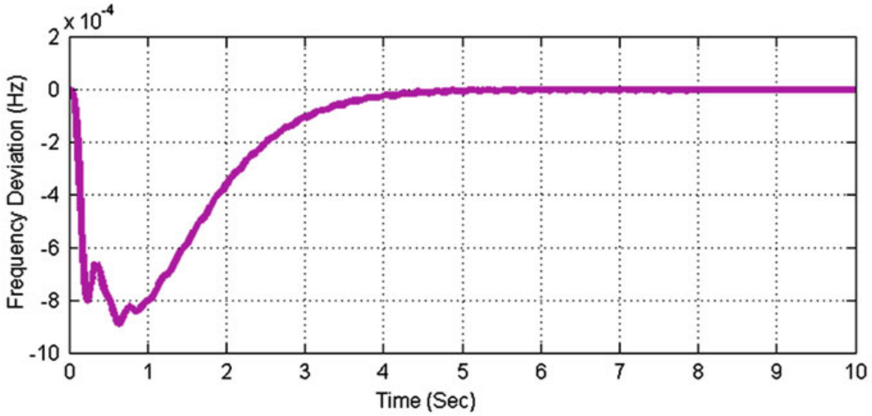

Fig. 12 The frequency deviation of area 2 with AWPSO based PID controller using IAE performance indices

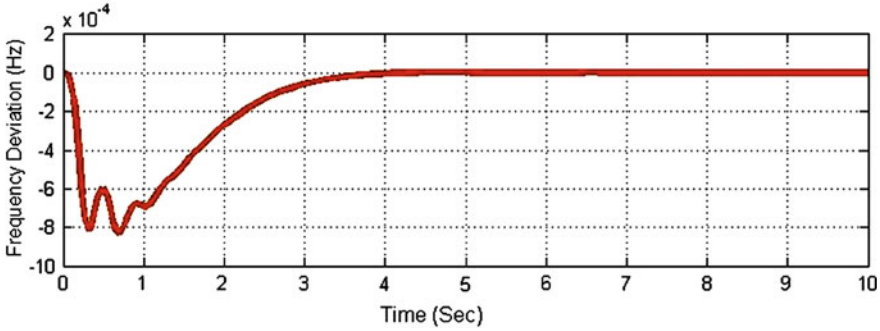

Fig. 13 The frequency deviation of area 2 with AACPSO based PID controller using IAE performance indices

The output results using AACPSO is less than the value using AWPSO by 0.6164 s. And the value of settling time in case of PSO is almost double the value of settling time when using AACPSO.

2. The parameters value of area 1 PID controller (Kp2, Ki2, Kd2) also shown in Table 3.

Figure 14 presents error index (IAE) of area control error ACE of the system with PSO. Figure 15 displays error index (IAE) of ACE of the system with AWPSO. While; Fig. 16 shows error index (IAE) of the system with ACE with AACPSO.

All previous results indicate that the best way using to reduce the IAE error of the two area power systems is AACPSO.

Because of the results of AACPSO which is the best results of all methods to have a minimum value of IAE error at a small value of settling time. So using these values to make a training of ANFIS. Figure 17 shows the two-Area Power Systems SIMULINK Model using ANFIS controller and all necessary changes of the model.

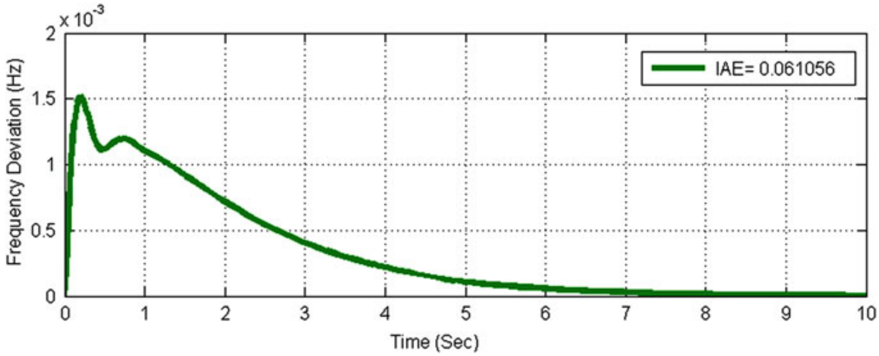

Fig. 14 Error index of ACE with PSO based PID controller in case of using IAE error

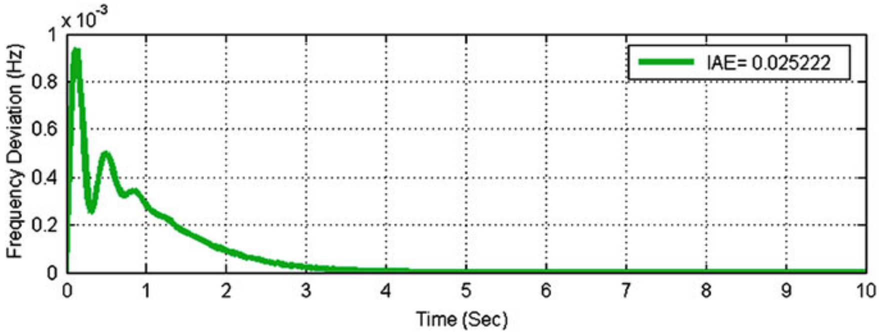

Fig. 15 Error index of ACE with AWPSO based PID controller in case of using IAE error

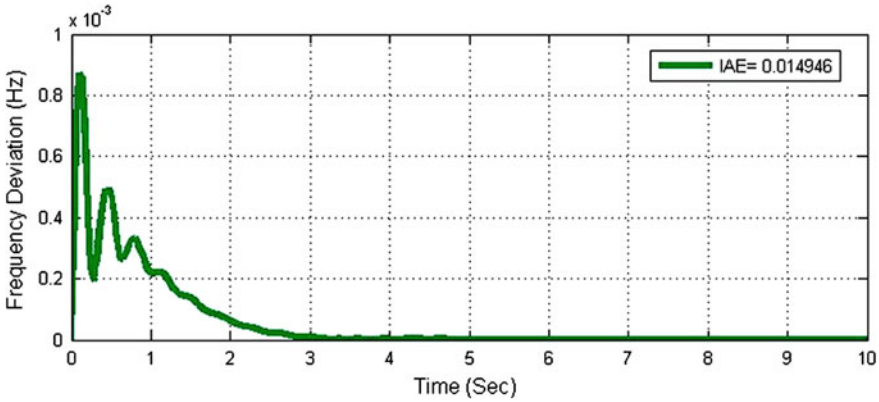

Fig. 16 Error index of ACE with AACPSO based PID controller in case of using IAE error

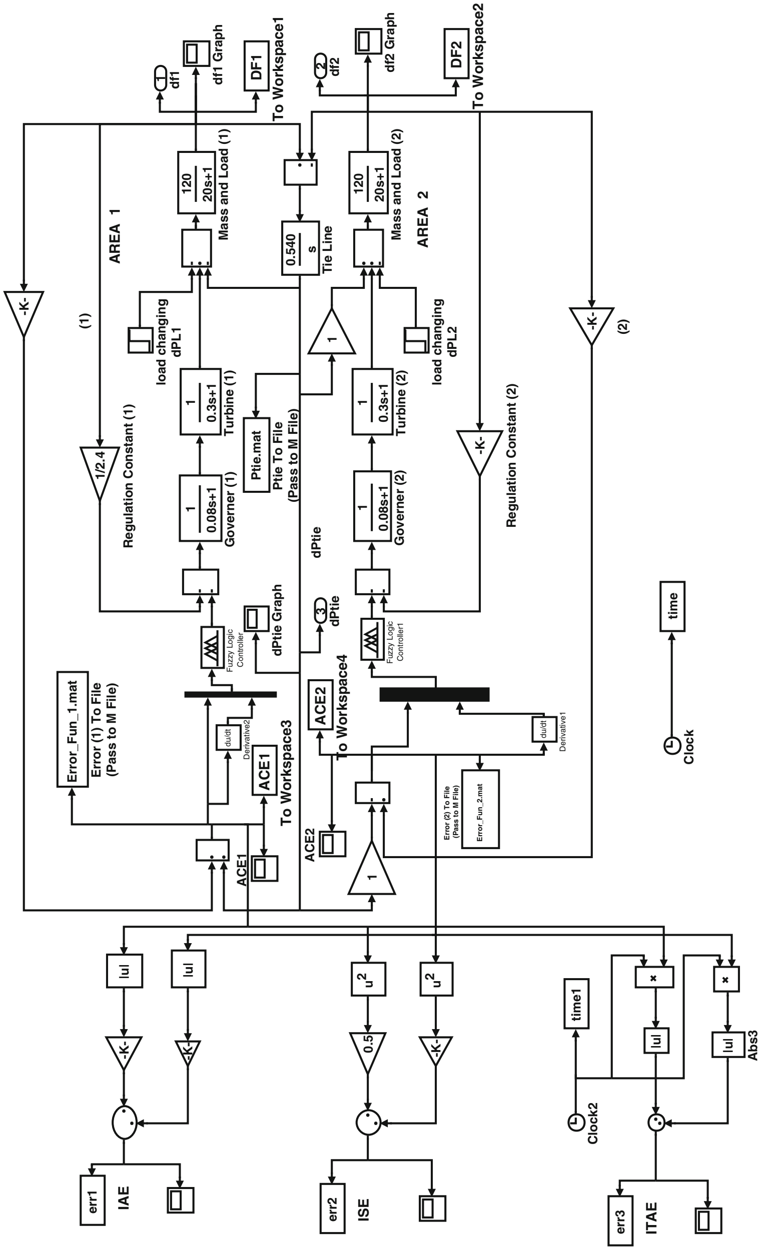

Fig. 17 Two-area power systems SIMULINK model using adaptive fussy controller ANFIS

Table 5 Comparison between PSO, AWPSO, AACPSO and ANFIS

Item of comparison	PSO	AWPSO	AACPSO	ANFIS
Max frequency deviation of area 1 (Hz)	1.09E−06	9.03E−06	4.10E−05	0.0
Minimum frequency deviation of area 1 (Hz)	−0.006	−0.0039	−0.0036	−0.002637
Max frequency deviation of area 2 (Hz)	2.07E−06	2.89E−06	4.14E−06	0.0
Minimum frequency deviation of area 2 (Hz)	−0.0026	−8.91E−04	−8.32E−04	−0.001002

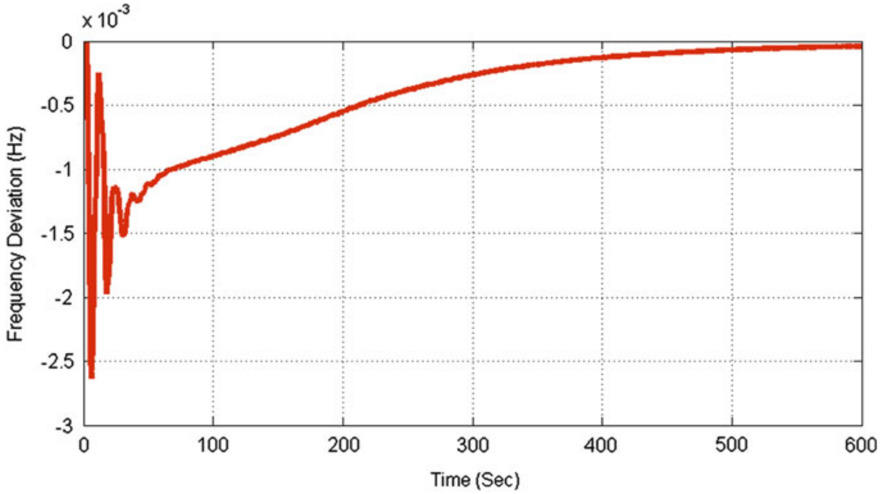

Fig. 18 Frequency deviation of area 1 using ANFIS

By using ANFIS, the results present the performance of the different tuning algorithms for PID controller of the two different areas. Table 5 shows the comparison between the four methods (PSO, AWPSO, AACPSO and ANFIS) used and shows the values of the maximum and minimum values of the frequency deviation of each area. Figures 18 and 19 illustrate the frequency deviation responses of area 1 and area 2 power systems controller tuned by using ANFIS.

The results in Table 5, Figs. 18 and 19 show that:

The maximum frequency deviation value of Area 1 in case of using ANFIS is the smallest value than other methods. PSO comes next after ANFIS method. The minimum Frequency deviation of area 1 using ANFIS is near the value by AACPSO and AWPSO. While; the settling time in case of ANFIS is about 600 s, this value is very big and not accepted because the range of permissible value of settling time is between (0–30 s) as presented in [26].

In area 2 the maximum frequency deviation by using PSO is near the value by using AWPSO and the best method used is ANFIS. However, the minimum

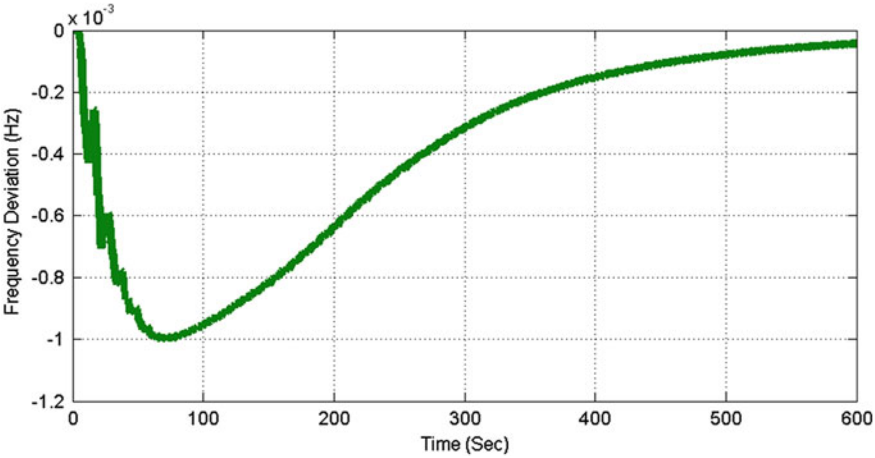

Fig. 19 Frequency deviation of area 2 using ANFIS

frequency deviation using ANFIS is the best and smaller value than other methods. But the settling time is very big value it is about 600 s and off course this value is not acceptable.

Generally, the result shown in Tables 4 and 5 indicate that:

1. The settling time in case of using AACPSO is smaller than its value by using PSO, AWPSO and ANFIS.
2. The maximum frequency deviation in case of using ANFIS is smaller than PSO, AWPSO and AACPSO.
3. The Settling time in case of using ANFIS is not acceptable.
4. Also the disadvantages of ANFIS here in case of IAE Performance Indices which make the using of ANFIS is not acceptable here and take AACPSO as the best method, but ANFIS has many advantages also like it is simple and easy to use compared with the other methods used in this study and it takes less time in the program running.

5.4 Results in Case of Choice ISE Error

Repeating the study with the next type of performance indices which is Integral of Squared Error ISE. Using the same network system presented in Fig. 3, MATLAB program and the parameters display before in Tables 1 and 2.

The study of the performance of the PID controller was compared in case of each intelligent technique (PSO, AWPSO, and AACPSO) and finally the best results of them will use in ANFIS algorithms. Table 6 displays the comparison of the results of the MATLAB program with PSO, AWPSO, and AACPSO. The figures which

Table 6 The results of the program using PSO, AWPSO and AACPSO

Item of comparison	PSO	AWPSO	AACPSO
Number of iterations	500	500	500
Error ISE (integral of absolute error)	4.99E−05	4.78E−05	4.98E−05
Settling time _Area 1 (s)	7.0179	2.2362	1.9323
Settling time _Area 2 (s)	8.4312	4.2489	4.1854
Settling time _Tie line (s)	8.697	4.3416	4.2082
Kp1	5.4209	6.3466	8.1472
Ki1	3.9619	5.7263	7.5774
Kd1	5.1968	2.5784	2.7603
Kp2	0.6806	5.015	3.4998
Ki2	7.64	1.6752	1.6218
Kd2	2.4418	5.6665	8.6869

show the wave form of the frequency deviation of area 1 and area 2 without using PID controller shown above in Figs. 5 and 6.

In the following sections discuss the impact the way the AI techniques used on the Tie Line and area control error ACE of the system.

5.4.1 Tie Line Power

Table 7 presents the comparison between the values of the maximum, minimum frequency deviations and settling time of the Tie line at different types of Artificial Intelligence techniques (PSO, AWPSO and AACPSO).

Figure 20 displays the frequency change of the Tie line power with using PSO, AWPSO and AACPSO based PID controller.

The results display in Tables 7 and Fig. 20 show that:

1. The settling time of Tie line in case of using AACPSO is less than its value in case of using AWPSO by about 0.13 s, and less its value when using PSO by about 4.5 s.

Table 7 Tie line behavior at different typed of control

Items of comparison	PSO	AWPSO	AACPSO
Settling time _Tie line (s)	8.697	4.3416	4.2082
Maximum frequency of tie line power (Hz)	2.59E−05	5.24E−07	4.24E−07
Time at Maximum frequency of tie line power (s)	6.5054	6.5591	22.2727
Minimum frequency of tie line power (Hz)	−4.65E−04	−4.46E−04	−3.66E−04
Time at minimum frequency of tie line power (s)	1.4896	0.7096	0.612

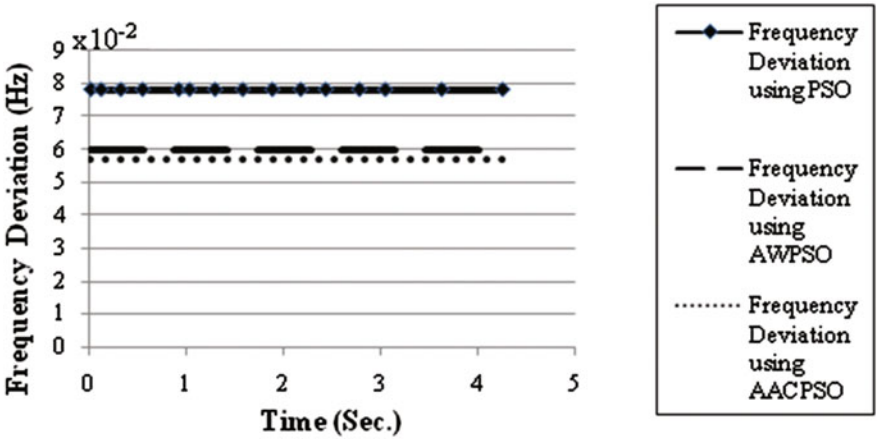

Fig. 20 Tie line power changes using PSO, AWPSO and AAPSO Based PID controller in case of choice ISE error

2. The maximum frequency of Tie line power in case of using AACPSO is less than its value of the other methods of controller used by a very small value.
3. In general the maximum frequency of Tie line power is construed to be zero.
4. Time at maximum frequency deviation of Tie line power in case of using AACPSO is much larger than the other values of PSO and AWPSO. But the value of the time at PSO and AWPSO is almost the same.
5. The minimum frequency deviation of Tie line power in case of using PSO and AWPSO are almost equal. And its value in case of AACPSO is smaller than PSO and AWPSO by a very small value near zero. All the valve of minimum frequency deviation almost is zero.
6. Time at minimum power in case of using AACPSO is less than the other values of PSO and AWPSO. The difference between that time in case of AACPSO and AWPSO is about 0.1 s and its value between AACPSO and PSO is about 0.88 s.

5.4.2 Integral of Squared Error of Area 1 and Area 2

The second choice of the MATLAB program used in this study is ISE as described above. In the following there are the figures describe the output of the system after controlling the error on area 1 and area 2.

From the results shown in Table 6 and also the figures all these show that:

1. The settling time of area 1 in case of using AWPSO is less than the settling time using PSO by 4.78 s to reach to the steady state. While; by using AACPSO the settling time is less than that value by using AWPSO by 0.03 s. So the best method used to reach minimum value of settling time in area 1 is AACPSO.
2. The parameters value of area 1 PID controller (K_{p1}, K_{i1}, K_{d1}) also shown in Table 6.

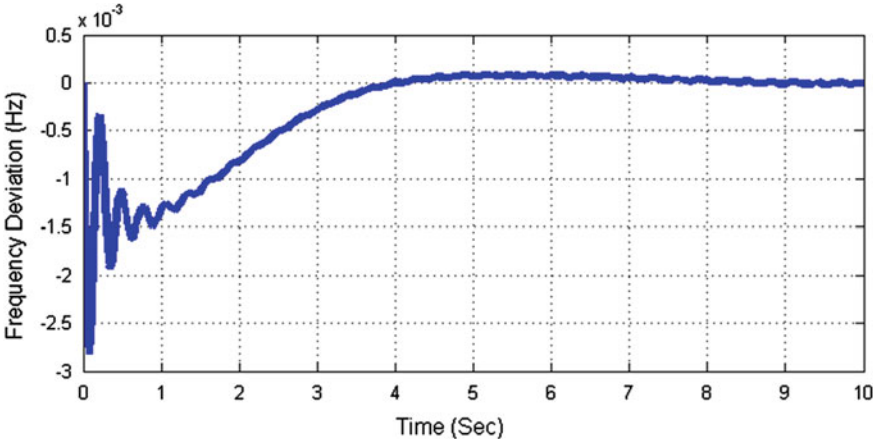

Fig. 21 The frequency deviation of area 1 with PSO based PID controller using ISE performance indices

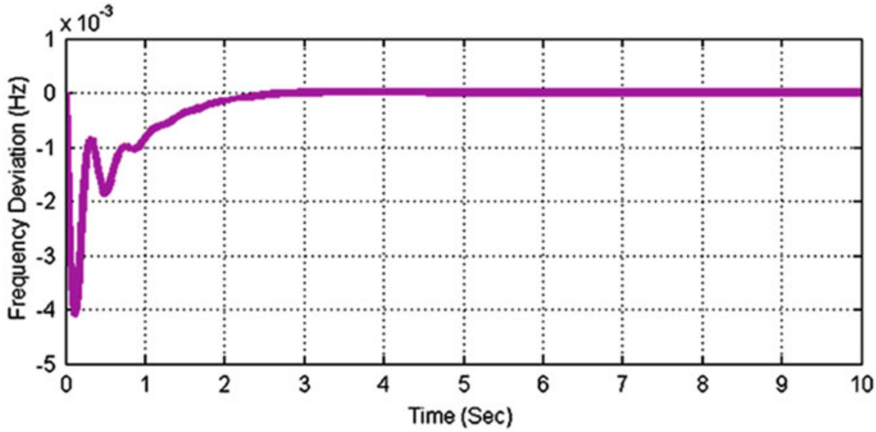

Fig. 22 The frequency deviation of area 1 with AWPSO based PID controller using ISE performance indices

Figure 21 presents the frequency deviation of area 1 with PSO based PID Controller, Fig. 22 presents the frequency deviation of area 1 with AWPSO based PID controller and Fig. 23 illustrates the frequency deviation of area 1 with AACPSO based PID controller.

The figures present the behavior of area 2 in different cases of Artificial Intelligence techniques as follow.

Figure 24 shows the frequency deviation of area 2 with PSO based PID controller using ISE performance indices; Fig. 25 presents the behavior of the frequency deviation of area 2 in case of using AWPSO, while; Fig. 26 displays the frequency deviation of area 2 with AACPSO based PID controller.

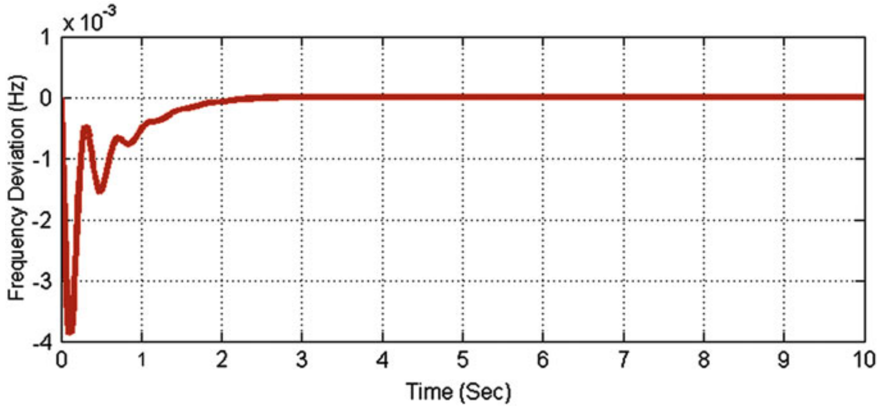

Fig. 23 The frequency deviation of area 1 with AACPSO based PID controller using ISE performance indices

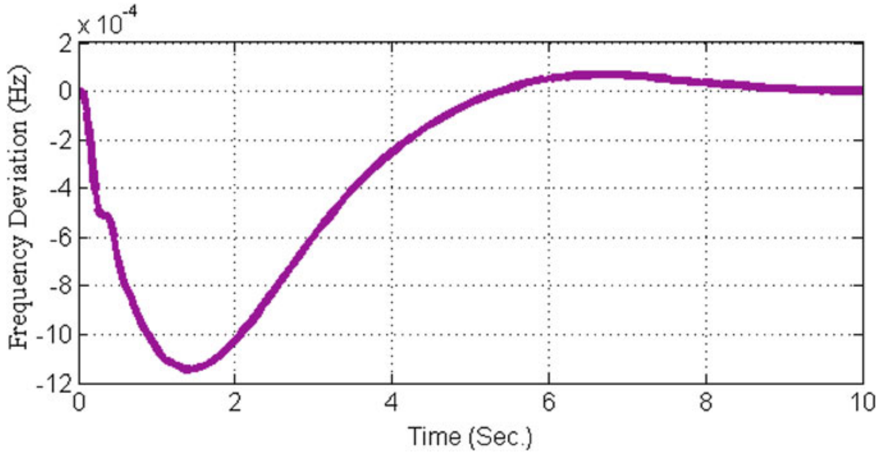

Fig. 24 The frequency deviation of area 2 with PSO based PID controller using ISE performance indices

Figure 27 presents error index (ISE) of area control error ACE of the system with PSO. Figure 28 displays error index (ISE) of ACE of the system with AWPSO. While; Fig. 29 shows error index (ISE) of the system with ACE with AACPSO.

These Figs. 27, 28 and 29 show the change of the frequency deviations of the system with the change of AI techniques (PSO, AWPSO and AACPSO). From all these figures and values shown in Table 6. All previous results indicate that the best way using to reduce the ISE error of the two area power systems is AACPSO.

Because of the results of AACPSO which is the best results of all methods to have a minimum value of ISE error at a small value of settling time. So using these values to make a training of ANFIS. Figure 17 was shown above presents the two-

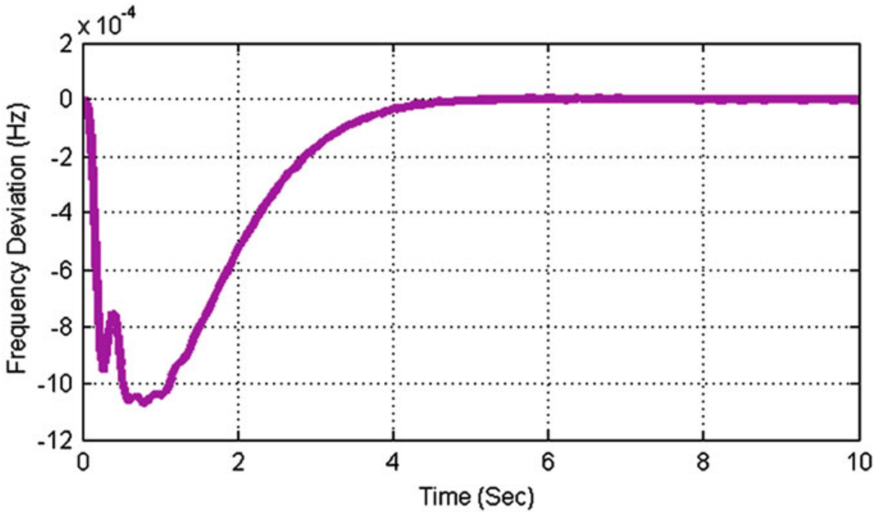

Fig. 25 The frequency deviation of area 2 with AWPSO based PID controller using ISE performance indices

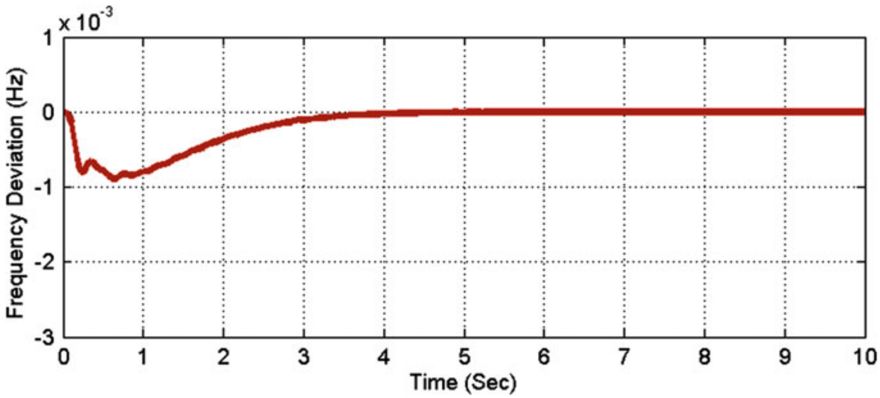

Fig. 26 The frequency deviation of area 2 with AACPSO based PID controller using ISE performance indices

Area Power Systems SIMULINK Model using ANFIS controller and all necessary changes of the model.

By using ANFIS, the results present the performance of the different tuning algorithms for PID controller of the two different areas. Table 8 shows the comparison between the four methods (PSO, AWPSO, AACPSO and ANFIS) used and shows the values of the maximum and minimum values of the frequency deviation of each area.

Figures 30 and 31 illustrate the frequency deviation responses of area 1 and area 2 power systems controller tuned by using ANFIS.

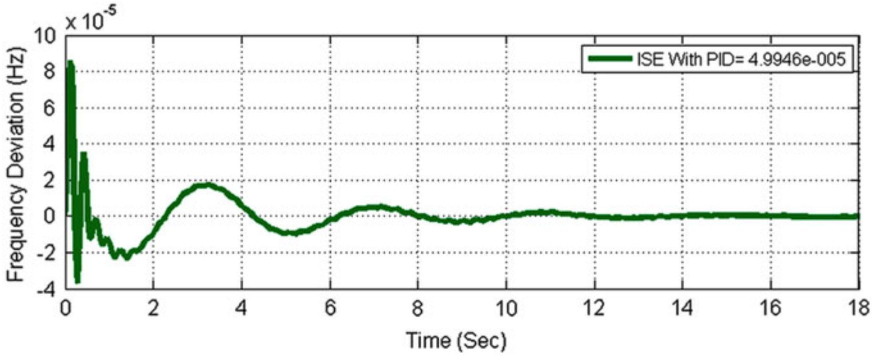

Fig. 27 Error index of ACE with PSO based PID controller in case of choice ISE error

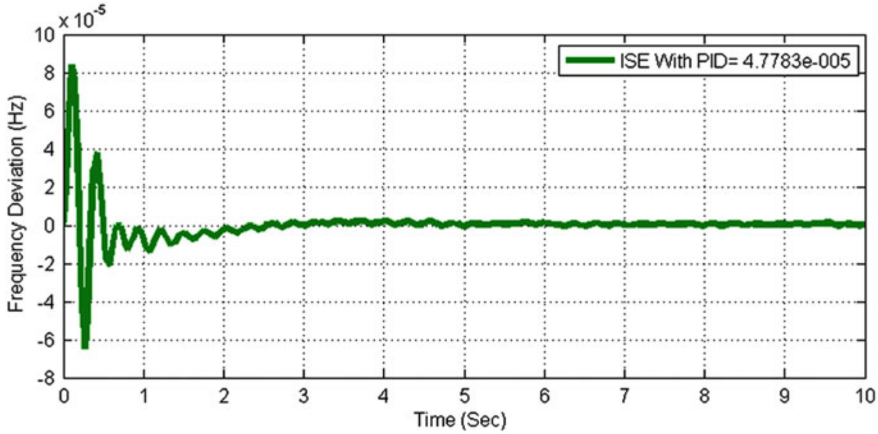

Fig. 28 Error index of ACE with AWPSO based PID controller in case of choice ISE error

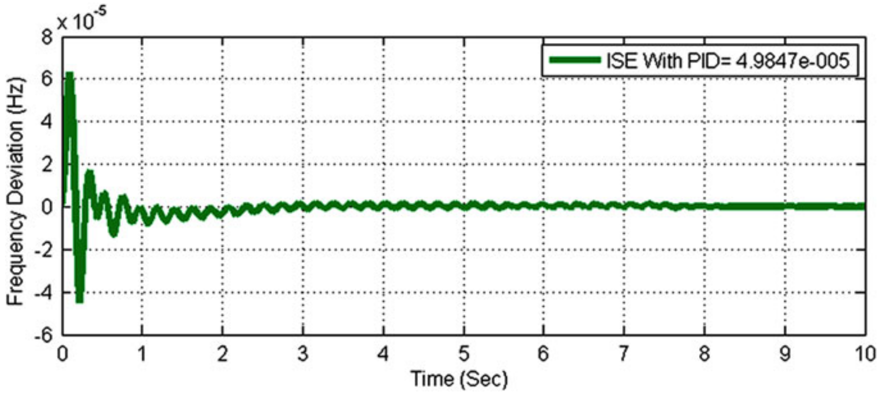

Fig. 29 Error index of ACE with AACPSO based PID controller in case of choice ISE error

Table 8 Comparison between PSO, AWPSO, AACPSO and ANFIS

Item of comparison	PSO	AWPSO	AACPSO	ANFIS
Max frequency deviation of area 1 (Hz)	8.63E−05	1.77E−05	9.03E−06	0.0003608
Minimum frequency deviation of area 1 (Hz)	−0.0028	−0.0041	−0.0039	−0.002098
Max frequency deviation of area 2 (Hz)	6.91E−05	3.83E−06	2.89E−06	0.0
Minimum frequency deviation of area 2 (Hz)	−1.10E−03	−0.0011	−8.91E−04	−0.001035

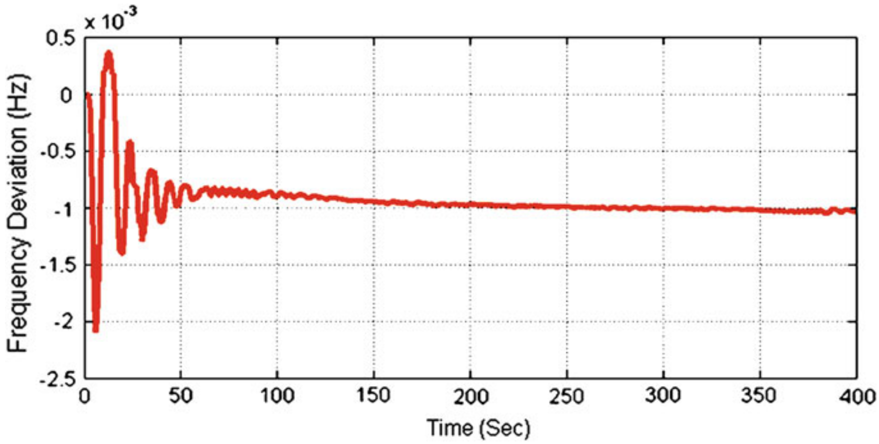

Fig. 30 Frequency deviation of area 1 using ANFIS

The results in Table 8, Figs. 30 and 31 show that:

1. The maximum frequency deviation value of Area 1 in case of using ANFIS is the biggest value than other methods. PSO comes next after ANFIS method.
2. The minimum Frequency deviation of area 1 using ANFIS is near the value by AACPSO.
3. While; the time in case of ANFIS is about 150 s, this value is very big and not accepted because the range of permissible value of settling time is between (0–30 s) as presented in [27].
4. In area 2 the maximum frequency deviation by using AWPSO is near the value by using AACPSO and the best method used is AWPSO. However, the minimum frequency deviation using AWPSO.
5. The maximum frequency deviation by using ANFIS is almost zero. But the settling time is very big value and not acceptable.

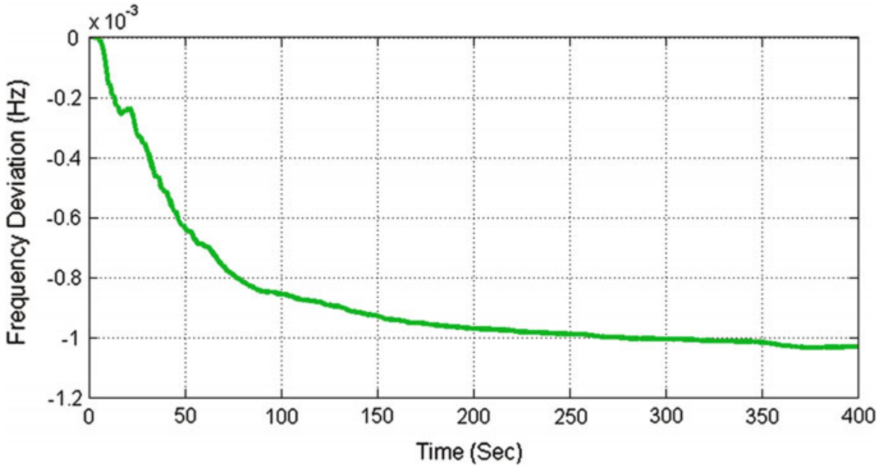

Fig. 31 Frequency deviation of area 2 using ANFIS

Generally, the result shown in Tables 6 and 8 indicate that:

1. The settling time in case of using AACPSO is smaller than its value by using PSO, AWPSO and ANFIS.
2. ANFIS is not acceptable here because of the very large settling time.
3. Also the disadvantages of ANFIS here in case of ISE Performance Indices which make the using of ANFIS is not acceptable here and take AACPSO as the best method, but ANFIS has many advantages also like it is simple and easy to use compared with the other methods used in this study and it takes less time in the program running.

5.5 Results in Case of Choice ITAE Error

Repeating the study with the next type of performance indices which is Integral of Time Weighted Absolute Error (ITAE). Using the same network system presented in Fig. 3, MATLAB program and the parameters display before in Tables 1 and 2.

The study of the performance of the PID controller was compared in case of each intelligent technique (PSO, AWPSO, and AACPSO) and finally the best results of them will use in ANFIS algorithms. Table 9 displays the comparison of the results of the MATLAB program with PSO, AWPSO, and AACPSO. The figures which show the wave form of the frequency deviation of area 1 and area 2 without using PID controller shown above in Figs. 5 and 6.

In the following sections discuss the impact the way the AI techniques used on the Tie Line and area control error ACE of the system.

Table 9 The results of the program using PSO, AWPSO and AACPSO

Item of comparison	PSO	AWPSO	AACPSO
Number of iterations	500	500	500
Error ITAE (integral of time weighted absolute error)	0.0834	0.0608	0.0405
Settling time _Area 1 (s)	3.4403	1.8334	1.7267
Settling time _Area 2 (s)	6.0358	3.3931	2.5288
Settling time _Tie line (s)	5.9679	3.5421	2.5696
Kp1	9.6238	8.8698	3.7517
Ki1	6.1351	9.1419	6.0754
Kd1	4.5189	3.9391	0.8947
Kp2	2.882	3.5254	4.9802
Ki2	8.398	8.0131	1.2982
Kd2	5.5715	3.5553	8.4839

5.5.1 Tie Line Power

Table 10 presents the comparison between the values of the maximum, minimum frequency deviations and settling time of the Tie line at different types of Artificial Intelligence techniques (PSO, AWPSO and AACPSO).

Figure 32 displays the frequency change of the Tie line power with using PSO, AWPSO and AACPSO based PID controller.

The results display in Tables 9 and 10, Fig. 32 show that:

1. On the Tie line power, the value of settling time in case of using AACPSO is the best results and has a smaller value comparing with the other methods used (PSO, AWPSO).
2. The settling time of Tie line in case of using AACPSO is less than its value in case of using AWPSO by about 0.97 s, and less than its value when using PSO by about 3.4 s.
3. Settling time by AWPSO is smaller than using PSO by 2.4 s.
4. The maximum frequency of Tie line power in case of using AWPSO is less than its value of the other methods of controller used by a very small value.
5. The maximum frequency of Tie line power in both AACPSO and PSO is almost equal.

Table 10 Tie line behavior at different typed of control

Items of comparison	PSO	AWPSO	AACPSO
Settling time _Tie line (s)	5.9679	3.5421	2.5696
Maximum frequency of tie line power (Hz)	4.01E−07	5.59E−06	4.98E−07
Time at Maximum frequency of tie line power (s)	23.5062	4.6552	4.0135
Minimum frequency of tie line power (Hz)	−3.22E−04	−3.15E−04	−9.13E−04
Time at minimum frequency of tie line power (s)	0.7932	0.5915	0.442

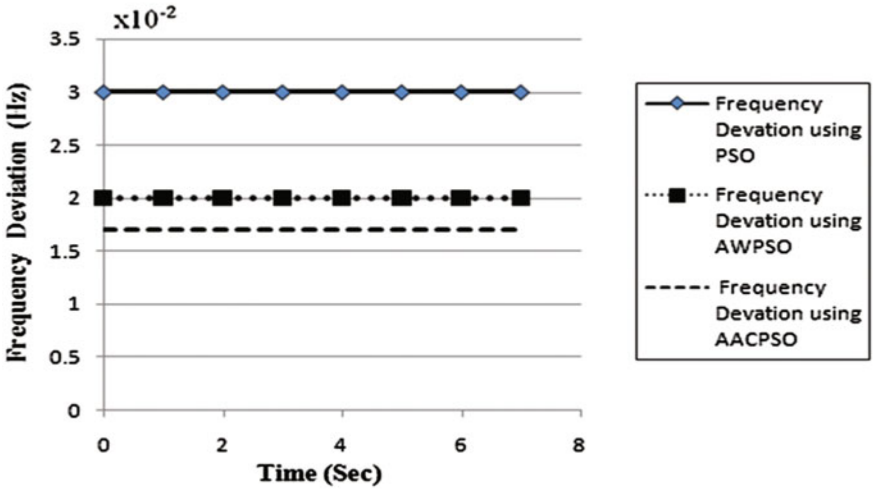

Fig. 32 Tie line power changes using PSO, AWPSO and AAPSO based PID controller in case of choice ITAE error

6. In general the maximum frequency of Tie line power is construed to be zero.
7. Time at maximum power in case of using AACPSO is less than the other values of PSO and AWPSO. This value is less than the time of maximum power in case of using PSO by about 19.5 s and less than its value in case of using AWPSO by about 0.64 s.
8. The minimum Tie line power in case of using PSO and AWPSO are almost equal.
9. The minimum Tie line power in case of using AACPSO is less than its value in case of using PSO and AWPSO.
10. Time at minimum power in case of using AACPSO is less than the other values of PSO and AWPSO.

5.5.2 Integral of Time Weighted Absolute Error of Area 1 and Area 2

The third choice of the MATLAB program used in this study is ITAE as described above. In the following there are the figures describe the output of the system after controlling the error on area 1 and area 2.

Figure 33 presents the frequency deviation of area 1 with PSO based PID Controller, Fig. 34 displays the frequency deviation of area 1 with AWPSO based PID controller and Fig. 35 illustrates the frequency deviation of area 1 with AACPSO based PID controller.

From the results shown in Table 9 and also the Figs. 33, 34 and 35 all these show that:

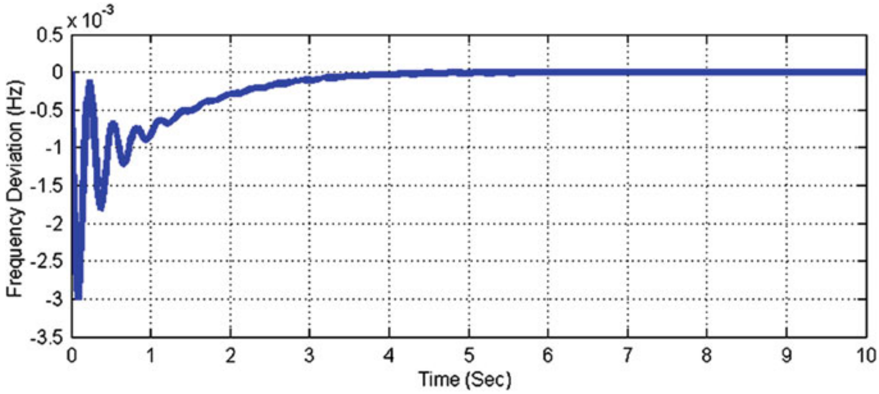

Fig. 33 The frequency deviation of area 1 with PSO based PID controller using ITAE performance indices

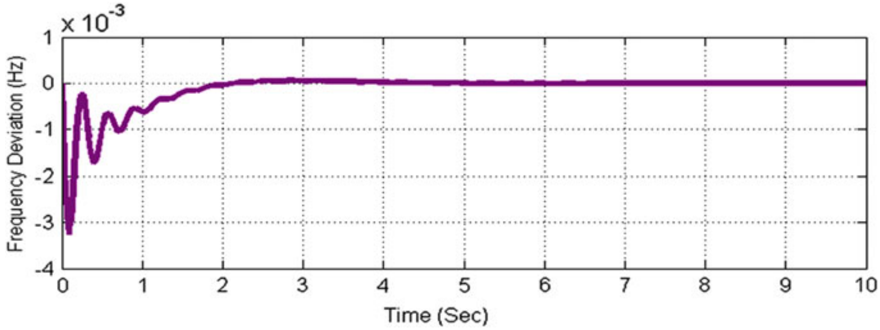

Fig. 34 The frequency deviation of area 1 with AWPSO based PID controller using ITAE performance indices

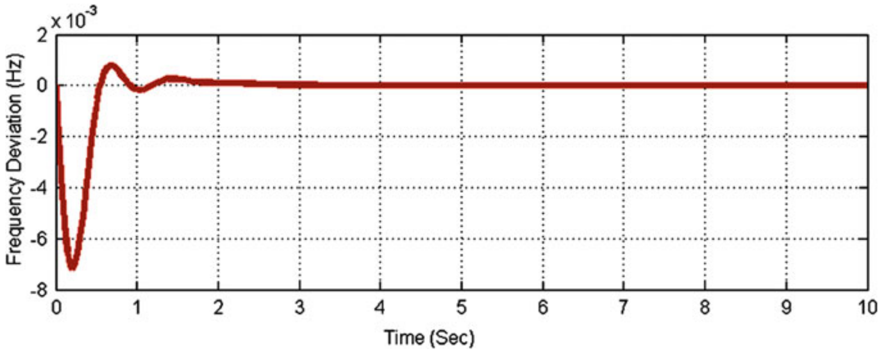

Fig. 35 The frequency deviation of area 1 with AACPSO based PID controller using ITAE performance indices

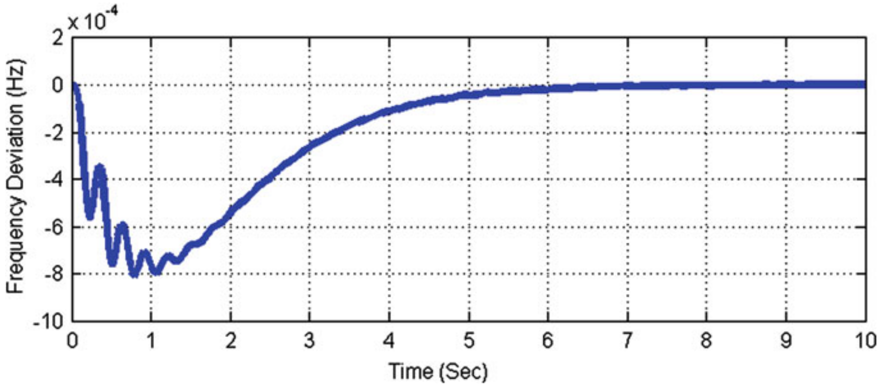

Fig. 36 The frequency deviation of area 2 with PSO based PID controller using ITAE performance indices

1. The ITAE value in case of using AACPSO is less than these values by using PSO and AWPSO. The value of ITAE by using AACPSO is less than PSO by about 0.04 and less than that value by using AWPSO by about 0.02.
2. The settling time of area 1 to reach to the steady state in case of using AACPSO is less than the value of settling time using PSO by about 1.7 s.
3. The settling time by using AACPSO in the program is less than that value by using AWPSO by about 0.1 s.
4. All these results present that: the best method used to reach the minimum ITAE error value at less value of settling time in area 1 is AACPSO.

The next Figures present the behavior of area 2 in different cases of Artificial Intelligence techniques.

Figure 36 shows the frequency deviation of area 2 with PSO based PID controller using ITAE performance indices; Fig. 37 presents the behavior of the frequency deviation of area 2 in case of using AWPSO, while; Fig. 38 displays the frequency deviation of area 2 with AACPSO based PID controller.

From the results shown in Table 9 and also the Figs. 36, 37 and 38 all these show that:

1. The settling time of area 2 by using AWPSO is less than its value by using PSO by 2.64 s. While; the settling time becomes smaller if using AACPSO. The output results using AACPSO is less than the value using AWPSO by 0.86 s. And the value of settling time in case of PSO is almost double the value of settling time when using AWPSO.
2. The parameters value of area 1 PID controller (K_{p2}, K_{i2}, K_{d2}) also presented in Table 9.

The following Figs. 39 and 40 present the shape and values of Integral of Time Weighted Absolute Error ITAE of the system with the using of the different types of control used.

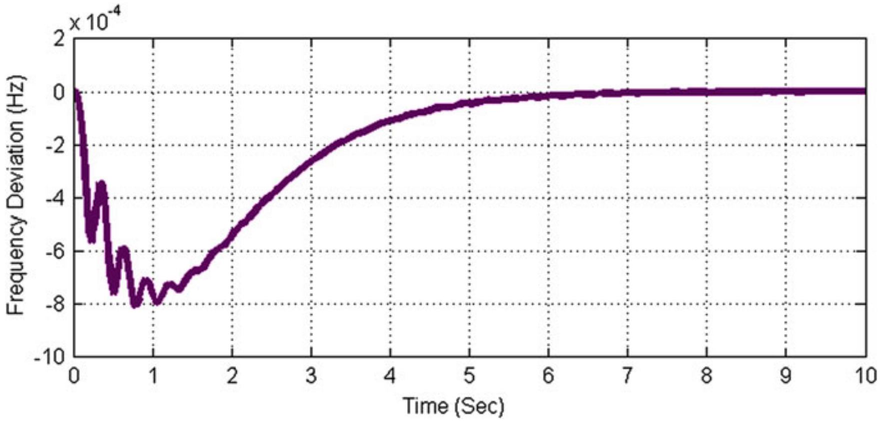

Fig. 37 The frequency deviation of area 2 with AWPSO based PID controller using ITAE performance indices

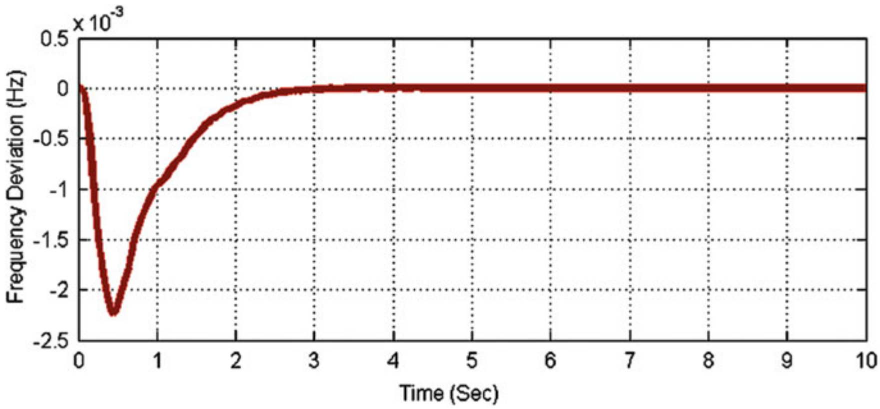

Fig. 38 The frequency deviation of area 2 with AACPSO based PID controller using ITAE performance indices

Figure 39 presents error index (ITAE) of area control error ACE of the system with PSO. Figure 40 displays error index (ITAE) of ACE of the system with AWPSO. While; Fig. 41 presents error index (ITAE) of the system with AACPSO.

All previous results indicate that the best way using to reduce the ITAE error of the two area power systems is AACPSO.

Because of the results of AACPSO which is the best results of all methods to have a minimum value of ITAE error at a small value of settling time. So using these values to make a training of ANFIS. Figure 17 illustrated the two-Area Power Systems SIMULINK Model using ANFIS controller and all necessary changes of the model.

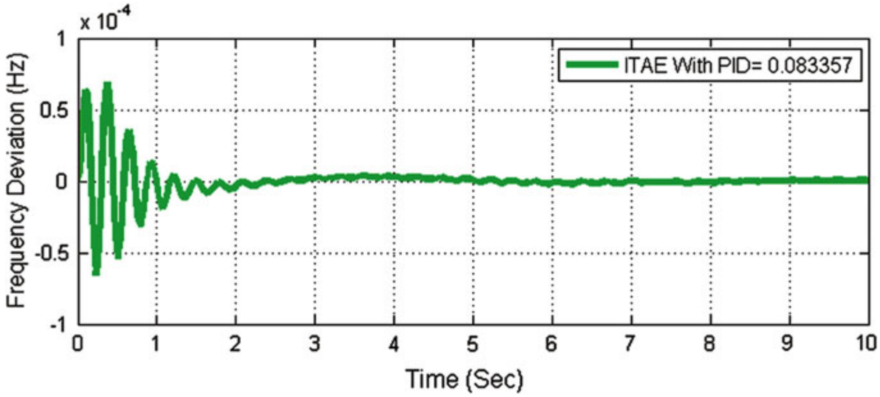

Fig. 39 Error index of ACE with PSO based PID controller in case of choice ITAE error

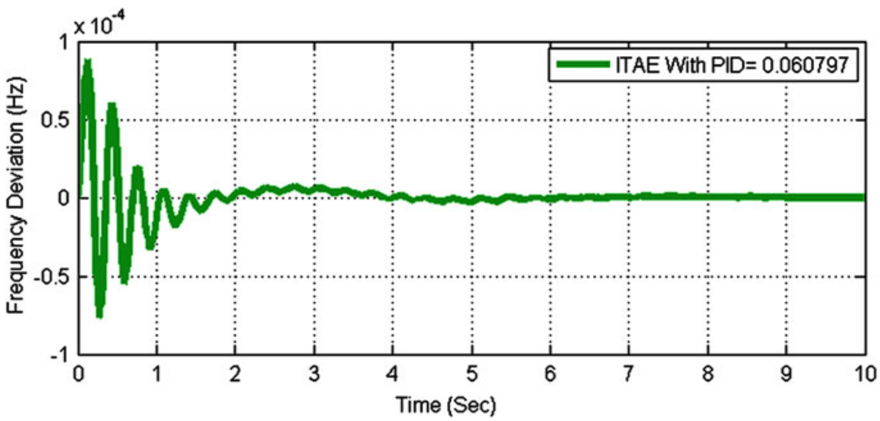

Fig. 40 Error index of ACE with AWPSO based PID controller in case of choice ITAE error

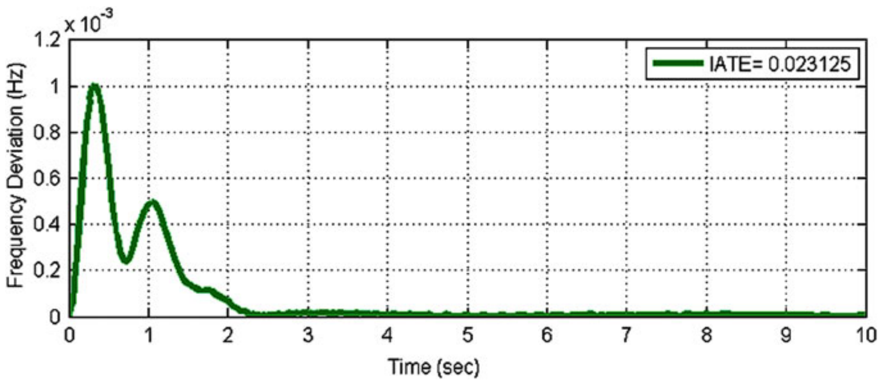

Fig. 41 Error index of ACE with AACPSO based PID controller in case of choice ITAE error

Table 11 Comparison between PSO, AWPSO, AACPSO and ANFIS

Item of comparison	PSO	AWPSO	AACPSO	ANFIS
Max frequency deviation of area 1 (Hz)	4.71E−06	6.45E−05	7.91E−04	2.223E−005
Minimum frequency deviation of area 1 (Hz)	−0.003	−0.0033	−0.0072	−0.002818
Max frequency deviation of area 2 (Hz)	1.77E−06	1.08E−05	4.95E−06	2.857E−006
Minimum frequency deviation of area 2 (Hz)	−8.10E−04	−8.19E−04	−0.0022	−0.0007645

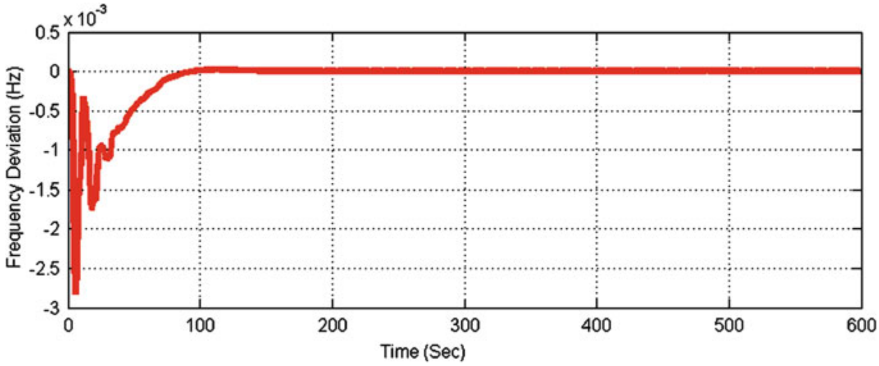

Fig. 42 Frequency deviation of area 1 using ANFIS

By using ANFIS, the results present the performance of the different tuning algorithms for PID controller of the two different areas.

Table 11 shows the comparison between the four methods (PSO, AWPSO, AACPSO and ANFIS) used and shows the values of the maximum and minimum values of the frequency deviation of each area. Figures 42 and 43 illustrate the frequency deviation responses of area 1 and area 2 power systems controller tuned by using ANFIS.

The results in Table 11, Figs. 42 and 43 show that:

1. The maximum frequency deviation value of Area 1 in case of using PSO is the smallest value than other methods. AWPSO comes next after PSO method.
2. The minimum Frequency deviation of area 1 using PSO and AWPSO is almost equal. The value of the minimum Frequency deviation by AACPSO is the smallest value.
3. The settling time in case of ANFIS is about 100 s; this value is very big and not accepted because the range of permissible value of settling time is between (0–30 s) as explained in Rania [27].
4. In area 2 the maximum frequency deviation by using AWPSO is the smallest one. After that PSO comes next.

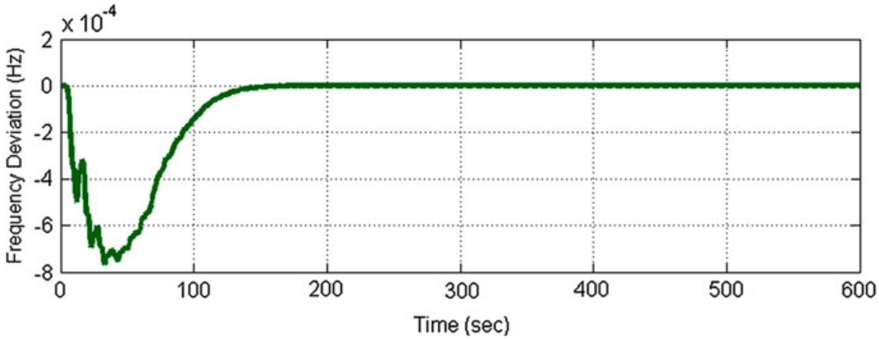

Fig. 43 Frequency deviation of area 2 using ANFIS

5. The difference value between the maximum frequency deviations of area 2 is very small.
6. The minimum frequency deviation in area 2 using ANFIS is the best and smaller value than other methods. But the settling time is very big value it is about 150 s and off course this value is not acceptable.

Generally, the result shown in Tables 9 and 11 indicate that:

1. The settling time in case of using AACPSO is smaller than its value by using PSO, AWPSO and ANFIS.
2. The maximum frequency deviation in case of using ANFIS is smaller than PSO, AWPSO and AACPSO.
3. The Settling time in case of using ANFIS is not acceptable.
4. Also the disadvantages of ANFIS here in case of ITAE Performance Indices which make the using of ANFIS is not acceptable here and take AACPSO as the best method, but ANFIS has many advantages also like it is simple and easy to use compared with the other methods used in this study and it takes less time in the program running.

6 Comparative Study

A comparison study has been carried out with Genetic Algorithm, ordinary PI controller, Ziegler Nichols tuned PID, Bacteria Foraging Optimization (BFO) tuned PID controller as described in [2, 3, 33]. And the results display above for all cases using Particle Swarm Optimization (PSO), Adaptive Weighted Particle Swarm (AWPSO), Adaptive Acceleration Coefficients based PSO (AACPSO), and Adaptive Neuro Fuzzy Inference System (ANFIS) according to the three types of performance Indices (IAE, ISE and ITAE) in order to assess the results.

Table 12 Comparison between different controllers in the first area

Controller	Overshoot (Hz)	Settling Time (s)
Genetic-PID	0.0037	3.6389
BFO based PID	0.0168	4.0415
Ziegler-Nichols PID	0.0149	6.3522
Conventional PI	0.0222	35.0893
AACPSO with IAE	4.10E−05	1.6514
AACPSO with ISE	9.03E−06	1.9323
AACPSO with ITAE	7.91E−04	1.7267

6.1 The First Area

Table 12 displays the Comparison between Adaptive Acceleration Coefficients based PSO (AACPSO), Genetic based PID, BFO based PID, Ziegler-Nicholas Tuned PID and Conventional PI Controller in terms of the frequency deviation in First Area of the power system.

From these results display in Table 12:

1. The settling time of AACPSO with the three types of performance Indices (IAE, ISE and ITAE) was near each other.
2. The result of the settling time by using AACPSO with IAE is the best one from all methods used.
3. The Overshoot value of AACPSO with ISE is small than its value by using other methods of performance Indices.
4. The results by using Conventional PI are the worst one. The value of the settling time is very big and not accepted.

This comparison illustrates that the AACPSO method has the best results of settling time and over shoot frequency deviation for the First Area in all cases studied of performance Indices (IAE, ISE, and ITAE) comparing with the other methods of controller (Genetic based PID, BFO based PID, Ziegler-Nicholas Tuned PID, Conventional PI Controller).

6.2 The Second Area

Table 13 displays the Comparison between Adaptive Acceleration Coefficients based PSO (AACPSO), Genetic based PID, BFO based PID, Ziegler-Nicholas Tuned PID and Conventional PI Controller in terms of the frequency deviation in the Second Area of the system.

From these results:

1. The result of the settling time by using AACPSO with ITAE is the best one from all methods used, so this method is the best one.

Table 13 Comparison between different controllers in the second area

Controller	Overshoot (Hz)	Settling time (s)
Genetic-PID	0.0014	5.208
BFO based PID	0.0123	3.433
Ziegler-Nichols PID	0.0099	8.3539
Conventional PI	0.0178	38.2914
AACPSO with IAE	4.14E−06	3.569
AACPSO with ISE	2.89E−06	4.1854
AACPSO with ITAE	4.95E−06	2.5288

2. The settling time of AACPSO with IAE was near its value by using BFO based PID, but the Overshoot value of AACPSO with IAE is small than its value by using BFO.
3. The overshoot value by using AACPSO with ISE is the best one, but the settling time in this method was bigger than its value by using BFO and AACPSO with IAE and ITAE.
4. The results by using Conventional PI are the worst one. The value of the settling time is very big and not accepted.

6.3 Tie Line Power

Table 14 presents the Comparison between Genetic based PID, BFO based PID, Ziegler-Nicholas Tuned PID and Conventional PI Controller in terms of the Tie Line Power Deviation.

From these results:

1. The result of the settling time by using AACPSO with ITAE is the best one from all methods used.
2. The Overshoot value of AACPSO with ISE is small than its value by using other methods of performance Indices.
3. The overshoot value by using AACPSO in near each other with different methods of performance Indices (IAE, ISE, and ITAE).
4. The results by using Conventional PI are the worst one. The value of the settling time is very big and not accepted.

Table 14 Comparison between different controllers in the tie line

Controller	Overshoot (Hz)	Settling time (s)
Genetic-PID	0.0014	5.208
BFO based PID	0.0123	3.433
Ziegler-Nichols PID	0.0099	8.3539
Conventional PI	0.0178	38.2914
AACPSO with IAE	1.06E−06	3.6553
AACPSO with ISE	4.24E−07	4.2082
AACPSO with ITAE	4.98E−07	2.5696

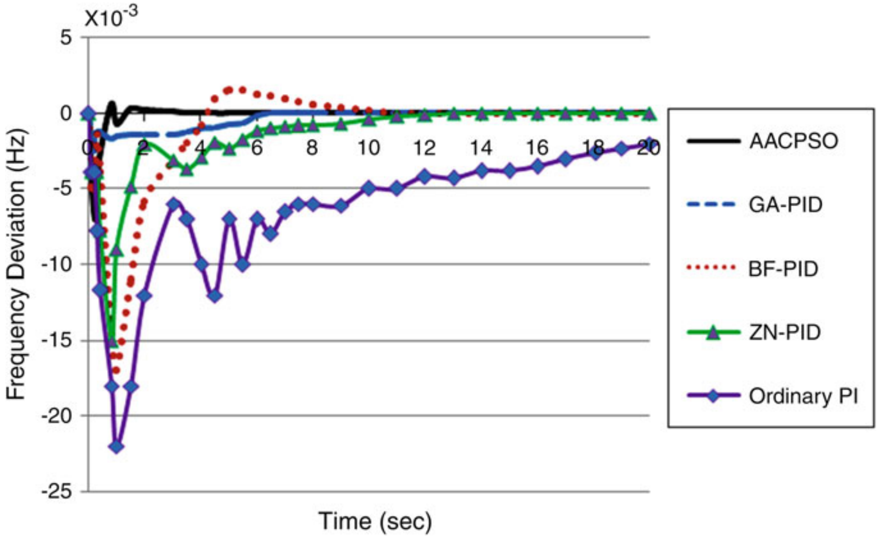

Fig. 44 First area frequency response with AACPAO tuned PID compared to GA-tuned PID, conventional PI, ZN- PID, and BFO-PID

This comparison show that the AACPSO methods have the best results of settling time and over shoot frequency deviation for the Tie line power in all cases studied of performance Indices (IAE, ISE, and ITAE) comparing with the other methods of controller (Genetic based PID, BFO based PID, Ziegler-Nicholas Tuned PID, Conventional PI Controller).

From the results presented in Tables 11, 12 and 13 AACPSO results for first and second area with ITAE performance indices are chosen to compare with Genetic Algorithm, ordinary PI controller, Ziegler Nichols tuned PID and Bacteria Foraging Optimization (BFO) tuned PID controller [2, 3, 33].

Figure 44 presents the time response of the first area using AACPSO tuned PID compared with the Genetic based PID controller with the conventional PI controller, conventionally tuned PID controller (Ziegler Nichols method) and Bacteria Foraging Optimization based PID controller; system was simulated with step change of 0.01 p.u.

Figure 45 presents the time response of the second area using AACPSO tuned PID compared with the Genetic based PID controller with the conventional PI controller, conventionally tuned PID controller (Ziegler Nichols method) and Bacteria Foraging Optimization based PID controller; system was simulated with step change of 0.01 p.u.

Figure 46 displays the time response of the Tie line power using AACPSO tuned PID compared with the Genetic based PID controller with the conventional PI controller, conventionally tuned PID controller (Ziegler Nichols method) and Bacteria Foraging Optimization based PID controller.

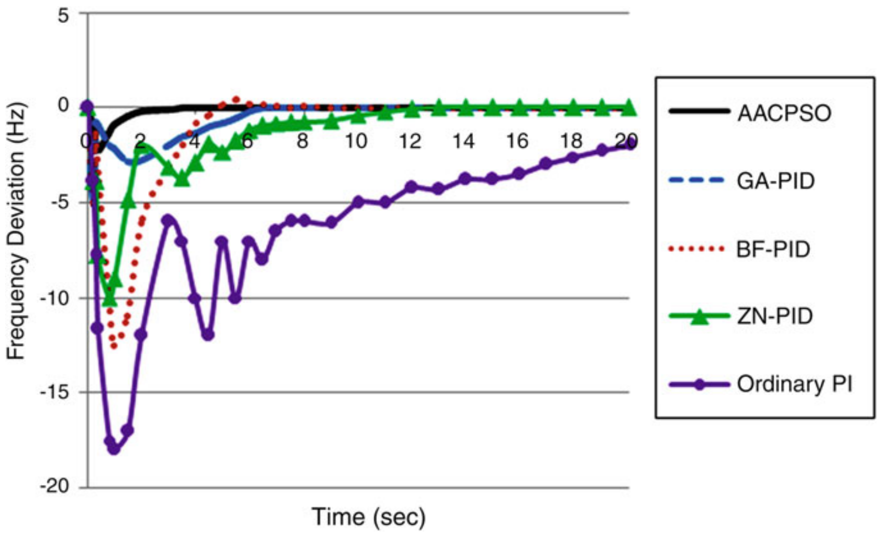

Fig. 45 Second area frequency response with AACPAO tuned PID compared to GA-tuned PID, conventional PI, ZN- PID, and BFO-PID

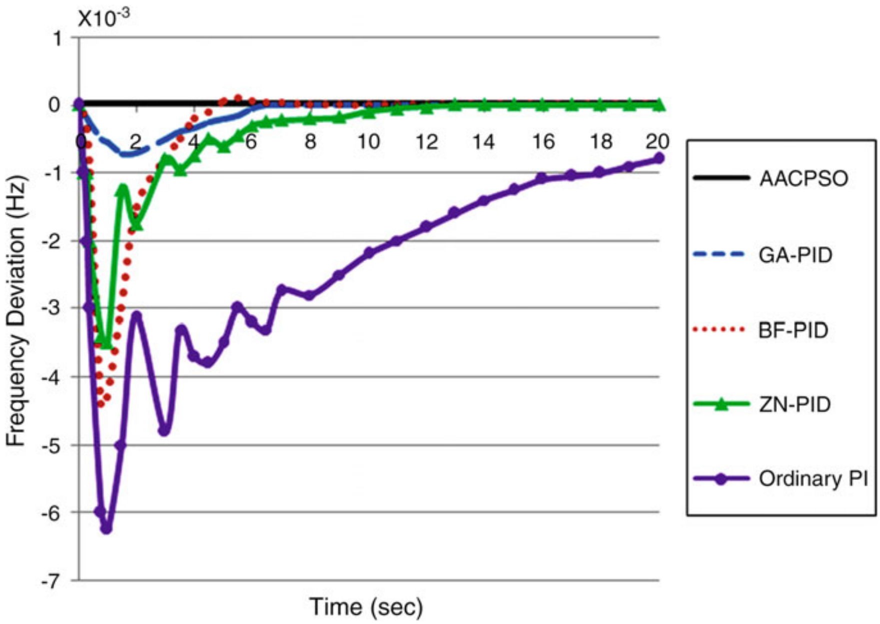

Fig. 46 Tie line power frequency response with AACPAO tuned PID compared to GA-tuned PID, conventional PI, ZN- PID and BFO-PID

7 Conclusion

The simulation of the proposed controllers explained in this chapter, indicate that:

1. Adaptive Acceleration Coefficients based PSO (AACPSO) is the best method which gives the best values of settling time and overshoot frequency deviation comparing with Particle Swarm (PSO) and Adaptive Weighted Particle Swarm (AWPSO).
2. ANFIS was not acceptable here because of the very huge value of settling time when ANFIS used, ANFIS has many advantages also like it is sample and easy to use compared with the other methods used in this study and it takes less time in the program running. ANFIS method is better than using of other methods in some applications especially in case of complicated systems which need to solve the problems in very small time.
3. A comparative study has been carried out for AACPSO which is the best method used to tune the PID controller compared with PSO, AWPSO and ANFIS as presented before*, with* ordinary PI controller; Ziegler Nichols tuned PID, Bacteria Foraging Optimization (BFO) and Genetic tuned PID according to the three types of performance Indices (IAE, ISE and ITAE).
4. This comparative study indicate that the best type of the controller to have the small value of settling time and overshoot frequency deviation was made by PID controller tuning by AACPSO.

Appendix

Transmission line 1 parameters	
K_g1 = 1	
Kt1 = 1	
Tg1 = 0.08	
Tt1 = 20	
R1 = 2.4	
T11 = 20	
Kl1 = 120	
a12 = 1	
Transmission line 2 parameters	
K_g2 = 1	
Kt2 = 1	
Tg2 = 0.08	
Tt2 = 0.33	
R2 = 2.4	

(continued)

(continued)

Transmission line 1 parameters	
T12 = 20	
Kl2 = 120	
N = 25	Number of swarm beings
d = 6	Two dimensional problem
n = 500	Number of iterations
W0 = 0.15	Percentage of old velocity
A0 = 0.5	Acceleration factor constant between [0 1]
C_1 = 2.05	Percentage towards personal optimum
C_2 = 2.05	Percentage towards
x0range = [0 10]	Range of uniform initial distribution of positions
vstddev = 1	Std. deviation of initial velocities
C_{11} = 2	Percentage towards personal optimum used in ACC
C_{22} = 2.05	Percentage towards used in ACC

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