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Frequency Regulation in Hybrid Power Systems

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***Abstract*— combined operation of small generation sources and conventional energy sources is very common due to its inherent benefits. Present work is to investigate the variation in output power generation to load demand in a hybrid power system. This paper presents the comparative performance analysis of optimal load frequency controller problem to minimize frequency deviation and is designed using different optimization algorithms. Further its performance is tested on two hybrid power system configurations such as single area where Thermal Power System (TPS) is integrated with Diesel Engine Generators (DEGs), Wind Turbine Generators (WTGs), Battery Energy Storage System (BESS), Fuel Cells (FCs) and Aqua-Electrolyser (AE) and two area system with DG connected in area-1. The realization of an effective controller is a complicated task in a system with wind generation system results a complicated task due to dynamic nature of wind and random variations in load demand. The present paper proposes a comparative performance of robust PI controller whose parameters are tuned by Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and hybrid GA-PSO. The robustness of the controllers is thoroughly demonstrated on the test systems under various loading conditions.**

Keywords— ***Hybrid power system, Distributed generation, Genetic algorithm, Particle swarm optimization, Frequency controller***

I. Introduction

Generally in the electrical power industry, energy sources are broadly classified into two types, conventional and non-conventional. From past days the nation is dependent on conventional energy sources mostly but if it continues, at some point their existence may be terminated. Conventional energy sources are bulk sources of energy whereas nonconventional sources produce energy in small amounts, so the future demands cannot be met with only nonconventional sources. By integrating small generation sources to conventional generation reliable and high quality service can be provided to consumers and also increased load of an isolated community can be met. Number of small generation sources together called as distributed generation (DG). With the provision of DG system, the consumers in particular area can utilize the small electric power generation resources present in their locality. This combined utilization of DG and conventional power generation commonly called as a hybrid power system. The main aim of the power system is to supply good quality energy to consumers continuously. This can be achieved by proper controlling of power systems operations. Controlling of power system mainly involves voltage and frequency controlling due to the necessity of keeping them constant in both power system and load point of view. The frequency controlling issue is considered in this study, frequency deviation of the system can be maintained within acceptable limits by incorporating suitable controller which maintains the balance between power generation and load demand. In present hybrid power system there is a wind power generation which is more dynamic nature, which adversely affects the system frequency, so it necessary to maintain power balance by implementing automatic load frequency control (ALFC) in the system [1]. The study in this paper involves the design of load frequency controller (LFC) which maintains frequency stable following load and wind power generation variations in hybrid power system with DG resource having a significant effect on the system frequency profile.

The importance hybrid power system and load frequency regulation issue in such a hybrid power system is presented in [1-4]. The modeling of elements of distributed generation is presented in [3]. Brief survey related frequency control of both conventional and non-conventional power systems is presented in [2]. The importance of PI/PID controller and different methods to tune the gains of PI/PID controllers are given in [2, 13].ABC algorithm based PID controller design for LFC in two area power system is presented [15]. In the past, researchers have reported studies on LFC using different optimization techniques in a conventional system consist of thermal/hydro or a combination of them [2, 12, and 15]. The performance of designed controller not only depends on the optimization technique used but also depends on the objective function used for optimization [1]. The optimization techniques are particle swarm optimization (PSO), genetic algorithm (GA) and fuzzy logic are mostly used by many researchers with modifications in objective functions [8-13]. Application of PSO for OPF is presented in [14].The importance of Eigen values location for studying system stability is presented in [6, 7]. PSO based design of load frequency controller is explained in [8, 13]. Usage of a genetic algorithm for optimization is presented by many authors in [9-11].Optimal shifting of Eigen values for improving the system stability is presented in [6, 7].In hybrid GA – PSO technique features of both GA and PSO are combined to overcome limitations of conventional PSO algorithm[5]. Application hybrid GA-PSO for optimization is presented in [5].In this present study power system consists conventional thermal generation and DG, the sources in DG are more dynamic in nature which causes to unintentional structural changes this will further complicate the LFC problem.

This paper explores the design of PI load frequency controller which keeps frequency deviation as less as possible. The gains of PI controller are tuned using hybrid GA-PSO, genetic algorithm (GA) and particle swarm optimization (PSO) techniques. The controller performance is tested for different load disturbance and wind power changes and also for different levels of parameter variations of the power system. The results obtained with different control techniques are compared and it is observed that hybrid GA- PSO giving better results compared to GA and PSO algorithms.

II. TEST SYSTEM

1) Case -1: Single Area Hybrid Power System

In general LFC study limited small perturbationsso the linearized model of the system can be used for the studies. The hybrid power system under study formed by integration conventional thermal generation with the DG which is shown in Fig 3.This also gives the state variables representation for deriving state space model of the system.

The DG system under study consists of energy resources such as WTG, FC, DEG, and BESS. Wind power generation is affected by wind speed so weatherdependent so it may not reach the forecasted conditions exactly. This unpredictable wind generation affects the scheduling of other conventional generation sources and it also causes to active power imbalance.Active power imbalance affects the frequency deviation there by thestability of the system.the controllers for limiting frequency deviation should be designed by considering the effects of wind power variations.Therefore, an appropriate coordination between stability and controllability of active power in wind turbines should be further defined. AE present in DG used for hydrogen production by using part of wind power generation, this hydrogen used in FC to generate power. The BESS is used for the purpose of load leveling in the power system.

Power balance in the proposed system is given by equation (4) which is obtained from the transfer function shown in Fig 3.

$\Delta P_e = \Delta P_{TH+}\ \Delta P_{DGS} - \Delta P_D$ -------- (1)

Where ΔP_e is the mismatch between power generation and load demand, ΔP_{DGS} is the output power generation of DG, ΔP_{TH} is the output power generation by conventional reheat thermal system and ΔP_L is the change in load demand. By utilizing the features each source in DG, reliability and quality of power system can be improved. The designed controllers maintain power balance by sending proper control signals. The details of mathematical models of each source in DG are presented in [1-4].
Total output power generation by DG is given by:

$\Delta P_{DGS} = \Delta P_{WP+}\ \Delta P_{FC} + \Delta P_{AE} + \Delta P_{DEG} \pm \Delta P_{BESS}$ ------- (2)

Where $\Delta P_{WP,}$ ΔP_{FC}, ΔP_{AE}, ΔP_{DEG} and ΔP_{BESS} are the power generations by the WTG, FC, AE, DEG and BESS respectively. The impact of wind power generation is the main factor in the study of LFC issue in hybrid power system with DG sources.

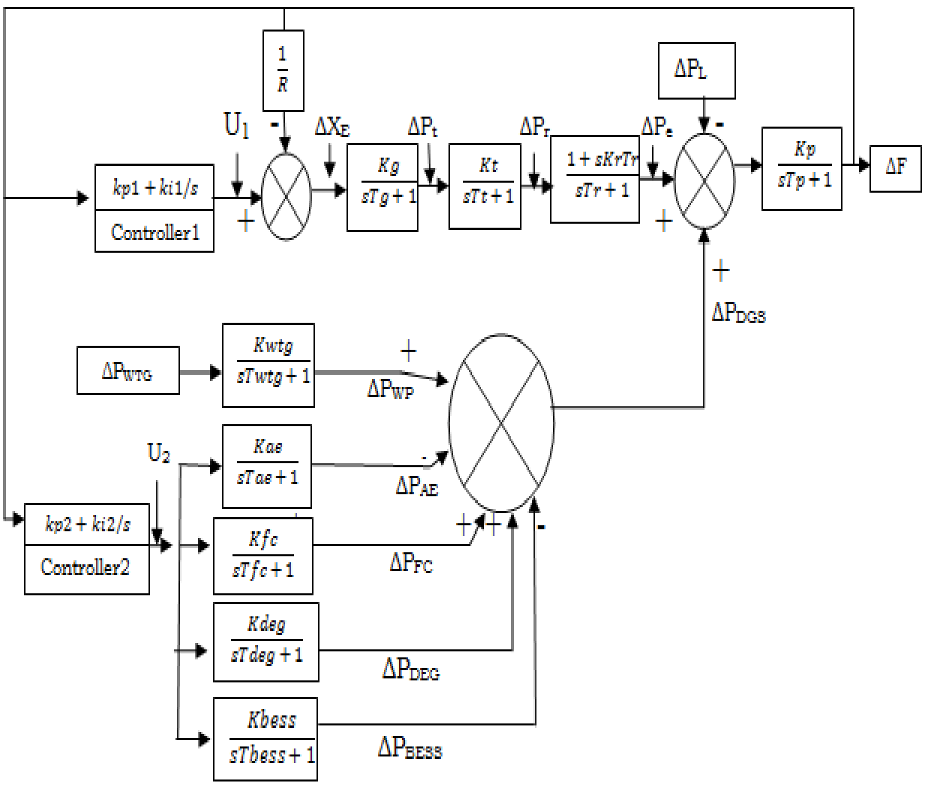


Fig.1 Case -1: Single Area Hybrid Power System -Transfer Function Model

The state space equation for single area hybrid power system can be written as follows:

$x=Ax+B_1w+B_2u$ ------- (3)
$y=Cx$ ------- (4)

In above two equations system state matrices obtained from the transfer function model as shown in Fig. 1

$$x=\begin{bmatrix}\Delta X_E\ \Delta P_t\ \Delta P_r\ \Delta f\ \Delta P_{WP}\ \Delta P_{AE}\ \Delta P_{FC}\\ \Delta P_{DEG}\ \Delta P_{BESS}\ \Delta P_{DGS}\ \int\Delta f\end{bmatrix}^T$$

$W=[\,W_1\ W_2\,]^T$
$U=[\,u_1\ \ u_2\,]^T$
$y=[\Delta f\ \ \int\Delta f]^T$

Where x denotes the system states,w_1&$w_2$are the disturbance inputs.,u_1& u_2 are the controlling inputs.Under steady state condition, the power generation is matched with load demand, then the frequency deviation reaches zero. By utilizing frequency deviation signal as input the designed controllers will send control signals to the system to maintain the power balance which is shown in Fig 1. The input disturbance signals w_1 andw_2 are the load disturbance and wind power variation respectively, i.e.

$W_1=\Delta P_L$; $W_2=\Delta P_{WTG}$

The control signal for proposed power system- 1 is written as:

$u=K_P\,\Delta f+K_i\int\Delta f$

$$=\begin{bmatrix}U_1\\U_2\end{bmatrix}=\begin{bmatrix}\text{Kp1} & Ki1\\ \text{Kp2} & Ki2\end{bmatrix}\begin{bmatrix}\Delta f\\ \int\Delta f\end{bmatrix}=Ky$$

Where K matrix contains the gains of PI controller. For regulating the system frequency the designed controllers will send the command signals to conventional thermal generation and DEG, AE, FC, BESS. In order to define the control parameter vector K, the closed loop system is obtained as below:

$x_{cl}=A_{cl}\,x_{cl}+B_{cl}\,w$ ------ (5)
$u=Ky$
$u=KCy$
$A_{cl}=A+B_2K\,C_2$; $B_{cl}=B_1$

The Eigen values of A_{cl} are nothing but closed system Eigen values. Based on the objective given in equation (9) controller gains are tuned using optimization techniques discussed in section (3)

2) Case-2: Two Area Hybrid Power System:

The two area hybrid power system is formed by incorporation of thermal and DG in area-1 and thermal power in area-2, respectively. The transfer function model is shown in Fig. 2.
The state space equation for two area hybrid power system can be written as follows:

$x=Ax+B_1w+B_2u$ ------ (6)
$y=Cx$ ------ (7)

$$x=\begin{bmatrix}\Delta X_{E1}\ \Delta P_{t1}\Delta P_{r1}\Delta f_1\Delta X_{E\,2}\,\Delta P_{t2}\\ \Delta P_{r2}\Delta f_2\Delta P_{TIE}\Delta P_{WP}\Delta P_{AE}\Delta P_{FC}\\ \Delta P_{DEG}\Delta P_{BESS}\int ACE1\quad \int ACE2\end{bmatrix}^T$$

$W=[\,W_1\ W_2\ W_3]^T$
$U=[\,u_1\ \ u_2\ u_3\,]^T$

$y=[\,ACE1\ \int ACE1\ \ \ ACE2\ \ \int ACE2]^T$

Where x denotes the system states,w_1, w_2&w_3 denotes the disturbance inputs,u_1, u_2& $u_3$are the controlling inputs.As same as the single area hybrid power system the designed controllers will send a control signal to bring the frequency deviation to zero with less error and quickly is shown in Fig 2. The input disturbance signals w_1, $w_2$and w_3 are the load disturbance in area-1, area-2 and wind power variation respectively, i.e.

$W_1=\Delta P_{L1}$; $W_2=\Delta P_{L2}$ $W_2=\Delta P_{WTG}$

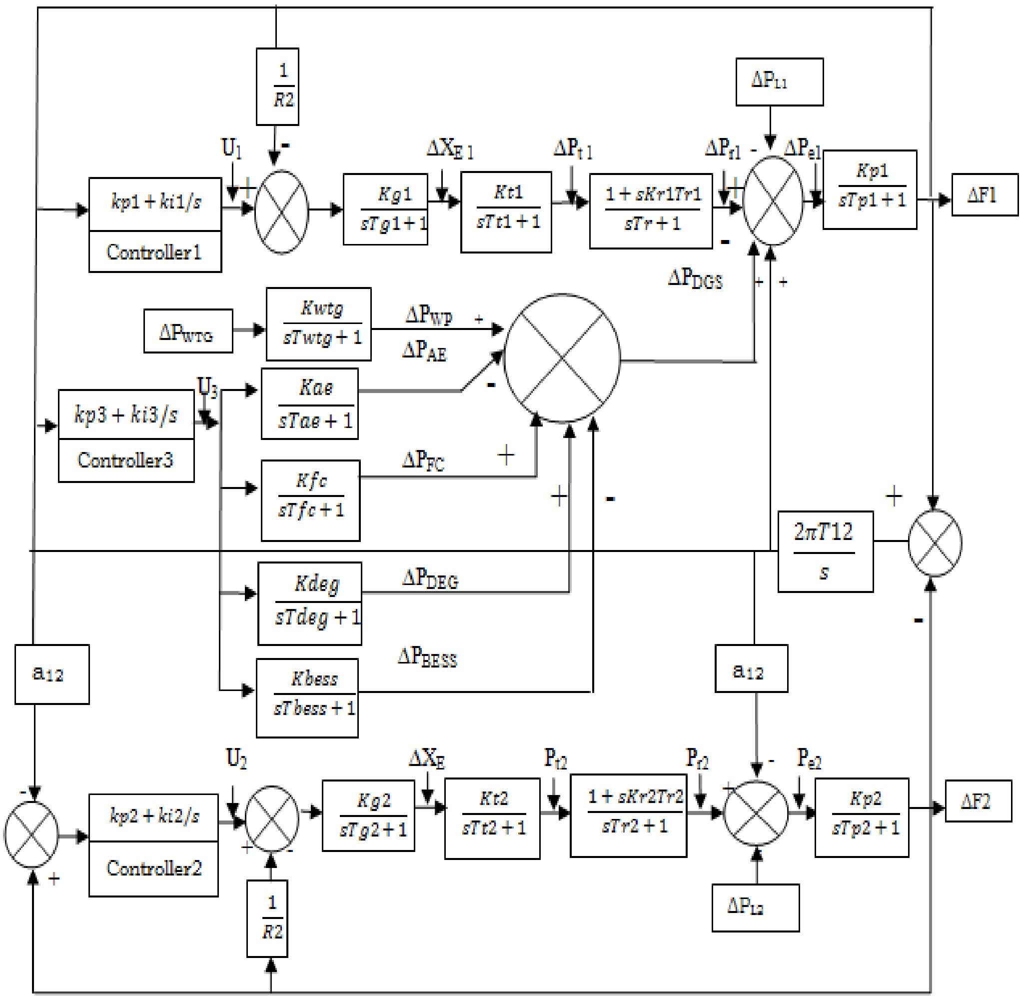


Fig.2 Case study -2: Two Area Hybrid Power System -Transfer Function Model

The control signal for proposed power system- 2 is written as:

$u = K_P\,\Delta f + K_i \int ACE = Ky$

$$= \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \begin{bmatrix} Kp1 & Ki1 & 0 & 0 \\ Kp2 & Ki2 & 0 & 0 \\ 0 & 0 & Kp3 & Ki3 \end{bmatrix} \begin{bmatrix} ACE1 \\ \int ACE1 \\ ACE2 \\ \int ACE2 \end{bmatrix}$$

In order to define the control parameter vector K, the closed loop system is obtained as below:

$y = C_2 x;$
$u = KCy$
$x_{cl} = A_{cl} x_{cl} + B_{cl} w$ -------(8)
$A_{cl} = A + B_2 K C_2;\ B_{cl} = B_1$

Where K matrix contains gains of the PI controller. In the same way as power system -1 gains of the PI controller are tuned using different optimization algorithms based on the objective function given by equation (9). For tuning PI controller gains hybrid GA-PSO, GA and PSO algorithms are used and results are presented in below section.

III. DESIGN OF AN OPTIMAL CONTROLLER

The controller should be designed such way that it reduces frequency deviation of the system to minimum possible level without affecting the stability of the system. The process of obtaining minimum frequency deviation is generally known as optimization. For the optimization purpose, there should be an objective function which represents the mathematical form of controller design requirement. By using optimization techniques the objective function is optimized to achieve desired response. The objective considered in present work is a single objective function which is based on the Lyapunov stability criterion.

The objective function to design the load frequency controller is given by equation(9),based on this objective function the Eigen values of system shifted to the most left of S-plane in order improve the system damping factor, settling time and relative stability. The closed loop Eigen values of the system shifted to the left of the vertical line represented by the desired level damping factor. The parameters of PI controller i.e K_P and K_I are tuned to have the minimum value of the following objective function.

$$J = \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2 \qquad \text{------ (9)}$$

Where,
σ_i = Real part of i^{th} Eigen value
σ_0 = chosen threshold

Where σ_0 is the desired level of damping, in order to achieve this level of damping dominant Eigen values of the systemare shifted to the left of s= σ_0 line in the s-plane. This also improves the relative stability of the system. The $\sigma_i \geq \sigma_0$ condition is considered in objective function in order shift the Eigen values which are located right to the desired level of damping. The value of σ_0 gives the relative stability of the system. This will place the closed loop Eigen values the system in the region formed by condition $\sigma_i \leq \sigma_0$.Genetic algorithm (GA), Particle swarm optimization (PSO) and Hybrid GA-PSO techniques are used to tune the gains of PI controller. Those techniques are briefly discussed below.

1) Conventional PI Controller:

Conventional methods of tuning PI controller are trial & error method and Ziegler Nicholas method. In trail & error method PI controller gains are tuned by observing the response every time for every set gain values and gains are changed the desired response is obtained. Ziegler Nicholas method [2] has proposed certain rules to get the PI controller gains based on the transient response of proposed system. These conventional techniques may not give desired results for this type of complicated systems and they are difficult to apply.

2) *Genetic algorithm (GA):*

It was originally developed by Jon Holland in 1975. Biological evaluation is the inspiration to the development of this algorithm. It was used in the optimization or search problems for computing the true or approximate value of the function. This algorithm has been used to solve the problems whose objective functions are of higher order, multi-modal, discontinuous and non-differentiable. It works on the theory survival fittest, according to this theory, all the species of organisms arise and develop through the natural selection of small, inherited variations that increase the individual's abilities to compete, survive and reproduce. The variables to be optimized are considered as individuals of GA algorithm.

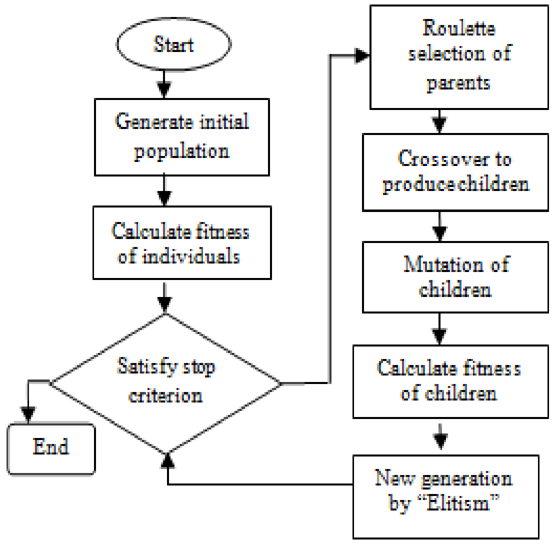


Fig.3 Flow Chart of Genetic Algorithm

The basic operations involved in the GAs are the selection, cross over and mutation. The main disadvantage of GA is there may be a chance of convergence of optimization problem to local optima rather than global optimal. The flow chart of the genetic algorithm is shown in Fig 3.The limitations of this algorithm is Involvement of large number of parameters and convergence towards local optima rather than global optimal. These limitations can be minimized by using PSO algorithm.

3) Particle swarm optimization (PSO):

From the inspiration of social behavior of bird flocking or fish schooling, an evolutionary algorithm particle swarm optimization (PSO) is developed by Dr. Eberhart and Dr. Kennedy in 1995.As same as GA this algorithm also a population based optimization algorithm. The optimization starts with initialization population with random solutions and the optimum solution is obtained by continuous updating generations with the particles having better fitness values, which are evaluated by the fitness function to be optimized. Particles have velocities, which direct the flying of the particles. The particles reach the global optimum solution by following through the current optimum particles. PSO algorithm flow chart is shown in Fig 4.

From the simulation of bird flocking in two-dimensionalspace, PSO algorithm was developed. XY position in two-dimensional spaces represents the position of each agent and V_X and V_Y expresses the velocity of that particular agent. The best value of agent so far is given by pbest and best value so far in the group among pbest is given by gbest. gbest provides the knowledge about the performance of other agents in the population. Modification of the agent position is realized by using the information of current positions, current velocities and the distance of current position from the pbest and gbest.

Modification agent position is done by considering the concept of velocity. The velocity of each agent can be modified by the following equation:

$$V_k{}^{k+1} = V_i{}^K + C_1 * rand1 * (pbest - S_i{}^k) + C_2 * rand2 * (gbest - S_i{}^k) \quad \text{------ (10)}$$

Where

v_i^k - for iteration k velocity of agent i
w - weighing function.
C_1& C_2 - acceleration factors
rand - random number between 0 and 1
$S_i{}^k$ - for iteration k position of agent i
$pbest_i$ - particle best agent i
gbest - global best of the group

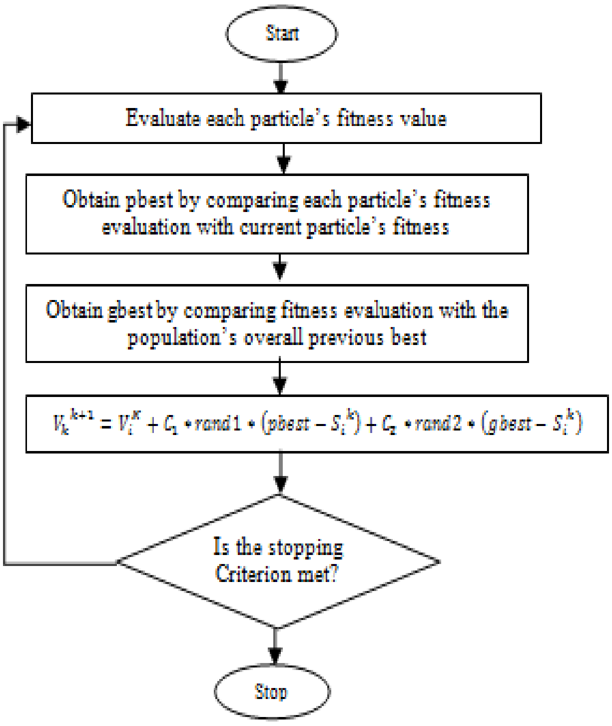


Fig.4 Flow Chart of Particle Swarm Optimization

The weighing function generally utilized is

$$W_i = \frac{W_{max} - W_{mn}}{iter_{max} * iter}$$

Where,
W_{nax} - initial weight
W_{min} - final weight
$iter_{max}$ - maximum iteration number
iter - current iteration number

Particular velocity which gradually gets close to pbest and gbest can be calculated using equation (10). Position agent in each iteration modified using the following equation:

$$S_i^{k+1} = S_i^k + V_i^k \qquad \text{------- (11)}$$

S_i^k current agent position
S_i^{k+1} modified agent position
V_k current velocity
V_{k+1} modified velocity

4) Proposed hybrid GA-PSO:

As the name suggesting this algorithm is the combination of GA and PSO algorithm. This algorithm utilizes the features both algorithms. To overcome the limitation GA and PSO this algorithm was developed. One of the disadvantages of PSO is that the swarm may converge to the point which is not guaranteed for a local optimum [5].This point may be the line between particle best and global best. This problem may also caused by the fast rate of information flow between particles, this increases the possibility of being trapped in local optima due to a loss in diversity.

Another drawback of this type of stochastic approaches is problem-dependent performance. This problem dependent performance is caused by the parameter setting requirement in this type of algorithms. The problem-dependent performance can be addressed by combining advantages of different approaches through the hybrid mechanism. A hybrid algorithm with GA was proposed to overcome the limitations of PSO. This hybrid algorithm is expected have merits of PSO along with GA merits. One major advantage of PSO over GA is it can be easily applied to wide range of problems. GA has the ability to control convergence. One simple way to combine the GA and PSO techniques is an initial population of PSO is assigned by the solution of GA. The total number of iterations is equally shared by GA and PSO. First half of the iterations are run by GA and the solutions are given as initial population of PSO and the remaining iterations are run by PSO.

IV. RESULTS AND ANALYSIS

1) Case -1: single area hybrid power system

Step change load:

The load disturbance and wind power variation applied to the hybrid DG system are considered as ΔP_L=0.01 pu and ΔP_{WTG}=0.01 pu.For knowing about the robustness of design algorithms results are obtained for 40% over loading and 30% under loading conditions. Responses with hybrid GA- PSO, particle swarm optimization(PSO) and genetic algorithm(GA) designed controllers are presented in Fig 5.

In the responses shown in Fig. 5 frequency deviation is less with hybrid GA-PSO based controller compared to conventional PSO and GA based controllers. For over loading and under loading conditions also the system is in stable condition with designed controllers but there is an increase in frequency deviation.

Random step change load:

The random step change load variation as shown in Fig 6(a) and ΔP_{WTG}=0.01 pu are applied to the system. Dynamic response in frequency deviation of the proposed system for these input conditions is shown in Fig. 8 for different loading conditions with different optimization techniques.

Random load change:

The random load variation as shown in 6(b) and ΔP_{WTG}=0.01 pu are applied to the system. Dynamic response in frequency deviation e of the proposed system for these input conditions is shown in Fig 9 for different loading conditions with different optimization techniques.

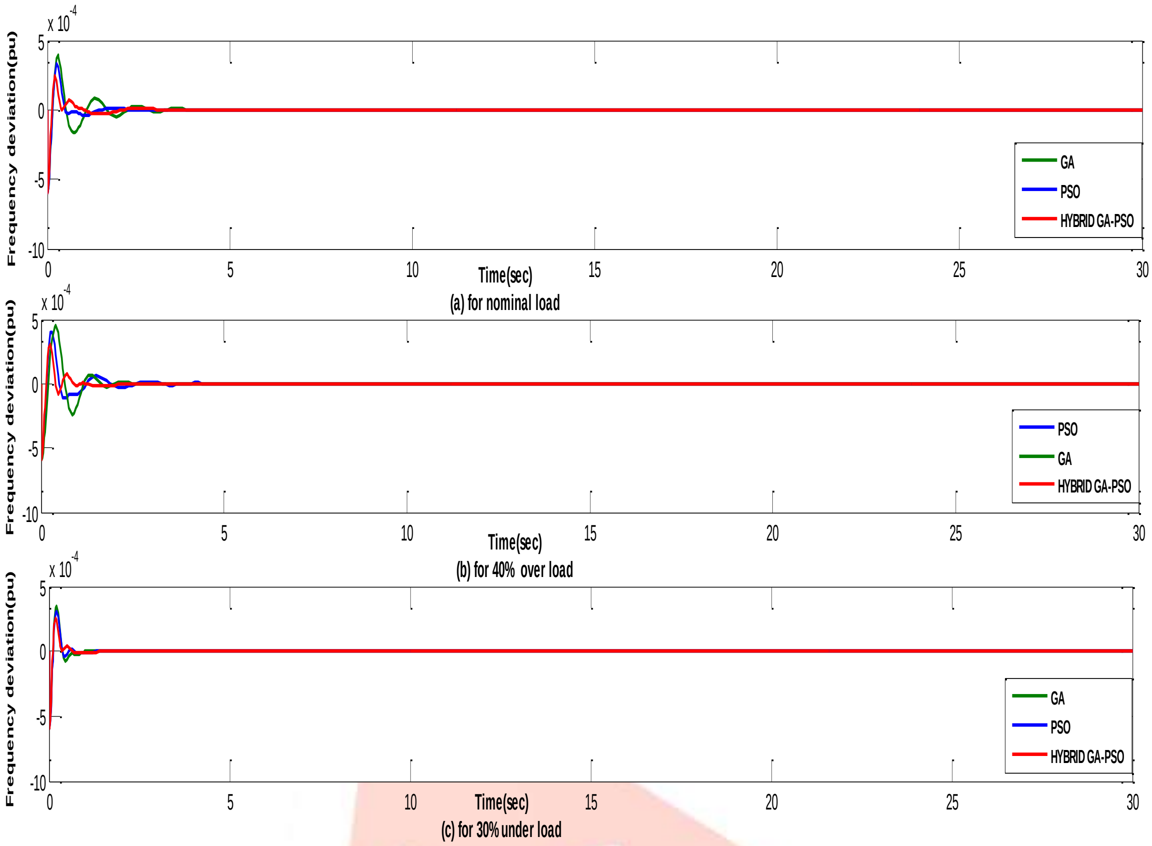


Fig.5 Dynamic Response in Frequency Deviation

Random step wind power change:

The random step wind power variation as shown in Fig. 7(a) and ΔP_L=0.01 pu are applied to the system. Dynamic response in frequency deviation of the proposed system for these input conditions is shown in Fig 10 for different loading conditions with different optimization techniques.

Random wind power change:

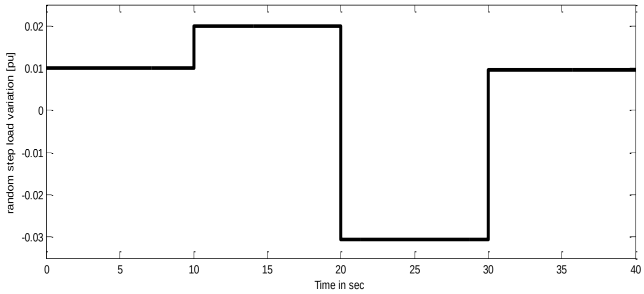
The random wind power variation as shown in Fig.7 (b) and ΔP_L=0.01 pu are applied to the system. Dynamic response in frequency deviation of the proposed system for these input conditions is shown in Fig 11 for different loading conditions with different optimization techniques.

2) Case-2: two area hybrid power system

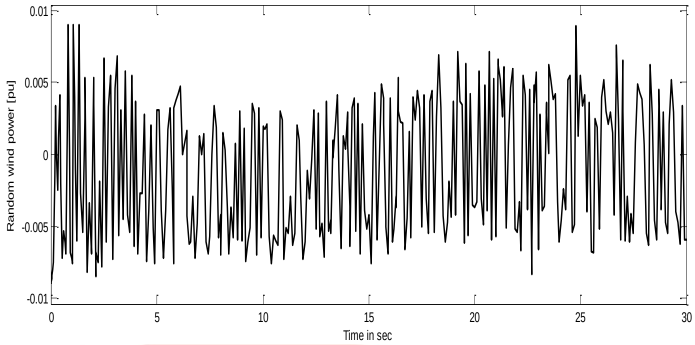
The load disturbance and wind power variation applied to the power system-2 is considered as ΔP_{L1}=0.01 pu, ΔP_{L2}=0.01 pu and ΔP_{WTG}=0.01 pu.In case two area power system disturbance on area affects the frequency deviation profile in another area.The responses obtained by incorporating the PI controllers in the two area power system. PI controller gains are tuned by the hybrid GA –PSO, GA, and PSO. Area -1 dynamic response in frequency deviation, Area -2 dynamic response in frequency deviation and dynamic response in tie – line power are shown in Fig. 12, and Fig. 13 and Fig. 14 respectively.

The responses are presented for 40% over load and 30% under load along with nominal loading condition.It can be observed that responses are within tolerable limits for over load and under conditions also thus the controllers are robust with respect to parameter variations.

Results prove that, dynamic response in frequency deviation has less peak overshoot and less setting time with hybrid GA–PSO based controller as compared to conventional GA and PSO based controller.

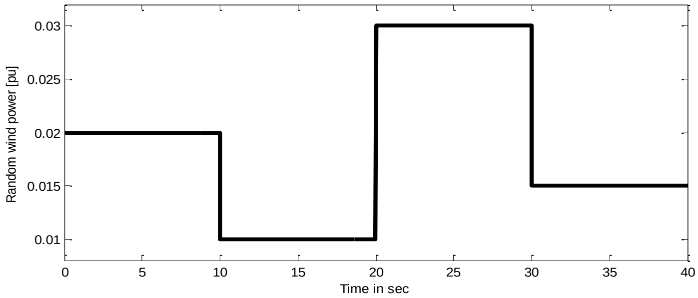


(a) Random Step Load variation

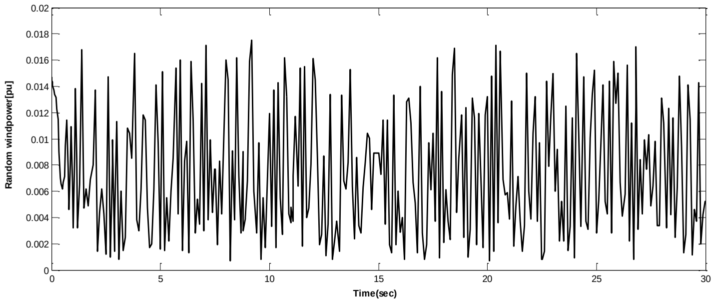


(b) Random Load Variation

Fig. 6 Load Disturbance signals



(a) Random Step Wind Power Variation



(b) Random Wind Power Variation

Fig. 7 Wind Power Variation signal

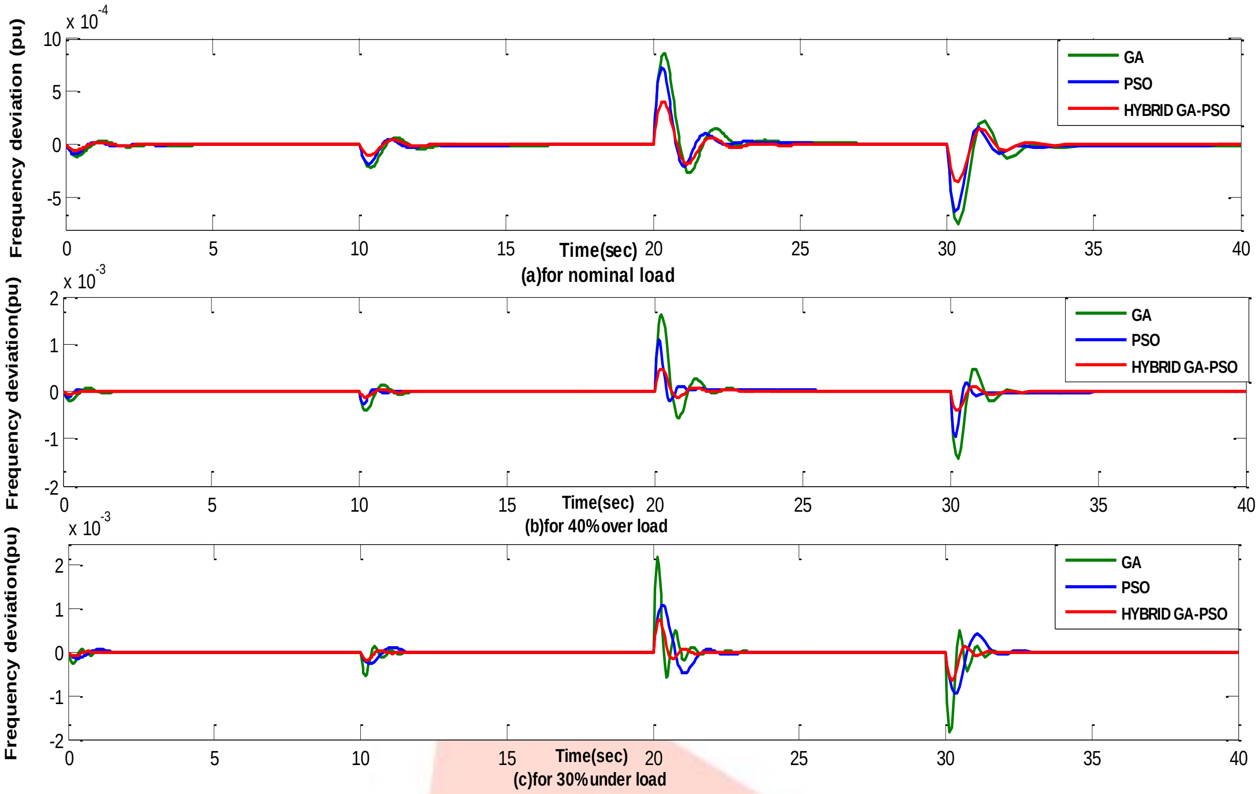


Fig.8. Dynamic Response in Frequency Deviation for Random Step Load variation

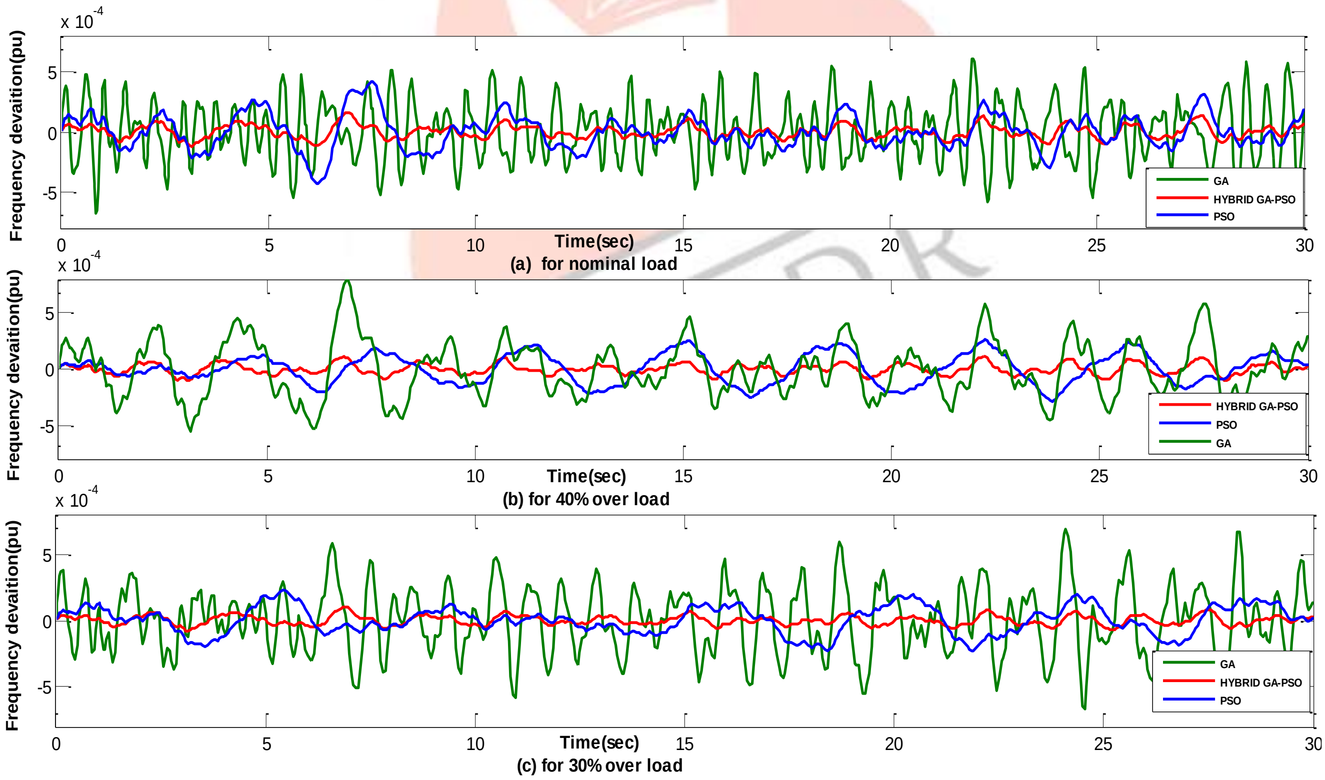


Fig.9. Dynamic Response in Frequency Deviation for Random Load variation

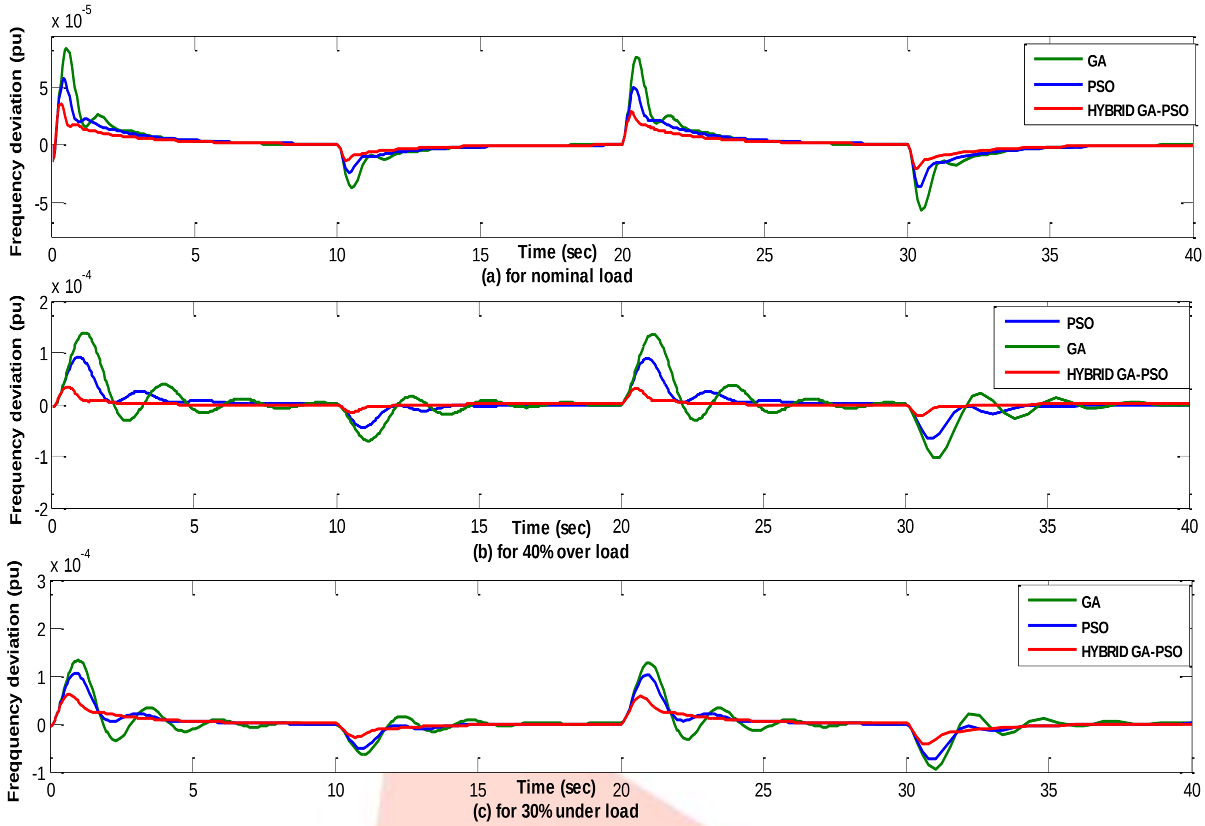


Fig.10. Dynamic Response in Frequency Deviation for Random Step Wind Power variation

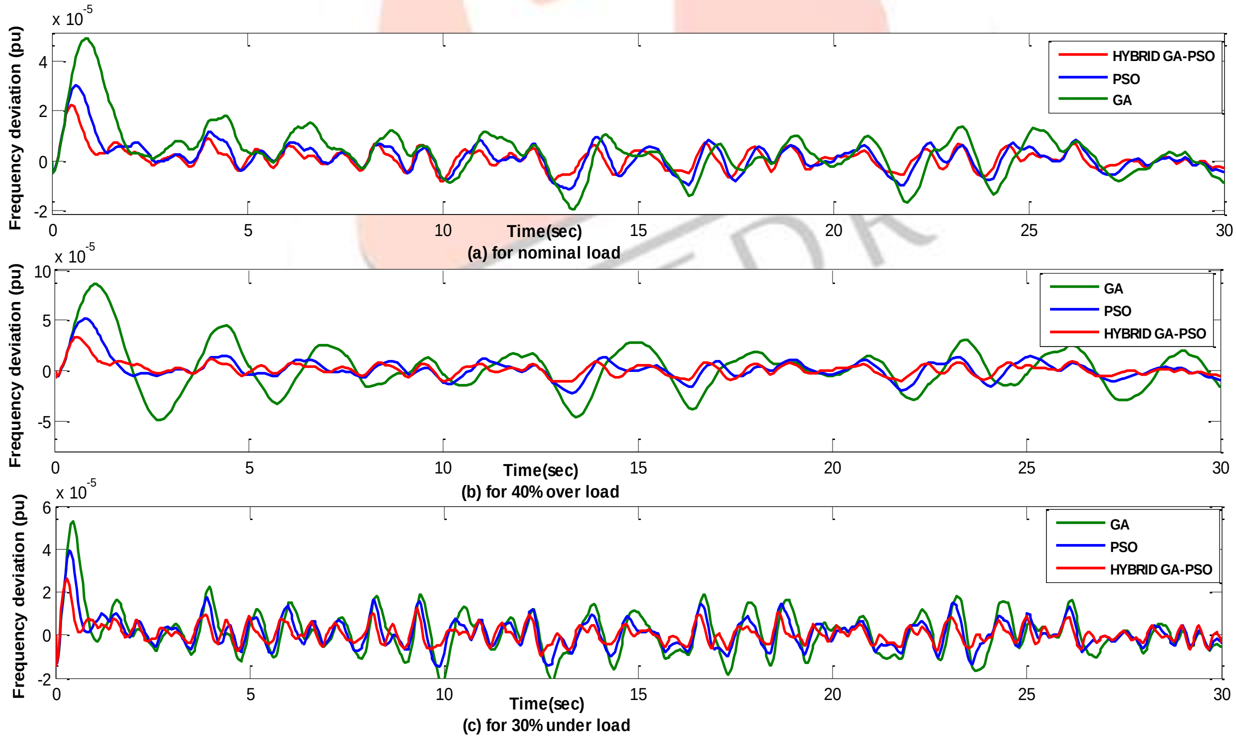


Fig.11. Dynamic Response in Frequency Deviation for Random Wind Power Variation

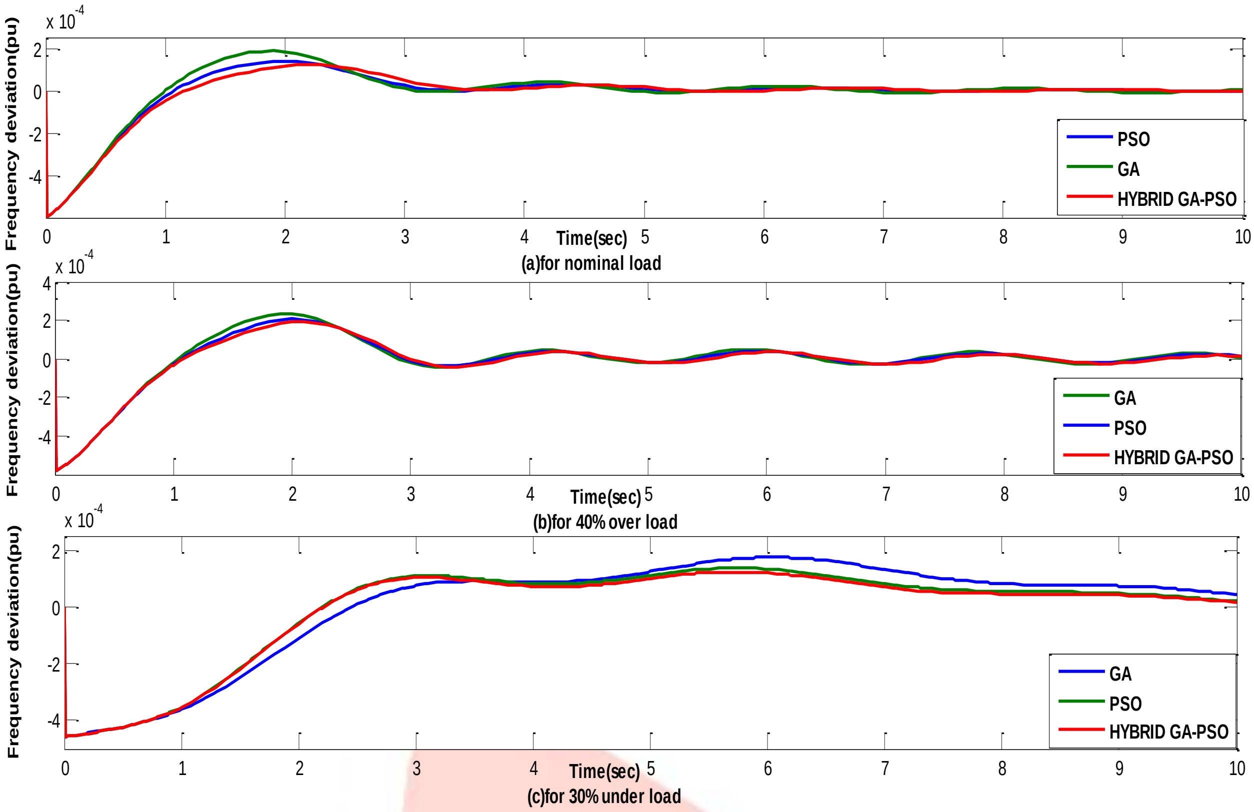


Fig 12. Area -1 Dynamic Response in Frequency Deviation

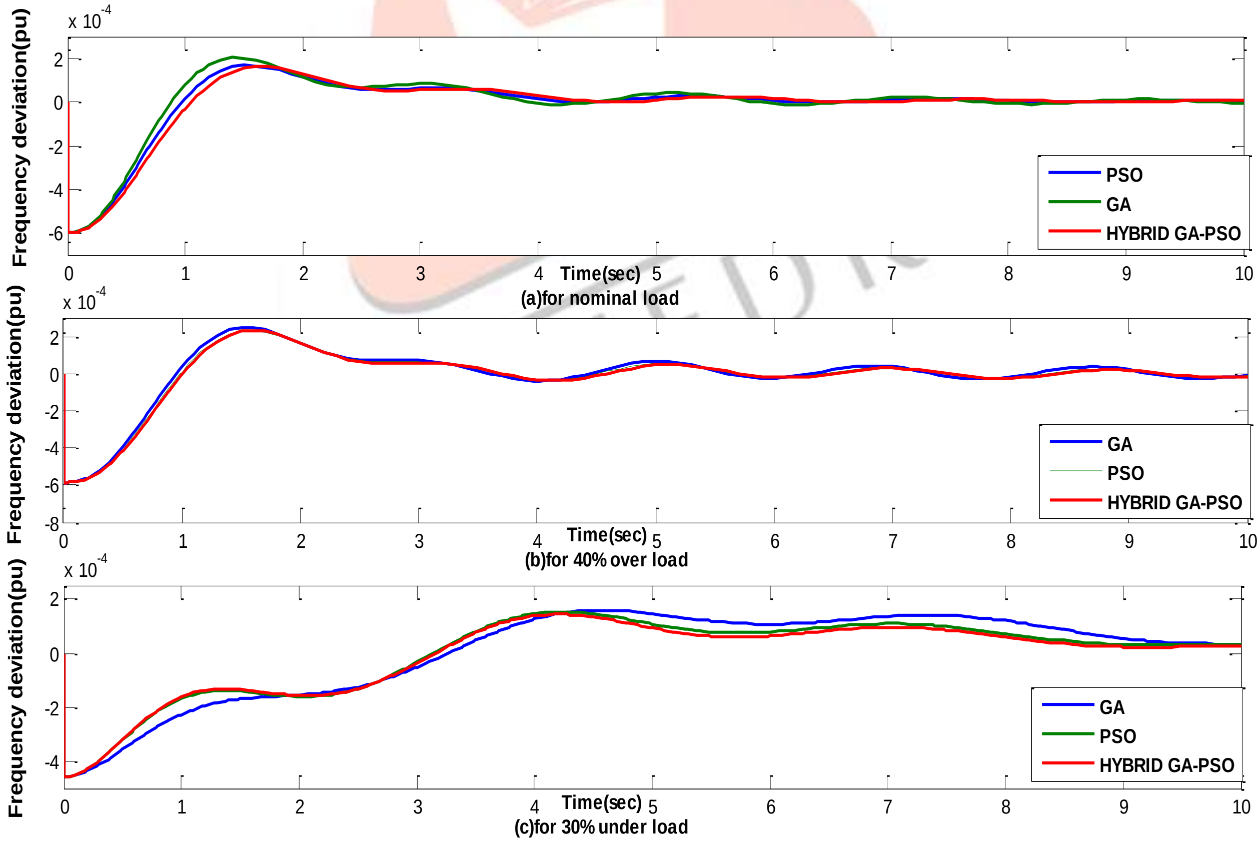


Fig 13. Area -2 Dynamic Response in Frequency Deviation

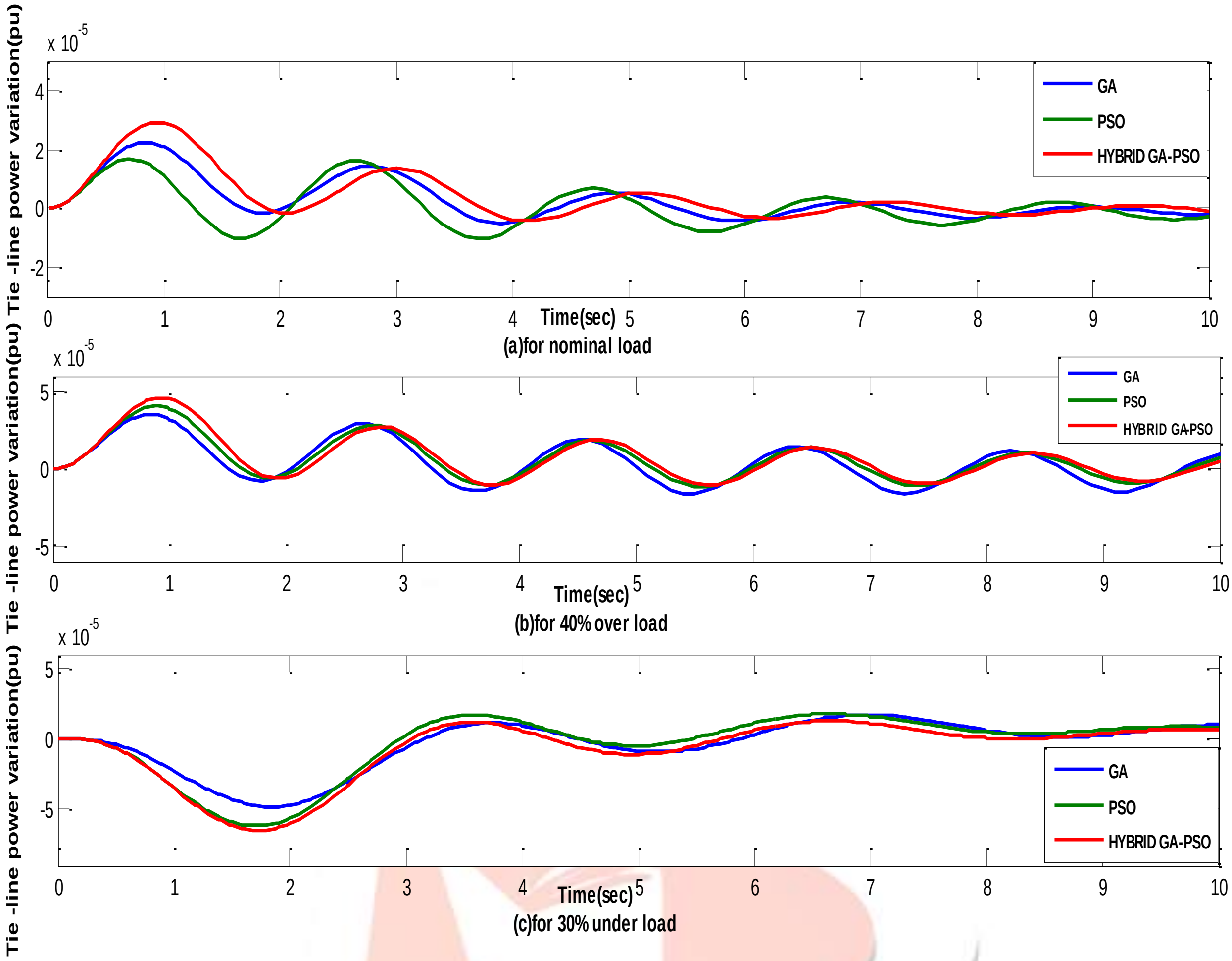


Fig 14. Dynamic Response in Tie Line Power

V. CONCLUSION

Hybrid power system minimizes the limitationas of conventional power system. Due to the dynamic nature of renewable energy soures and increased complexity in hybrid power system, conventional control techiques are not suitable for designing the Load Frequency Controllers.So the population based agorithms viz., Genetic algorithm (GA) ,Particle Swarm Optimization and hybrid GA- PSO techinique are applied to design LFC controller. In order to minimize the limitations in the GA and PSO algorithms, the proposed controller is designed using hybrid GA-PSO. From the presented results in table 1 it can be observed that hybrid GA-PSO based controller giving better responses as compared to PSO and GA algorithms.

Table 1 Time reponse specifications of dynamic response in frequency Deviation for step load change

Operating condition	With hybrid GA-PSO			With PSO			With GA		
	% over shoot	% under shoot	Settling time(sec)	% over shoot	% under shoot	Settling time	% over shoot	% under shoot	Settling time
Normal loading	0.0002	0.0006	4sec	0.00032	0.006	6 sec	0.0004	0.0006	6 sec
40% over loading	0.00025	0.0006	5 sec	0.00045	0.006	7 sec	0.0006	0.006	8 sec
30% under loading	0.00025	0.0006	3 sec	0.00035	0.0006	4 sec	0.0004	0.0006	5 sec

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