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Simulation study for hybrid power systems using Differential Evolution (DE) algorithm and PID based robust controller design

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Abstract: This paper investigate the output power against load demand in a system having Distributed Generation (DG) resources connected to the existing conventional power system. So an approach has been undertaken for investigating the Load Frequency Control (LFC) problem is presented considering a widely used two area interconnected power system with Distributed Generation (DG) connected in area-1. In this article, a Differential Evolution (DE) algorithm has been proposed for optimizing the gains of Proportional Integral Derivative (PID) controller . The corresponding performance index of the system can be calculated in terms of Integral Time multiply Absolute Error (ITAE) and settling time (Ts). Finally, the robustness of the PID controller over the PI controller is thoroughly demonstrated in the below hybrid power systems with different conditions of load disturbances, wind power and parameter variations. it's observed that the proposed controller are robust and ensures satisfactory system performance in presence variation in system parameters and operating load conditions.

Keywords: Load Frequency Control (LFC); Proportional Integral Derivative (PID); Differential Evolution (DE) algorithm; Integral Time multiply Absolute Error (ITAE); Thermal power system (TPS); Wind Turbine Generators (WTGs); Diesel Engine Generators (DEGs); Fuel Cells (FCs); Aqua-Electrolyzer (AE); Battery Energy Storage System (BESS).

I. INTRODUCTION

To meet the growing energy demand of power system the installation of Distributed Generation (DG) resources has being increased. During the past few years much attention has been given to the benefits of distributed generation (DG) installed on the utility “grid” or distribution system. The DG system makes use of small electric power generation resources located nearby to its consumers and load centers. These generation resources includes the wind energy, diesel generator, fuel cells and energy storage systems. so the expansion of DG systems may be achieved through interconnection with conventional generation resources, to meet the increased load demand of an isolated community, The resulting hybrid power system intends to provide reliable and high quality service to its consumers, Emergency backup during sustained utility outages, reduced voltage sags, increased reliability. The Integration of DG resources especially based on wind turbines imposes new challenge to power systems control, making the electric power industry become more complicated. In such hybrid system, deviations in load demand and stochastic variation in wind power adversely affect the frequency, so it is necessary to preserve the power balance between generation and demand, being achieved through automatic Load Frequency Control (LFC) in some acceptable range. The frequency control issue in power systems having high penetration of wind systems is addressed in [1–5]. The wind system output power fluctuation dynamics has negative contribution to the power imbalance and thus to the frequency deviation, which should be taken into account in the existing LFC control scheme. The frequency deviation in significant range may lead to under/over frequency relay trip and thus disconnection of system loads and generation. In this paper the present study is related to the frequency regulation issue in two area reheat thermal power systems with DG resources in area1 having negative impact on system frequency profile. Several control strategies for LFC of power systems have been proposed by different researchers to keep the system frequency and tie-line power flow at their scheduled values during normal and disturbed conditions. so in this paper an attempt has taken to improve the performance of AGC with Proportional Integral Derivative (PID) controller. In the present study, Differential Evolution (DE) algorithm is proposed for optimized gains of Proportional Integral Derivative (PID) controller design to achieve minimum frequency deviation and the power system configurations is considered by considering two area reheat interconnected power system comprising of DG resources in area-1,which comprises wind turbine generators (WTGs), diesel engine generators (DEGs), fuel cells (FCs), aqua-electrolyzer (AE) and battery energy storage system (BESS) is considered in simulation study. The model of the system under study has been developed in MATLAB/SIMULINK environment.

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II. MATERIALS AND METHODS

A. Power System Invistigated

This paper consists of two area thermal power plant comprising of DG resources in area-1,which comprises wind turbine generators (WTGs), diesel engine generators (DEGs), fuel cells (FCs), aqua-electrolyzer (AE)

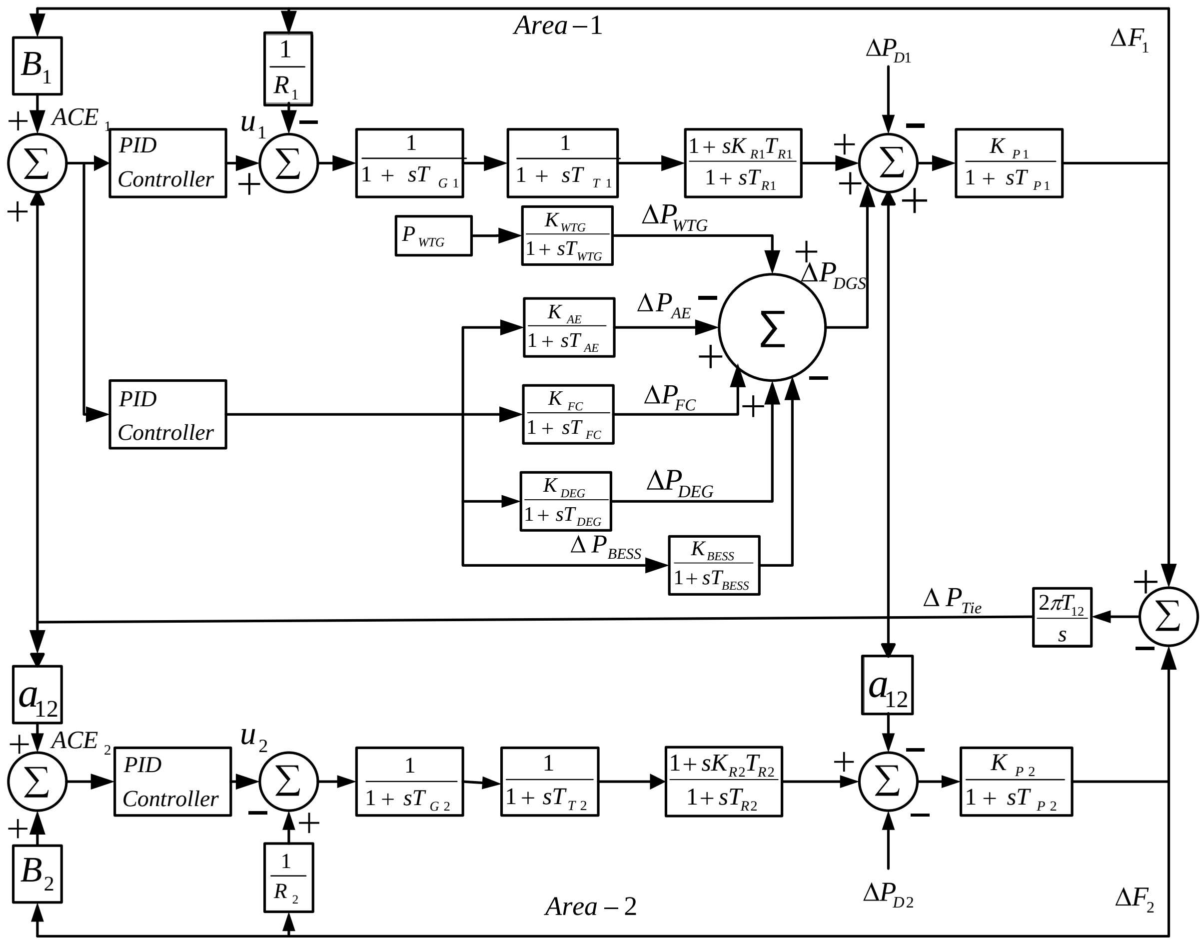

Fig.1 MATLAB/SIMULINK model of two-area thermal interconnected power system comprising of DG resources in area-1

and battery energy storage system (BESS) is connected by tie-line. Each area of power plant consists of speed governing system, turbine and generator having three inputs and two outputs.

Each area of the power plant supplies according to its respective user requirement and the tie-lines allow electric power to flow in between these areas. Therefore, areas are affect each other, that is, any change in load in one of the areas affects the output frequencies of other areas as well as the tie-line power. Due to this, the control system of each area needs detailed information about the transient situation in all the other areas in order to bring the local frequency to its steady state value.

The above statement can be verified in Fig. 1 which shows the complete block diagram of an interconnected two-area reheat power system. In Fig. 1, ACE_1 and ACE_2 are area control errors; B_1 and B_2 are the frequency bias parameters; u_1 and u_2 are the control outputs from the controller; R_1 and R_2 are the governor speed regulation parameters in pu Hz; T_{G1} and T_{G2} are the speed governor time constants in sec; T_{T1} and T_{T2} are the turbine time constant in sec; ΔP_{D1} and ΔP_{D2} are the load demand changes; ΔP_{Tie} is the incremental change in tie line power in pu; K_{PS1} and K_{PS2} are the power system gains; T_{PS1} and T_{PS2} are the power system time constant in sec; K_{WTH} is the gain constant of the WTG; T_{WTH} is the time constant of the WTG; K_{AE} is the gain constant of the AE; T_{AE} is the time

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constant of the AE; T_{FC} is the time constant of the FC; K_{FC} is the gain constant of the FC; K_{DEG} is the gain constant of the diesel generator; T_{DEG} is the time constant of the diesel generator; K_{BESS} is the gain constant of BESS; T_{BESS} is the time constant of the BESS (s); ΔP_{WTG} is the change in wind turbine power generation (pu MW); T_{12} is the synchronizing coefficient and ΔF_1 and ΔF_2 are the system frequency deviations in Hz. The relevant parameters are given in appendix A.

B. Control strucutre and Objective function

The PID controllers are provided in each area to control the frequency, also the controller is provided in DG system that connected in area1 as it is having fast reaction on change of the controller input (D mode), increase in control signal to lead error towards zero (I mode) and suitable action inside control error area to eliminate oscillations (P mode). PID control is robust, and PID controller transient response to command input ratio remains good over a wider range of plant parameter variation as compared to PI controller[7]. The structure of the PID controller is shown in Fig.2, where K_P, K_D, K_I are the proportional, integral, and derivative gains, respectively. The error inputs the controllers are the respective ACE given by:

$$e_1(t) = ACE_1 = B_1\Delta F_1 + \Delta P_{Tie} \quad (1)$$

$$e_2(t) = ACE_2 = B_2\Delta F_2 - \Delta P_{Tie} \quad (2)$$

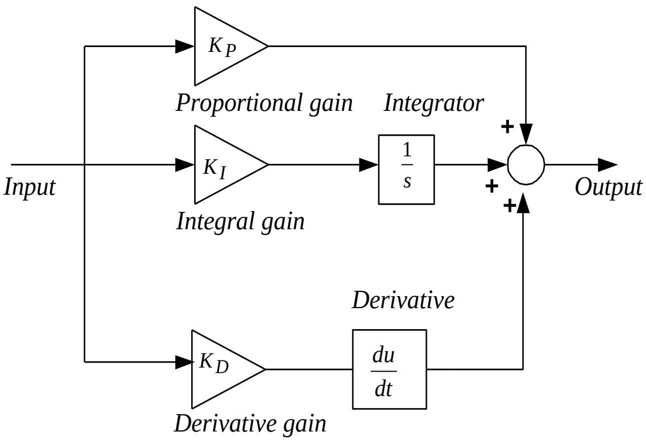

Fig.2 Structure of PID controller

In the design of a modern heuristic optimization technique based controller, the objective function is first defined based on the desired specifications and constraints. Performance criteria usually considered in the control design are the Integral of Time multiplied Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE) and Integral of Absolute Error (IAE). ITAE criterion reduces the settling time which cannot be achieved with IAE or ISE based tuning. ITAE criterion also reduces the peak overshoot. ITSE based controller provides large controller output for a sudden change in set point which is not advantageous from controller design point of view. It has been reported that ITAE is a better objective function in LFC studies [8]. Therefore in this paper ITAE is used as objective function to optimize the scaling factors and proportional, integral and derivative gains of DE PI/PID controller. Expression for the ITAE objective function is depicted in equation (3).

$$J = ITAE = \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|\right) \cdot t \cdot dt \quad (3)$$

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

III. OVER VIEW OF DE ALGORITHM

Differential Evolution (DE) algorithm is a heuristic search algorithm introduced by Storn and Price [9-11]. It is a simple, efficient, reliable algorithm with easy coding. The main advantage of DE over Genetic Algorithm (GA) is that GA uses crossover operator for evolution, while DE relies on mutation operation. based on the difference of

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randomly sampled pairs of solutions in the population. An optimization task consisting of D variables can be represented by a D-dimensional vector. At the beginning a population of N_P solution vectors is randomly initialized within the parameter bounds. The population is then modified by applying mutation, crossover and selection operators. DE algorithm uses two generations; one is old generation and the other one is new generation of the same population size. Individuals of the current population become target vectors for the next generation. The mutation operation produces a mutant vector for each target vector which is obtained by adding the weighted difference between two randomly chosen vectors to a third vector. The crossover operation generates a trail vector by mixing the parameters of the mutant vector with those of the target vector. The trial vector first tries to obtain a better fitness value than the target vector and then it substitutes the target vector in the next generation. The evolutionary operators are described below :

A. Initialization of parameter

DE begins with a randomly initiated population of size N_P of D dimensional real-valued parameter vectors. Each parameter j lies within a range and the initial population should spread over this range as much as possible by uniformly randomizing individuals within the search space constrained by the prescribed lower bound X_j^L and upper bound X_j^U .

B. Mutation operation

For the mutation operation, a parent vector from the current generation is selected (known as target vector), a mutant vector is obtained by the differential mutation operation (known as donor vector) and finally an offspring is produced by combining the donor with the target vector (known as trial vector). Mathematically it can be expressed as:

$$V_{i,G+1} = X_{r1,G} + F.(X_{r2,G} - X_{r3,G}) \quad (4)$$

Where $X_{i,G}$ is the given parameter vector, $X_{r1,G}$ $X_{r2,G}$ $X_{r3,G}$ are randomly selected vector with distinct indices i , $r1$, $r2$ and $r3$, $V_{i,G+1}$ is the donor vector and F is a constant from (0, 2).

C. Crossover operation

After generating the donor vector through mutation the crossover operation is employed to enhance the potential diversity of the population. For crossover operation three parents are selected and the child is obtained by means of perturbation of one of them. In crossover operation a trial vector $U_{i,G+1}$ is obtained from target vector ($X_{i,G}$) and donor vector ($V_{i,G}$). The donor vector enters the trial vector with probability CR given by:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & if \quad rand_{j,i} \le CR \quad or \quad j = I_{rand} \\ X_{j,i,G+1} & if \quad rand_{j,i} > CR \quad or \quad j \ne I_{rand} \end{cases} \quad (5)$$

With $rand_{j,i} \sim U(0,1)$, I_{rand} is a random integer from $(1,2,....D)$ where D is the solution's dimension i.e. number of control variables. I_{rand} ensures that $V_{i,G+1} \ne X_{i,G}$.

D. Selection operation

To keep the population size constant over subsequent generations, selection operation is performed. In this operation the target vector $X_{i,G}$ is compared with the trial vector $V_{i,G+1}$ and the one with the better fitness value is admitted to the next generation. The selection operation in DE can be represented by:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if \ f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & otherwise. \end{cases} \quad (6)$$

where $i \in [1, N_P]$.

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TABLE I. OPTIMAL GAIN VALUES

	PARAMETERS	DE:PI	DE:PID
Controller-1	K_{P1}	-1.3862	-1.1670
	K_{I1}	-1.1931	-1.0506
	K_{D1}	0	-0.4630
Controller-2	K_{P2}	-0.7023	-0.7459
	K_{I2}	1.3765	0.3795
	K_{D2}	0	-0.2479
Controller-3	K_{P3}	-1.9469	-1.4819
	K_{I3}	-1.4820	-1.4824
	K_{D3}	0	-0.5416

TABLE II. PERFORMANCE INDEX VALUES

PARAMETERS		DE:PI	DE:PID
ITAE		**0.4157**	**0.1774**
Peak overshoot x10^{-3}	ΔF_1	0.0084	0.0037
	ΔF_2	0.0071	0.0049
	ΔP_{Tie}	0.0023	0.0021
Settling time (sec)	ΔF_1	1.6000	1.0300
	ΔF_2	1.6000	1.0100
	ΔP_{Tie}	1.0600	0.8000

IV. SIMULATION RESULTS

The usefulness of proposed controller was demonstrated by considering three cases. The DE algorithm has been used to optimize the controller coefficients. The optimization was repeated 50 times and the best final solution among the 50 runs is chosen as proposed controller parameters. The optimum values of the different controllers are given in Table I.

A. Case1

In the first instant the response variation is investigated for the proposed system[12] for 1% step load change in the entire thermal unit of area 1 and area 2 and also to the wind power module. The different controller parameters of PI/PID controller each area is obtained using DE algorithm employing ITAE as objective function. The different gain values of the PI/PID controllers as explained earlier and shown in Table II. It is clear from the Table II that the ITAE value is decreasing by employing PID controller (ITAE=0.1774) then PI controller (ITAE=0.4157). Consequently, better system performance in terms of settling times and also peak overshoot are obtained with PID controller whose dynamic performance is shown in Fig.3-5. Hence it is clear that PID controller output performs is better than the PI controller. Hence better system performance in terms of minimum settling times in frequency, peak overshoot, peak undershoot and tie-line power deviations is achieved with proposed PID controller.

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B. Case2

Further a case study is performed by considering a random white noise signal in thermal unit in each area of proposed system and 1% step load in wind power module and the corresponding frequency deviation is shown in Fig. 6-8. It is evident from Fig.6-8 that system performs satisfactory with PID controller compared to PI controller.

C. Case3

Finally the performance of the system is study by considering 1% step load in thermal units of individual area and random white noise to the wind power module and the corresponding frequency deviation and tie line power deviation is shown in Fig.9-11. It is evident from Fig.9-11 that system performs satisfactory with PID controller compared to PI controller.

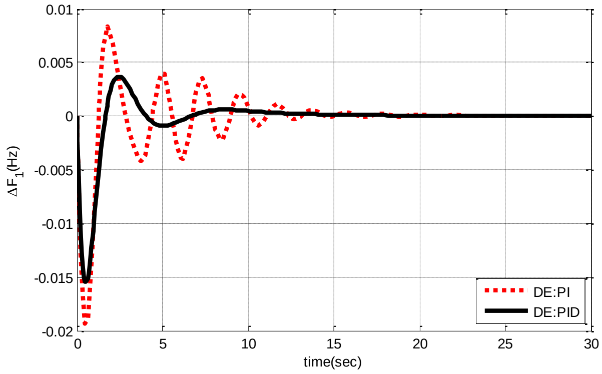

Fig.3 Frequency deviation in area-1 due to load disturbance and wind power variation of 1%.

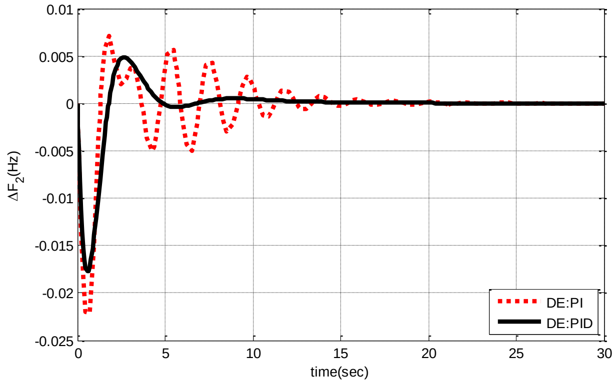

Fig.4 Frequency deviation in area-2 due to load disturbance and wind power variation of 1%.

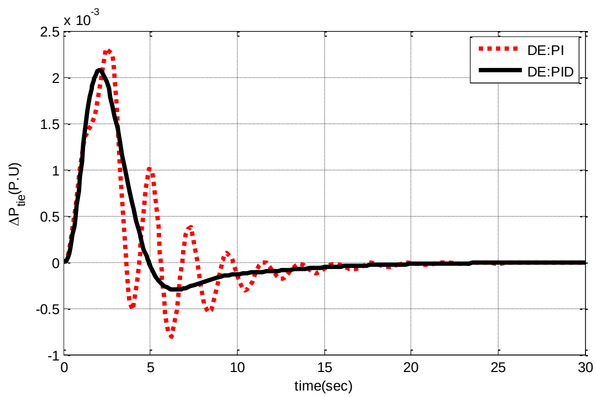

Fig.5 Tie line power deviation and wind power variation of 1%

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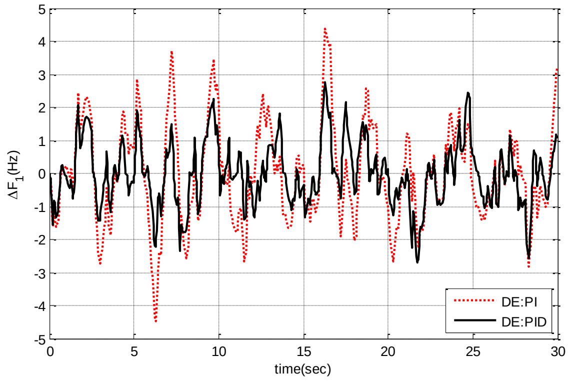

Fig.6 Frequency deviation in area-1 due to random noise as load disturbance and wind power variation of 1%

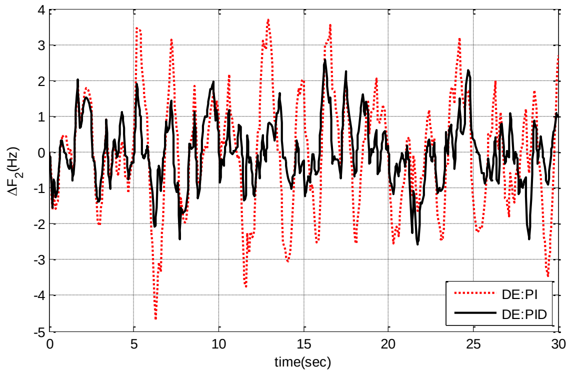

Fig.7 Frequency deviation in area-2 due to random noise as load disturbance and wind power variation of 1%.

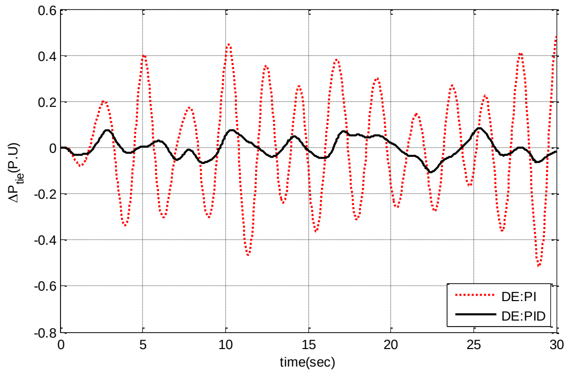

Fig.8 Tie line power deviation due to random noise as load disturbance and wind power variation of 1%.

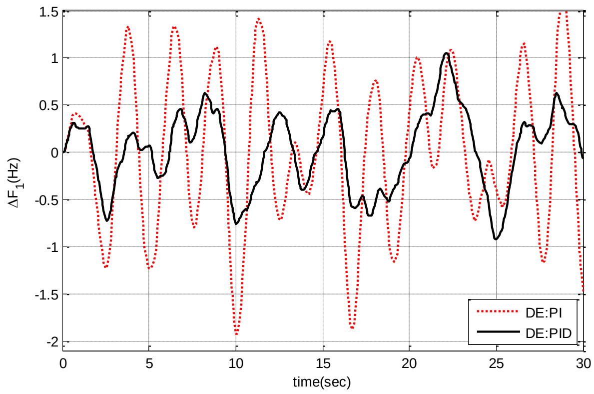

Fig.9 Frequency deviation in area-1 due to random noise as wind power variation and load disturbance of 1%.

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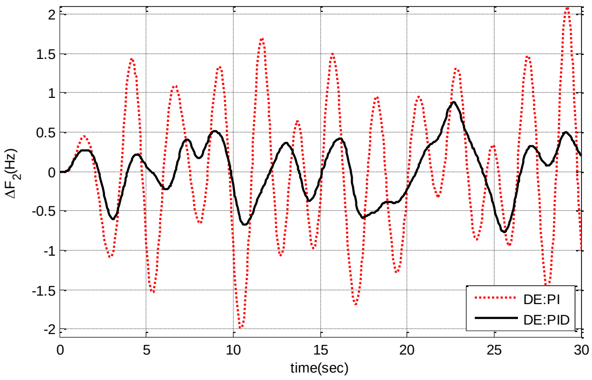

Fig.10 Frequency deviation in area-2 due to random noise as wind power variation and load disturbance of 1%.

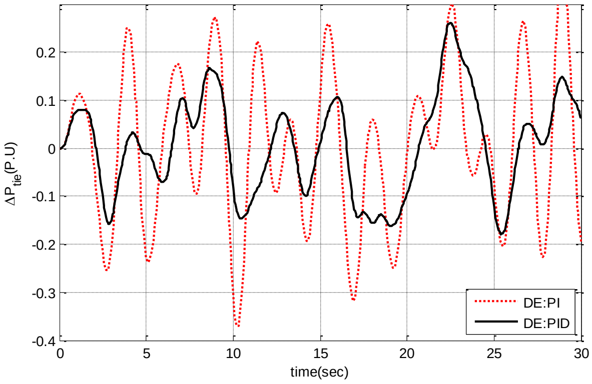

Fig.11 Tie line power deviation due to random noise as wind power variation and load disturbance of 1%

V. CONCLUSION

This paper addresses the distributed power generation technologies to optimize the LFC system. A widely used two area reheat thermal power system comprising of DG resources in area-1 is considered and the parameters of PID controller is optimized employing Differential Evolution (DE) algorithm using an ITAE based fitness function. The superiority of the proposed design approach has been shown by comparing the results of DE-optimized PI controller and DE-optimized PID controller for the same interconnected power system. From the simulation results, it is observed that significant improvements of dynamic performance of the system in terms Integral of Time multiplied by Absolute value of Error (ITAE), settling time, peak overshoot are obtained with PID controller.

APPENDIX A

Nominal Parameters of the Power System [6 &12]

$B_1 = B_2 = 0.425$ pu MW/Hz; $R_1 = R_2 = 2.4$ Hz/p.u.; $T_{G1} = T_{G1} = 0.08$sec $T_{T1} = T_{T2} = 0.3$s; $T_{R1} = T_{R2} = 10$ s; $K_{PS1} = K_{PS2} = 120$Hz/p.u. MW; $T_{PS1} = T_{PS2} = 20$ s; $T_{12} = 0.545$, $a_{12} = -1$; $K_{WTG} = 1.0$; $T_{WTG} = 1.5$s; $K_{AE} = 0.002$; $T_{AE} = 0.5$s; $K_{FC=}$ 0.01; $T_{FC} = 4.0$s;, $K_{DEG} = 0.003$; $T_{DEG=}$ 2s; $K_{BESS} = -0.003$; $T_{BESS} = 0.1$s; $P_{WTG} = 0.01$.

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