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A Novel 2DOF Fractional Controller for Wind-Solar Integrated Power System

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ABSTRACT

Power system is an integration of many power generating units with continuous load variation due to which the frequency of the power system changes. Using traditional proportional integral (PI) controllers, frequency transients are reduced, and with sufficient time delay zero steady-state error is obtained. In this proposed research article, a three-area thermal plant system with wind and solar photovoltaic power generating systems is considered. This integration of renewable system will lead to the frequency transients which has to be addressed seriously. To improve the frequency profile of this diverse-source interconnected power system, a novel two degree of freedom proportional fractional integral double derivative (2-DOF-PFIDD) controller is proposed. The integral square error (ISE) cost function is utilized to discover the best parameter gains of the proposed controller using the intelligent water drops algorithm (IWDs). The benefits of the proposed controller are evaluated using an IEEE-39 bus system with wind and solar photovoltaic (SPV) generation. Uncertainties in the wind and solar power system characteristics such as wind speed and irradiance are considered. Comparisons with typical proportional integral derivative (PID), two degree of freedom proportional integral derivative (2-DOF PID), and 2-DOF-PIDD controllers are presented to demonstrate the efficacy of proposed controller for improving the frequency and tie-line power profiles.

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1. INTRODUCTION

In conventional interconnected power systems with regulating power generating sources such as thermal, hydro, and gas power plants, power demand variation is a significant component for frequency disturbances and tie-line power changes. The demand variations are balanced by generating units with primary and secondary control schemes of load frequency control (LFC) [1]. Recently, the percentage contribution of wind and solar generation increases significantly reducing fuel costs and pollution. However, power balance is a difficult task because both generation and demand components are volatile due to varying wind speed, solar insolation, and load. Therefore, the study of the LFC concept from a wide perspective of the operational challenges of the power system in presence of renewables is increased over the last 2 decades [2]. Classical controllers such as proportional (P), integral (I), proportional-integral (PI), and proportional-integral-derivative (PID), greatly improve the frequency and tie-line power profiles of the power system in the presence of conventional generation via secondary control action [3]. These controllers were tested on wind and solar integrated systems to meet the objectives of LFC with generation uncertainties. In [4], To investigate the load frequency management characteristics in the context of significant renewable energy integration, an autonomous microgrid system is used. A harmony search optimization algorithm with a quasi-opposition approach is utilized to identify the best controller gains. Intelligent tools-driven PI/PID controllers are also a better choice to minimize the frequency oscillations of the high penetrating wind-integrated power system [5]. Recently, a sophisticated modelling approach is presented for the photovoltaic system to study its effect on LFC action [6]. Another technique known as Tustin's technique is employed in LFC of a realistic multi-source power system in presence of wind farms. This work extended to check the performance of the mechanism in LFC with communication delays [7]. Fractional order PID controller optimized with swarm intelligence is used for load frequency enhancement [8-10].

Different algorithms like whale optimization (WO) and weight-improved particle swarm optimization(W-IPSO) were used for the enhancement of system performance [11-12]. In addition to these research, numerous sophisticated cascade controllers were used to existing schemes to boost the LFC matrices. [13]. The ant lion optimization (ALO) algorithm is employed to optimize a double derivative controller for a traditional generation-based multi-area power system. [14-15]. For optimal parameter gains of the two degree of freedom proportional integral derivative (2-DOF PID) controller, the teaching and learning-based optimization (TLBO) algorithm is used [16]. The 2-DOF PID controller is widely used in multi-area power systems to reduce frequency disturbances during load fluctuations [17]. Recently, a 2-DOF-PIDD controller is introduced to reach the objectives of the LFC [18]. The application of these advanced controllers in LFC of interconnected power systems with renewables is limited in the literature. Few works are reported in [18]-[21]. In [19], a cascade controller is applied with PID blocks around LFC with renewable sources. Another popular cascade controller, proportional-integral-proportional-derivative (PI-PD) is applied for LFC applications [20].

This research introduces a novel controller strategy for meeting the LFC objectives of an interconnected power system integrated with renewables. The controller is implemented with 2-DOF PID, fractional integral, and double derivative components. The controller proposed is a two degree of freedom proportional fractional integral double derivative (2-DOF-PFIDD) controller. The intelligent water drops (IWDs) algorithm is employed to determine the controller's optimal gains. Several cases are examined in the paper to assess the controller's strengths and benefits. In the studies, both load and generation uncertainties are considered, and comparisons are made with the PID, 2-DOF PID, & 2-DOF PIDD controllers.

2. MODELLING OF MULTI-SOURCE POWER SYSTEM

2.1. Modelling of Load frequency control of a single area power system

LFC devices are installed for each generator in a single area network. Small fluctuations in load demand are handled automatically by the controllers, which are programmed for a specific working condition. Mathematical modeling of the single area power system is the initial phase in the control system analysis and design process. To generate a transfer function model of the component, the mathematical equations defining the system are linearized with the help of appropriate assumptions and approximations. Figure 1 shows the block diagram representation for LFC of single area network. Where T_{g1}, T_{t1}, T_{r1} ,T_{p1} are the time constants for governor, turbine, reheater and power system respectively. ΔP_c is the commanded change in power and ΔP_1 change in load demand. Δf1 represents the increase in frequency and R is the speed regulation of the load demand.

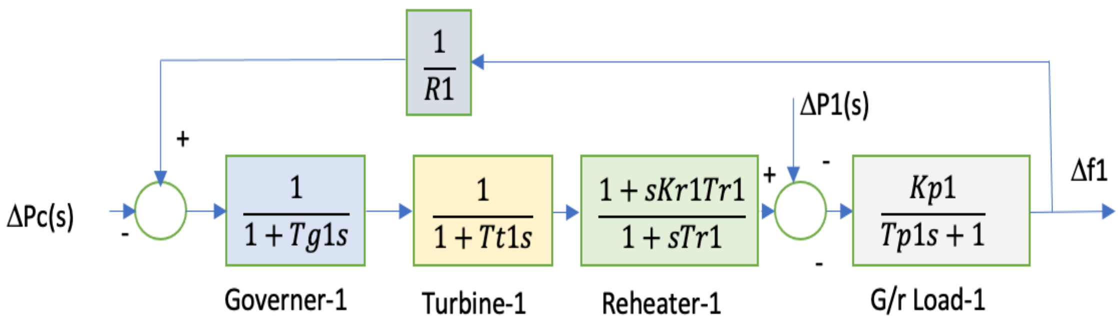

Figure 1. Block representation of the single area power system for LFC

2.2. Modelling of solar Photovoltaic generator

Photovoltaic modules are connected in series and parallel to obtain the desired configuration of voltage and current. Voltage to current ratio is not linear in nature in PV systems. Solar radiation, temperature and change in load affect the PV array's generation capacity. Generally, these parameters vary continuously during power generation and distribution. Equation (1) depicts mathematical transfer function model of Solar Photo Voltaic generator (SPVG). K_{spvg} , T_{spvg} are the gain and time constant for the SPVG.

$$\Delta P_{spvg} = \frac{K_{spvg}}{1+sT_{spvg}} \quad (1)$$

2.3. Modelling of Wind turbine generating System

Wind turbine generating system (WTGS) output depends on the wind speed. Integration of the WTGS introduces non-linearity in the existing power system leading to the frequency oscillations. To minimize the frequency oscillations, pitch controller is employed in WTGS. Equation (2) represents the transfer function model of WTGS. K_{wtg} , T_{wtg} are the gain and time constant for the WTGS

$$\Delta P_{wtg} = \frac{K_{wtg}}{1+sT_{wtg}} \quad (2)$$

2.4. Modelling of the proposed three area network with SPVG and WTG

For simulation studies, a 3-area interconnected power system has been opted in this paper with wind and solar plants included in area-1as shown in figure-1. All three areas consist of thermal plants and each area is represented with one machine model based on the equivalent models. Generations of wind and solar electricity are included in area-1 to examine the influence of renewable energy sources on load frequency control. These areas are linked together by tie-lines, which transmit active power to fulfill demand and balance the power. During the load perturbations, both primary and secondary control schemes of LFC are initiated their action so that generation meets the demand.

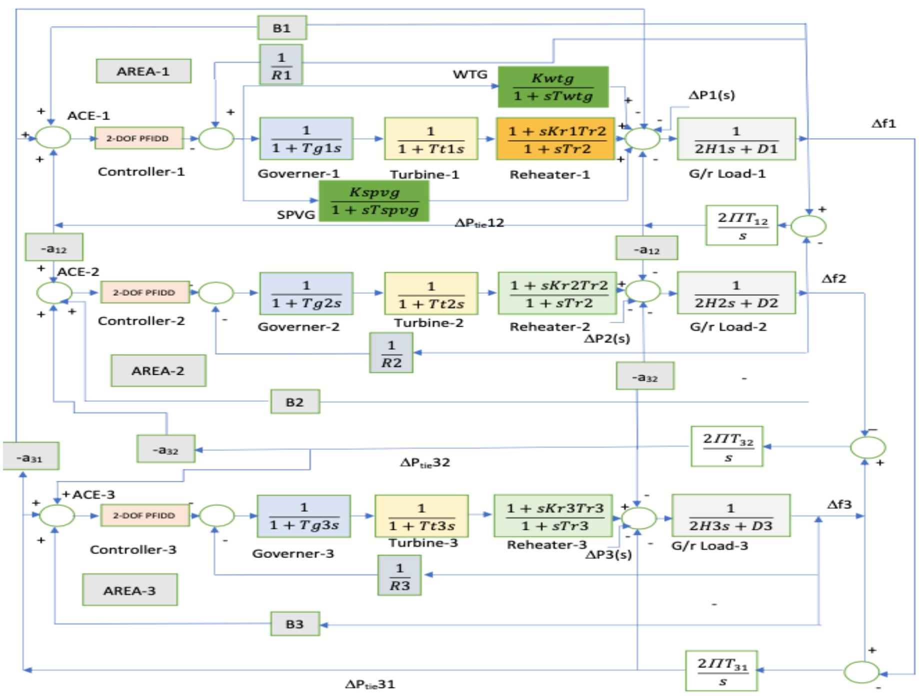

Figure 2. Three-area interconnected power system integrated with wind and solar in area 1

3. PROPOSED 2-DOF-PFIDD LFC CONTROL SCHEME

Classical controllers were extensively studied in the literature to minimize the frequency and tie-line power deviations of the interconnected power system with conventional power generating units. Among the classical controllers, the PID controller significantly effects the stability and practical applicability. Apart from classical controllers, several advanced intelligent, cascade, and modern controllers are applied to improve the LFC metrics. The usage of new and effective controllers plays an important role in modern power systems integrated with large capacity of wind and solar. In an interconnected power system with conventional power generating units, the demand side users effect the active power balance. Both demand and generation side components are responsible for power imbalances in modern systems. Therefore, a novel controller is used in this article as secondary controller to nullify the deviations of the frequency and inter area tie-line power disturbances. Figure 2 represents the control scheme for the proposed *2-DOF-PFIDD* LFC controller.

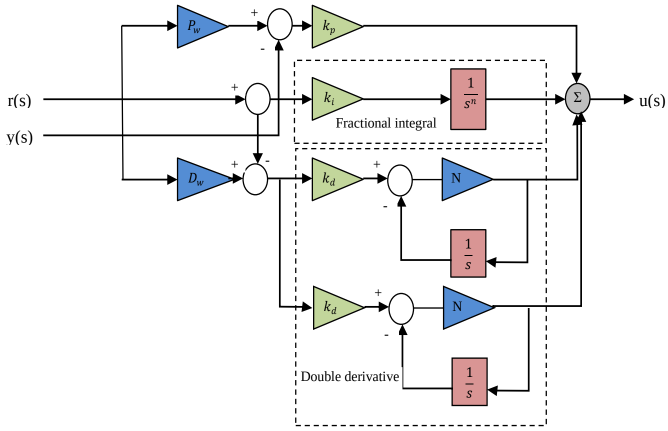

Figure 3. Functional schematic for the proposed 2-DOF-PFIDD LFC controller

The proposed controller is a novel form of a 2-DOFPID controller that inherits the advantage of fractional and double derivative control. This controller is strengthened by IWD algorithm for instantaneous tuning of proportional gain (K_p), fractional Integral gain (K_i), and derivative gains (K_{d1} and K_{d2}). The Figure 2 depicts the proposed controller's schematic representation. The input signals r(s) and y(s) are used to initiate the control action of the proposed 2-DOF-PFIDD controller. The range of n for integral gain is $0 < n < 1$. Due to the implementation of the fractional order integral controller, the 2-DOF-PFIDD LFC controller has shown robust and stable characteristics under varying process parameters. The area control error (reference signal) for each area network is generated by the equations (3), (4) and (5). ACE_1, ACE_2 and ACE_3 are the reference signals for the control area-1, area-2 and area-3 respectively.

$$ACE_1 = \Delta P_{12} + B_1 \, \Delta f_1 \quad (3)$$

$$ACE_2 = \Delta P_{21} + B_2 \, \Delta f_2 \quad (4)$$

$$ACE_3 = \Delta P_{31} + B_3 \, \Delta f_3 \quad (5)$$

As test system interconnects three identical areas through transmission lines, three simultaneous control signals are needed to control the plants in their corresponding areas. The generalized expression of control signal of i^{th} area is given by equation (6)

$$u_i(s) = k_{p_i}\left(P_{w_i} r - y\right) + \frac{k_{i_i}}{s^n}(r - y) + \left\{\sum_1^n \frac{k_{d_{ii}} s}{T_{fii} s + 1}\right\}\left(D_{w_i} r - y\right), i = 1,2,3. \quad (6)$$

In equation (6), u_i is the control signal generated by secondary controller of LFC in i^{th} area to control the plant of the i^{th} area. n is the fraction for integral controller.

4. COST FUNCTION-OPTIMIZER MECHANISM

Performance metrics must be used to determine the ideal controller settings shown in Figure 3 and Equation 6 in order to achieve the LFC's goals. Integral absolute error (IAE), integral absolute time error (IATE), integral square error (ISE), and integral square time error (ITSE) are notable performance measurements that were often utilized in early research investigations of the LFC, according to a literature review. One performance metric is required as the cost function of the LFC issue in order to compare the proposed controller's performance to other current controllers. Among IAE, IATE, ISE and ITSE, ISE is opted in this paper whose expression is given in Equation (7) valid for interconnected power system with 'n' areas.

$$\text{ISE}=\int_0^t \sum_{\substack{i=1\\ j=1\\ i\neq j}}^{n}[(\Delta f_i)^2+\left(\Delta P_{ij}\right)^2 dt \quad (7)$$

The fitness value of the cost function is decided by the numerical values of the decision variables generated by the heuristic algorithms provided in the search space represented in Equation (8) to Equation(12)

$$k_{min} \leq k_{p_i}, k_{i_i}, k_{d_i} \leq k_{max} \quad (8)$$

$$0 \leq N \leq N_{max} \quad (9)$$

$$P_{min} \leq P_w \leq P_{max} \quad (10)$$

$$D_{min} \leq D_w \leq D_{max} \quad (11)$$

$$n_{min} \leq n \leq n_{max} \quad (12)$$

There exist infinite solutions in the search-space and the best set of decision variables values need to identify among all solutions based on the fitness values of the cost function evaluated using Equation (7). This task is accomplished by meta-heuristic algorithms. To find the optimal gains of the proposed controller, intelligent water drop algorithm (IWDs) is opted in this paper. In the year 2009, Hamed shah-Hosseini introduced IWD algorithm to solve complex engineering unconstrained and constrained problems [21]-[22]. The algorithm mimics the water drops behaviour in the flow of river. The mechanism is influenced by velocity of the water and soil of the river. Surface behaviour of the soil and velocity are significant factors considered in the updating mechanism of IWDs algorithm. Further the factors used in IWDs algorithm are classified into two categories known as static and dynamic. The static parameters are constant during the lifetime of the algorithm whereas dynamic parameter changes for every trial. Like other heuristic algorithms, initialization, updating, and termination steps are usual in this IWDs algorithm. In initialization, first static parameters are initialized. Node set 'N' and edge set 'E' and graph (N, E) also need to define for algorithm. For particle T^{TB}, the quality of the solution set is at its worst value -∞. For updating of velocity and soil parameters, a_v, b_v, c_v, a_s, b_s and c_s values need to be addressed. After initialization, IWD's spread randomly and visited nodes and updated nodes. The next node 'j' may add in the visited node list with the probability $p_i^{IWD}(j)$ given by

$$p_i^{IWD}(j) = \frac{f(soil(i,j)}{\sum_{k\notin vc(IWD)} f(soil(i,k))} \quad (13)$$

Where $f(soil(i,j) = \frac{1}{\varepsilon_s + g(soil(i,j))}$ $and\ g(soil(i,j) = \begin{cases} soil(i,j) & if\ \min_{l\notin vc(IWD)}(soil(i,l)) \geq 0 \\ soil(i,j) - \min_{l\notin vc(IWD)}\left(soil(i,l)\right) & else \end{cases}$ (14)

Then , add the newly visited node j to the list vc (IWD)

The velocity for each IWD moving from i node to j node is given by

$$vel^{IWD}(t+1) = vel^{IWD}(t) + \frac{a_v}{b_v + c_v.soil^2(i,j)} \quad (15)$$

Further, change in soil function is calculated using equation (16)

$$\Delta soil(i,j) = \frac{a_s}{b_s + c_s time^2(i,j;vel^{IWD}(t+1))} \quad (16)$$

Finally, the soil is updated using the equation given by (17)

$$soil^{IWD} = soil^{IWD} + \Delta soil(i,j) \quad (17)$$

From all updating solutions, best solution of the soil ($soil(i,j)$) is identified based on the quality of the solution and update the soils on the paths that form the current iteration to best solution (T^{IB}) is

$$soil(i,j) = (1+\rho_{IWD})soil(i,j) - \rho_{IWD}\frac{1}{N_{IB}-1}soil_{IB}^{IWD} \quad (18)$$

The updating procedure continue until either up to maximum iterations or to reach at termination criteria. At the end of final iterations, the positions of the water particles represent the final optimal values of the controller gains.

5. SIMULATION RESULTS

To show the merits of the proposed controller in terms of improvements in the transient and steady state specifications of the output response, comparisons are provided with the PID, 2-DOF PID and 2-DOF PIDD controllers. Initially, investigations are carried out on 3-area interconnected power system without integration of wind and solar. Later, studies are extended to check the significance of the renewables and their influence on system frequency during simple load changes, random load perturbations and generation variations.

5.1. Performance of 2-DOF-PFIDD controller for 3-area interconnected power system without renewables

A three-area interconnected power system without renewable energy is first taken into consideration, and a simple load perturbation (SLP) of 1% is commenced in area 1 to evaluate the performance of the proposed controller.

The performance of the recommended controller is noticeably superior to PID, 2-DOF PID, and 2-DOF PIDD controllers in all three areas. These results are simulated at optimal gains of the controllers identified by IWDs algorithm and presented in Table1.

Table. 1. Optimal controller gains achieved using IWDs algorithm

Gains→Areas↓	k_p	k_i	k_{d1}	N_1	k_{d2}	N_2	P_w	D_w	n
Area-1	-1.99	-1.95	-1.93	200	-1.89	200	0.98	1	-0.984
Area-2	-1.54	-1.84	-1.65	200	-1.87	200	1	1	-0.104
Area-3	-1.24	-1.89	-1.28	200	-1.86	200	0.98	1	-0.964

Figures 4, 5, and 6 illustrate the frequency changes for areas 1, 2, and 3, respectively.

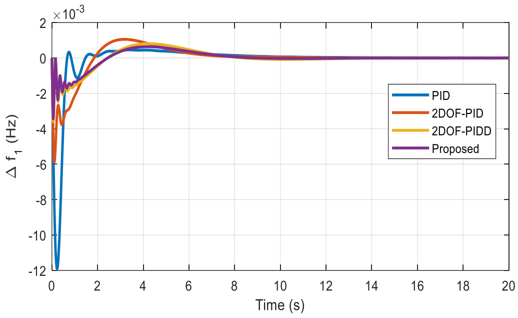

Figure 4. Area-1 frequency deviations with different controllers without wind and solar

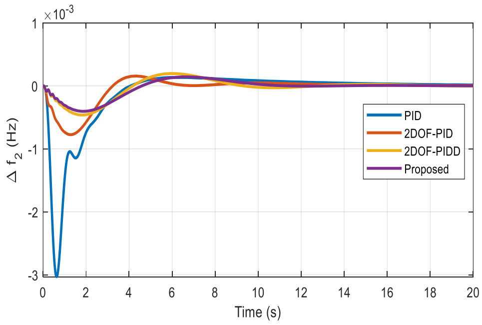

Figure 5. Area-2 frequency deviations with different controllers without wind and solar

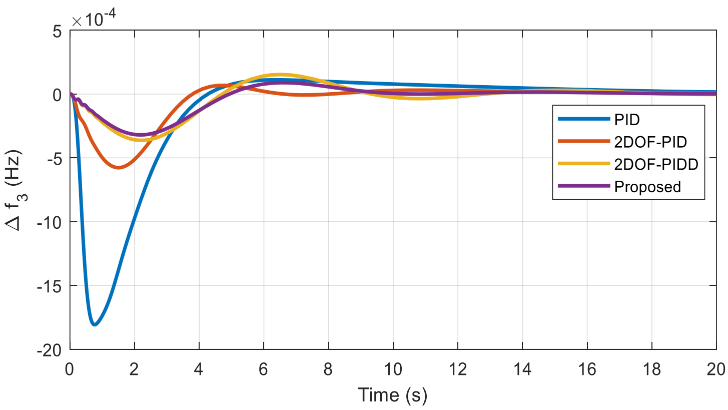

Figure 6. Area-3 frequency deviations with different controllers without wind and solar

The comparison of performances of different controllers when the renewable energy source is not integrated with the system is given is Table 2.

Table 2. System response for all controllers during step load change without renewables

controller	$\Delta f1$		$\Delta f2$		$\Delta f3$	
	Peak	Settling time	Peak	Settling time	Peak	Settling time
PID	-0.012	7.5	-0.003	10	-0.0017	14
2-DOF PID	-0.006	7	-0.0008	9	-0.0005	10
2-DOF PIDD	-0.0035	6.5	-0.0005	8.5	-0.0004	8.5
2-DOF PFIDD	-0.0034	6	-0.0004	8	-0.0003	8

5.2. Performance of 2-DOF-PFIDD controller for 3-area interconnected power system with renewables under load uncertainty

Area-1 of the power system under test is integrated with wind and solar power plants, the performance of the proposed controller is verified with step load perturbation (SLP). In this case, a 5% of load perturbation is initiated in area-1 in which renewables are integrated to test the applicability of the proposed 2-DOF-PFIDD controller. Figure 7, Figure 8, and Figure 9 shows the frequency disturbances associated with this system. In all results, the proposed controller yields better results compared to other controllers.

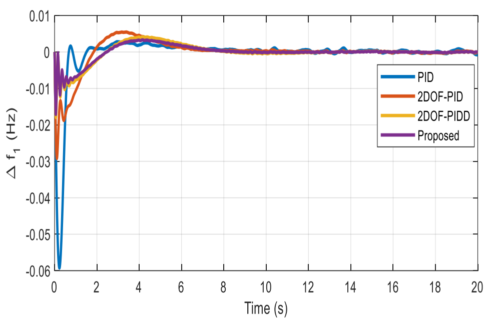

Figure 7. Area-1frequency deviations with different controllers with wind and solar in area 1

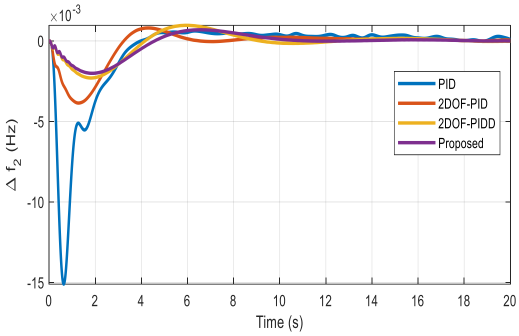

Figure 8. Area-2 frequency deviations with different controllers with wind and solar in area 1

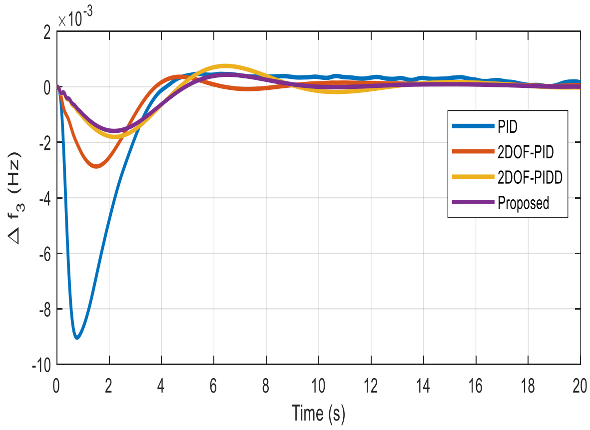

Figure 9. Area-3 frequency deviations with different controllers with wind and solar in area 1

The comparison of performances of different controllers when the renewable energy source are integrated with the system is given is Table 3.

Table 3. System response for all controllers during step load change with renewables

controller	$\Delta f1$		$\Delta f2$		$\Delta f3$	
	Peak	Settling time	Peak	Settling time	Peak	Settling time
PID	-0.06	8	-0.015	10	-0.009	14
2-DOF PID	-0.03	7	-0.004	9	-0.003	10
2-DOF PIDD	-0.019	6.5	-0.002	8.5	-0.0019	8
2-DOF PFIDD	-0.017	6	-0.0019	8	-0.0018	6

5.3. Performance of 2-DOF-PFIDD controller for 3-area interconnected power system with renewables under generation uncertainties

Since wind speed and solar irradiance are unpredictable in nature impacts the active power balance of the power system leading to frequency deviations. In this case, the wind and PV generation uncertainties are considered in three scenarios. In first case, 10% change is initiated in solar unit. In second case, 20% change is initiated in wind unit. In third scenario, both wind and solar generation perturbations are simulated together. In all three cases, the responses corresponding to proposed 2-DOF-PFIDD controller provided better outputs compared to other controllers. The system outputs are presented in Figure 10.

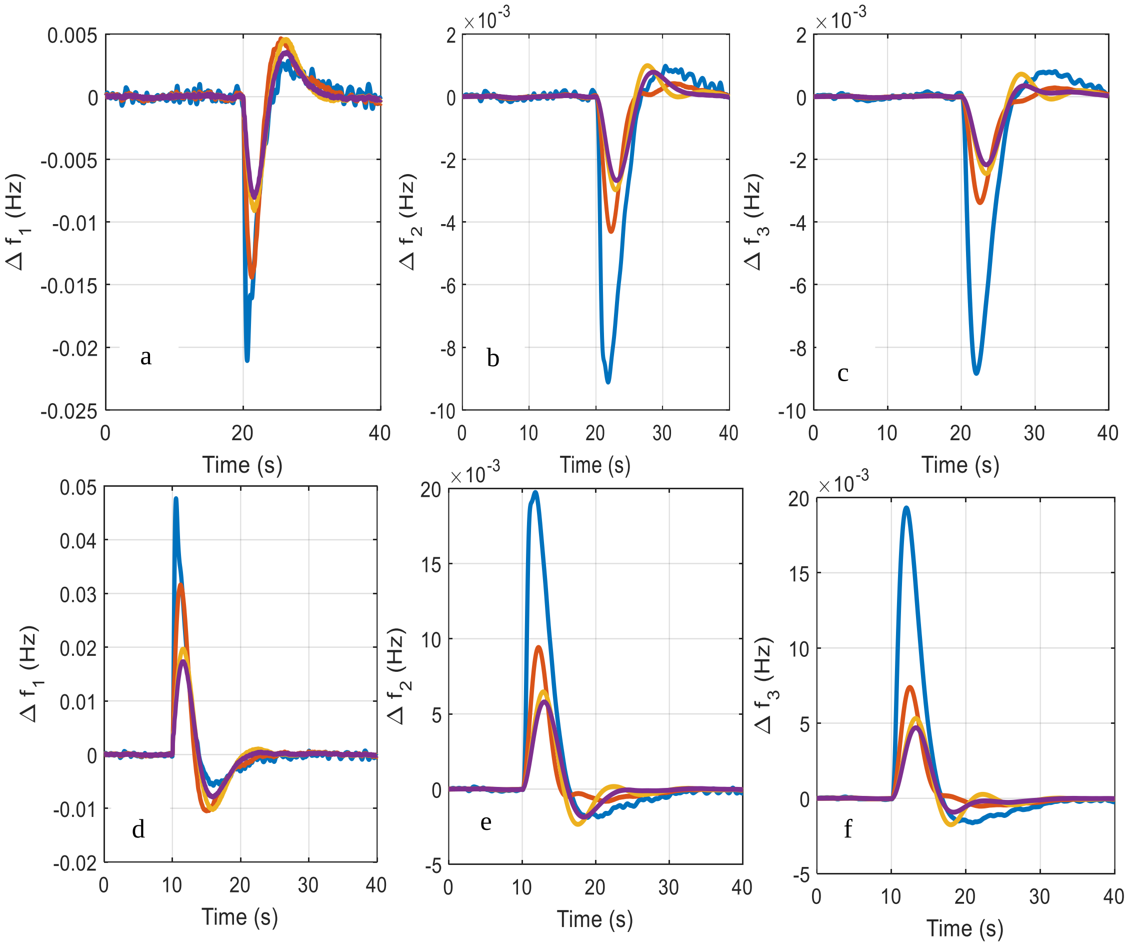

Figure 10. Responses of frequency deviations of Area-1(Figure-a), Area-2 (Figure-b), Area-3(Figure-c) in case of solar power changes, area 1(Figure-d), Area-2(Figure-e), Area-3(Figure-f) in case of wind power changes

The comparison of performances of different controllers when the renewable energy sources are integrated with the system & uncertainties are considered is given is Table 4.

Table 4. Comparison of performances of different controllers with system uncertainties

controller	$\Delta f1$ Peak	$\Delta f2$ Peak	$\Delta f3$ Peak	$\Delta f1$ Peak	$\Delta f2$ Peak	$\Delta f3$ Peak
	10 % SLP in solar unit			20 % SLP in wind unit		
PID	-0.021	-0.009	-0.008	0.049	0.02	0.019
2-DOF PID	-0.015	-0.0041	-0.003	0.03	0.01	0.075
2-DOF PIDD	-0.01	-0.003	-0.0021	0.02	0.0052	0.005
2-DOF PFIDD	-0.009	-0.0022	-0.002	0.0019	0.0051	0.004

6. COMPARISON

To show the benefits extracted in the AGC based on the proposed 2-DOF-PFIDD controller and the integration of renewables into the grid simultaneously, a comparison is provided. Fig. 11 to Fig. 13 shows the frequency variations of the area-1, area-2 & area-3 respectively simulated with load and generation variations. When simultaneous variations occur in the system, the system integrated with renewables minimize the frequency disturbances significantly compared to conventional system due to additional power balance by wind and solar as shown in area-1of test system.

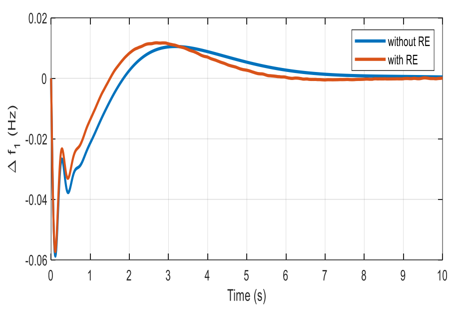

Figure 11. Comparisons of area-1 frequency deviations with and without renewables

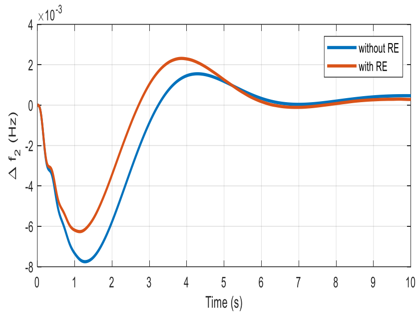

Figure 12. Comparisons of area-2 frequency deviations with and without renewables

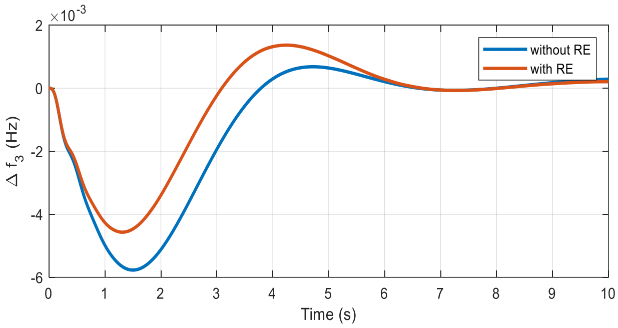

Figure 13. Comparisons of area-3 frequency deviations with and without renewables

The comparison of performances of different controllers with and without the renewable energy sources are given is Table 5.

Table 5. Comparison of performances of different controllers with and without the renewable energy sources

controller	$\Delta f1$ Peak overshoot		$\Delta f2$ Peak overshoot		$\Delta f3$ Peak overshoot	
	Without RES	With RES	Without RES	With RES	Without RES	With RES
2-DOF PFIDD	-0.06	-0.05	-0.008	-0.006	-0.006	-0.0041

7. CONCLUSION

In this study, a novel 2-DOF-PFIDD controller is presented to reduce the frequency deviations of the interconnected power system in the presence of renewable energy sources. The fitness function ISE was utilized in conjunction with the IWD method in this study to determine the best parameter gains for the proposed controller. The benefits of the proposed controller to enhance the frequency profile of the various regions under load and generation uncertainties are demonstrated by comparisons with the PID, 2-DOF PID, and 2-DOF PIDD controllers. This new approach of tuning 2-DOF-PFIDD with IWD algorithm improved the performance of the LFC. Moreover, the proposed controller was found adaptive enough to handle the uncertainty in the loads, RES power output and system parameters. The simulation results from the different scenarios validate that the proposed controller is able to minimize the frequency deviations significantly over the IWD-PID, IWD-2DOF-PID, IWD-2DOF-PIDD controllers. The peak overshoot value for deviation in frequency in area 1 is -0.06 without RES and -0.05 with RES. The peak overshoot value for deviation in frequency in area 2 is -0.008 without RES and -0.006 with RES. The peak overshoot value for deviation in frequency in area 3 is -0.006 without RES and -0.0041 with RES. So it is proved that the proposed controller is working is well even when the system is integrated with renewable energy resources.

APPENDIX

System variables under consideration for study:

T_{g1} =T_{g2}=T_{g3}= 0.08s	T_{P1} = 13.325s. T_{P2} = 12.669s. T_{P3} = 14.506s
T_{t1} =T_{t2}=T_{t3}= 0.3s	T_{12} = T_{23}=T_{31}=0.545 p. u
T_{r1}=T_{r2}=T_{r3}=10s	B_1=B_2=B_3= 0.425 p. u MW/Hz
K_{r1}=K_{r2}=K_{r3}=0.5 p.u MW	R_1=2.4545Hz/p. u.MW. R_2=2.0712Hz/p.u. MW. R_3=1.8912Hz/p.u.MW
K_{P1}= K_{P2}=K_{P3}=120.83Hz/p. u MW	a_{12}=a_{23}=0.5
K_{wtg} 1⁄41; T_{wtg} 1⁄41:5s	K_{spvg} 1⁄41; T_{spvg} 1⁄41:8s

NOMENCLATURE

PFIDD	Proportional Fractional Integral Double Derivative	D_w	Set point weight for derivative controller
IWD	Intelligent Water Drops	N	Noise coefficient
K_p	Proportional controller Gain	f	Frequency
K_i	Integral controller Gain	P_{tie}	Power of tie-line
K_d	Derivative Controller Gain	ISE	Integral square error
K_{wtg}	Gain constant of WTG Gain	T_{wtg}	Time constant of WTG
K_{spvg}	constant of SPVG Integral	T_{spvg}	Time constant of SPVG
n	Fraction	T_g	Time Constant of Governor
T_t	Turbine time constant	T_r	Time constant of Reheater
K_r	Reheater gain constant	K_p	Gain constant of Generator Renewable
2DOF	Two-Degree-of-Freedom	RE	Energy
P_w	Set point weight for P controller	R	Speed governor regulation parameter
B	Frequency bias constant	T	Coefficient of Synchronizing power Area
T_p	Generator time constant	a	capacity ratio

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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