Frequency Stability Enhancement of Wind Integrated Power System with TCSC

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Received: 27.10.2023 Accepted:11.12.2023

Abstract- Managing power system's frequency within allowable limits is a difficult challenge in the context of high wind penetration and generation uncertainty. This article provides a cascade controller based on a fractional-order integrated derivative (FOID) proportional integral derivative (PID) to improve the stability of the frequency of a wind integrated electric system. The effectiveness provided by the FOID-PID controller is evaluated using a large quantity of wind energy generation changes and compared with the PID controller to extract the benefits of the cascade controller. Additionally, the impact of the thyristor-controlled series capacitor(TCSC) is investigated. To achieve the goal of automatic generation control (AGC), the secondary controllers (PID/FOID-PID) optimal gain parameters are identified with zebra optimization technique (ZOA). To determine the controller gains, the integral absolute time error function is employed as the problem's cost function. The investigations are carried out in MATLAB SIMULINK.

Keywords Wind energy, automatic generation control, ZOA, TCSC.

1. Introduction

The use of wind energy is the ideal alternative to fossil fuels since it offers both environmental and economic answers to the rising need for electrical power generation. The generation of electricity in traditional thermal and hydro facilities uses automatic generation control (AGC) to regulate the continually changing requirement for electrical power [1]. The reports shows the majority conventional resources are replaced with the renewables in future and the AGC operational challenges need to be addressed with their integration since the power generation of the wind system is also varying with time along with the demand leads to power imbalance condition. The active power imbalance leads to frequency deviations and maintaining the frequency at nominal operating value is the preliminary objective of the AGC [2]. Due to the trend of rising energy from renewable sources participation in the power sector, mitigating frequency disturbances with appropriate secondary controller in conjunction with primary regulation in the face of significant participation from solar and wind is a developing field in these days.

There are several publications in the literature that propose classical, cascade, advanced, and intelligent secondary control strategies for reducing deviations in frequency in wind incorporated electrical system models. The following is a full summary of the literature works: Wind energy is turned into electricity utilizing induction generators that are doubly fed (DFIG) in the case of wind power. To regulate the power system frequency in presence of wind, the DFIG participation is well discussed in [3]. The input vulnerabilities of the wind speed variations are discussed in [3] using the DFIG participation. Particularly, the secondary controller selection and the parameter tuning play an important role in both normal and renewable integrated power system AGC models. The approach of identification of the

optimal parameter gains are presented in [4] for classical single area thermal system using particle swarm optimization (PSO). For finding optimal solution of secondary controller of the isolated and interconnected models of the power system, a fitness function is necessary to use the population search-based techniques like particle swarm optimizer (PSO). Integral square error (ISE) is suggested in [4]. Furthermore, previous research proposed several control strategies to adjust the frequency within the renewable integrating power system via secondary control of frequency loop [5]-[15]. In [5], fuzzy intelligent secondary control is used to minimize the frequency disturbances for a wind penetrated three area network. The PSO approach is used in the current investigation to optimize the fuzzy membership function parameters in order to increase the performance of the fuzzy to regulate the frequency for the system's operations. Another optimization approach for frequency regulation of the wind linked hybrid power system is provided in [6]. In [6], the PID controller gains are achieved with multi-verse optimizer algorithm. In both cases, identification of optimal gains or values of membership functions depends on the selection of the fitness function and choice of the optimizer for tuning. Model predictive control mechanisms are also well tested to the interconnected power system with wind participation [7]-[8]. A few papers [9],[10] propose integrating fuzzy along with classical control techniques to regulate the load frequency of a wind integrated power system. Fuzzy membership function parameters are adjusted with the help of the artificial bee colony (ABC) technique in [9], & PID controller gains are also employed in conjunction with fuzzy in [10] to enhance the output metrics. The combination of the fuzzy and classical controllers provided more acceptable results compared to the usage of the classical controller or fuzzy controller alone. Since solar and wind energy output is more erratic than load, intelligent controllers are better suited for renewable integrated systems than traditional systems. Understanding the wind plant penetration effect on AGC helps the selection of secondary controller (SC) [11] and several advanced controllers were suggested in such wind plant penetration.

These advanced controllers provided enhanced results compared to classical controllers with suitable performance specifications irrespective of the type of the system and different plant participations. A fractional order PID (FOPID) controller for an isolated renewables integrated hybrid power system is recommended in [12]. PSO is used to determine the SC gains. In order to lower the frequency and tie-line power variations in wind integrated multi sector linked power systems, a 2-degree of freedom-FOPID (two-DOF-PID) controllers is presented in [13]. Additionally, 2-DOF-hybrid controller is utilized in [14] to reduce frequency variations of the wind integrated power system when storage devices are present. To tune the parameter gains, the hybrid controller uses a tilt integral derivative controller with a modified sine cosine algorithm in addition to FOPID. As stated earlier, the best solution of gains of the controllers are examine with any suitable population search algorithms. However, the decision variables of the optimization process are increasing compared to the classical controller design problem. In these works, AC tie-line is used to transfer the active power between the areas reported from [4]-[14]. In [15], HVDC is used for transferring the active power which enhances the power transfer capacity and therefore minimize the frequency deviations during load perturbations. Flexible AC transmission systems (FACTS) further increase the AGC characteristics and the capacity for power transfer. In [16], FACTS are recommended to increase stability when wind farms are present. In [17], to increase frequency stability in an interconnected power system, a thyristor-controlled series capacitor (TCSC) is placed. For wind integrated model also, the application of FACT devices is available in AGC perspective [18]. Overall, the cascade control strategies provide better frequency control for wind integrated systems compared to classical controllers and stability of the system further increases with FACT devices. Different power system structures are investigated in the literature to meet the goal of the AGC with classical, cascade and intelligent controllers [19]-[26]. The studies are focused on the implementation of different controllers to reduce the disturbances caused by the load variations and selection of the suitable optimizer to examine the correct solution set of the gains attain minimum cost function like ISE etc.

In this work, the linked power system's AGC goals are met in the presence of wind power through the employment of a FOID-PID controller. And the system performance is investigated for small, random, and simultaneous load-wind input variations. In each stage, comparisons are provided with classical PID controller. Using the integral time absolute error (ITAE) measure as cost function of the optimization problem, the zebra optimization algorithm (ZOA) [19]–[20] is utilized to tune the PID and FOID-PID controllers. Furthermore, the impact of TCSC is also studied in presence of wind when FOID-PID cascade controller acting as SC. This FOID-PID controller provide better results compared to classical controller and reduces peak frequency deviations during random load and wind generation uncertainties.

2. Test System

Different types of models were studied in the AGC studies to investigate the performances of the secondary controllers. The effect of TCSC and the recommended proposed controllers are examined in this article. Consequently, in order to conduct simulation experiments in the presence of load and generation disturbances, a linked two area power system with wind integration is used for this work. Figure 1 displays the standard test system block diagram structure. For-each individual area consists of the following plants, non-reheat thermal plant (NRTP) and wind plant (WP). The generation input of the WP is random in nature and stochastic variation of generation inputs are included in the system to simulate such generation changes. In order to maintain the planned power and standard frequency during fluctuations in load and generation, the NRTP generation is managed by the primary & SC. Unlike conventional systems, the power imbalance is caused by both the demand and generation of electricity which is balanced by the conventional generation. The SC plays a key role to achieve AGC objectives of the system. Apart from the classical controllers, cascade structured schemes provide better controlling in the presence of the continuous disturbances of the generation and load. This paper suggested

FOID-PID cascade controller as SC of NRTP in both areas. The arrangement of the FOID-PID cascade controller is depicted in Figure 2. When comparing the suggested controller to classical controllers, the number of variables that must be identified by the optimisation issue rises. Figure 2 shows how the FOID-PID cascade controller is configured. The approach of examine the tuning values of the controller using ZOA is presented in section 3.

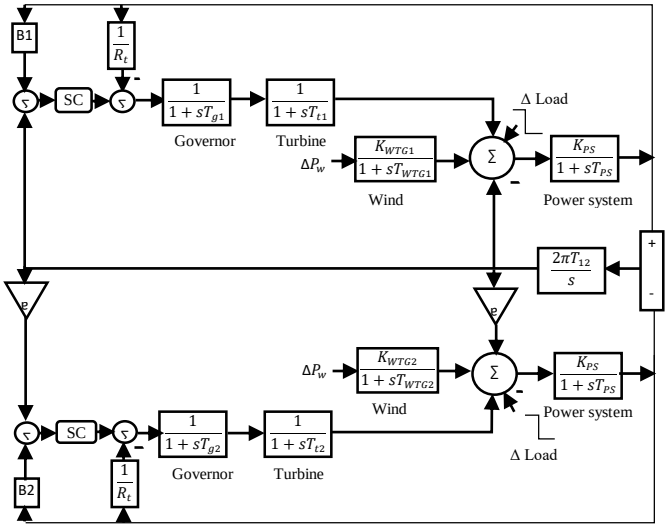


Fig. 1. Wind integrated interconnected power system block diagram model.

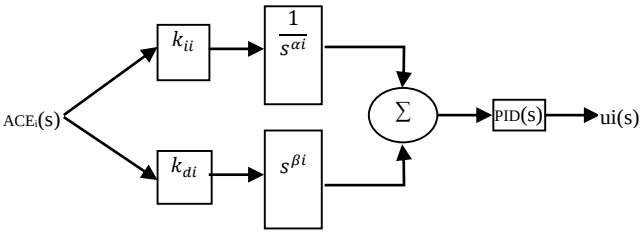


Fig. 2. FOID-PID cascade controller scheme.

Equation (1) is the output expression of the proposed controller, which regulates the frequency of the system via thermal power production. The overall control input of the NRTP is provided in Equation (2).

$$u_i = ACE_i(S)\left\{\left(k_{ii}.\frac{1}{s^{\alpha i}} + k_{di}s^{\beta i}\right).PID(s)\right\} \quad (1)$$

$$\Delta P_{NRTP} = u_i + \frac{\Delta f_i}{R_t} \quad (2)$$

Along with these load perturbations, wind power generation also changes with time and the stochastic equations of these variables are given in Equation (3) with the help of step functions available in MATLAB [21]. Equation (4) provides the power balancing equation for every area to govern power system stability, and it is further strengthened with the FACT device. In this work, TCSC is used to improve system stability under load disruptions. The generalized transfer function of the TCSC is provided in Equation (5)

$$\Delta P_w = a_0U(t) + a_1U(t-t_1) + a_2U(t-t_2) + \cdots \quad (3)$$

$$\Delta P_L = \Delta P_{NRTP} + \Delta P_{Wind} + \Delta P_{tie-line} \quad (4)$$

$$G_{TCSC}(S) = \frac{K_{TCSC}}{ST_{TCSC}+1} \quad (5)$$

In Equation (5), K_{TCSC} is the amount of gain & T_{TCSC} represents the FACT device's time constant. The system's numerical values are given in Appendix.

3. Fitness Function and Tuning Algorithm

The secondary controller gains must be found in order to fulfil the AGC targets for the system under test in the face of wind power & electrical demand changes. The system's reaction is determined by the SC gains chosen, & a metric is necessary to quantify the response. ITAE is used to fitness function to measure the response and to find the optimal gains of the SC attain better response. Mathematically, Equation (6) shows the ITAE fitness function valid for the 2-area interconnected power system.

$$\left.\begin{array}{c} min\ J = \int_0^t (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{tie}(t)|)tdt \\ S.To,\ \ k_{min} < k_{pi,}k_{ii,}k_{di,}\alpha_i,\beta_i < k_{max} \end{array}\right\} \quad (6)$$

The optimal selection of the gain parameters from the extensive possible solutions is an optimization problem using the Equation (6) as objective function. The decision variables of the problem are SC gains and generated within the boundaries of the variables as shown in Equation (6). In the given limits of the controller gains provided in Equation (6), the optimal values need to identify using the search mechanism. This problem is solved by using the ZOA. ZOA is a population search-based technique proposed in the year 2022 by mimicking the nature of the zebras into search and updating process [19]-[20]. The initial search mechanism, finding the best from the initial set and updating the position towards best using the nature of the zebras are the main steps in the ZOA. The solutions represents the position of zebras generated randomly within the search space region created using the Equation (6). The initial positions of the zebras are given by .

$$\begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ x_{N,1} & \cdots & x_{N,j} & \cdots & x_{N,m} \end{bmatrix}_{N\times M} \quad (7)$$

In Equation (7), X_i is i^{th} zebra, $x_{i,j}$ is value for the j^{th} decision variable proposed by the i^{th} zebra. This solution matrix is NXM in size, representing N zebras (Population members) and M choice variables. The fitness function (F) is evaluated with each solution and provided in Equation (8)

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N\times 1} \quad (8)$$

The solutions are updating in two strategies. In strategy 1, it utilize the Equation (9) and Equation (10).

$$x_{i,j}^{new,P1} = x_{i,j} + r.(PZ_j - Ix_{i,j}) \quad (9)$$

$$X_i = \begin{cases} X_i^{new,P1}, F_i^{new,P1} < F_i; \\ X_i,\ else \end{cases} \quad (10)$$

In Equation (9), According to the first phase, $X_i^{new,P1}$ is the newest position of the i[th] zebra. PZ, also known as the Pioneer Zebra, is the best member. Based on objective function, position is updating with Equation (10). In second strategy, it utilize the Equation (11) and (12)

$$x_{i,j}^{new,P2} = \begin{cases} S_1: x_{i,j} + R.(2r-1) \\ \left(1-\frac{t}{T}\right).x_{i,j}, \\ S_2: x_{i,j} + R.\left(AZ_j - I.x_{i,j}\right), else, \end{cases} \quad (11)$$

$$X_i = \begin{cases} X_i^{new,P2}, F_i^{new,P2} < F_i; \\ X_i, \ else \end{cases} \quad (12)$$

Where $X_i^{new,P2}$ new solution. R is a constant (0.01 is preferable), AZ represents the state of the assaulted zebra, and Ps is a randomly selected integer in an interval [0, 1] that is used to choose one of the two potential methods. The new positions of the zebras replace old positions, the process is iterative and continue until the convergence criteria is fulfilled. The final best solution available after all iterations is taken for the assessment since it provided better response with metric ITAE. The objective of the search process is to minimize the ITAE with the controller gains generated as solutions by ZOA. In each time, if the position of the controller gain exceeds its limit as provided in Equation (6) then the value of the solution is fixed at the extreme. Therefore, the selection of the controllable variables of the ZOA is also important in the application

4. Simulation Results

The test system's SC, the FOID-PID cascade controller, is utilized to validate tiny, random, & stochastic load disturbances, wind generation alternations, and parameter modifications by comparing it to a PID controller. Furthermore, the impact of the TCSC is also investigated in the presence of PID and FOID-PID controllers. The most optimal parameters gain for PID & FOID-PID controllers. The key issues of the AGC studies are presented in a comprehensive manner to provide the merits of the proposed study. To simulate the disturbances in Simulink, step and random functions are useful. The detailed explanation of each study is presented in case wise from the section 4.1 to 4.6.

4.1. Simple Load Changes

In area 1, 1% load perturbations are begun to validate the effectiveness of the PID & FOID-PID controllers. The change in area-1 frequency deviations are plotted in Figure 3.a. The deviations are minimized with the presence of FOID-PID controller compared to the PID in terms of the peak overshoot and performance metrices. For area-2 frequency deviations, Figure 3.b is provided to show the comparative results of the both PID and FOID-PID controllers. The inter-area tie-line power variances are also shown in Figure 3.c. In the case of second area deviations in frequency and tie line power changes, the FOID-PID controller outperformed the PID controllers, as evidenced by the performance metrics values shown in Figure 4. The suggested controller's advantages are stated in terms of maximum overshoot and settling time, as shown in Figure 3, which are acceptable in comparison to the PID controller. Because the function for fitness is framed with information about frequency as well as tie-line power alterations, the optimal controller achieves the lowest value at the conclusion of the optimizer's last iteration.

Table 1. Tuning values of the controllers

Controller	Fractional part				PID part		
	k_{ic}	k_{dc}	α	β	k_p	k_i	k_d
Area-1							
PID	--	--	--	--	-0.746	-0.998	-0.419
FOID-PID	0.5438	0.8500	-0.0736	0.0236	-0.222	-0.970	-0.470
Area-2							
PID	--	--	--	--	-0.377	-0.227	-0.078
FOID-PID	0.9239	0.8234	-0.3726	0.2617	-0.7843	-0.8452	-0.3729

Of course, other performance indicators such as ISE etc. also provided similar results instead of the ITAE as cost function.

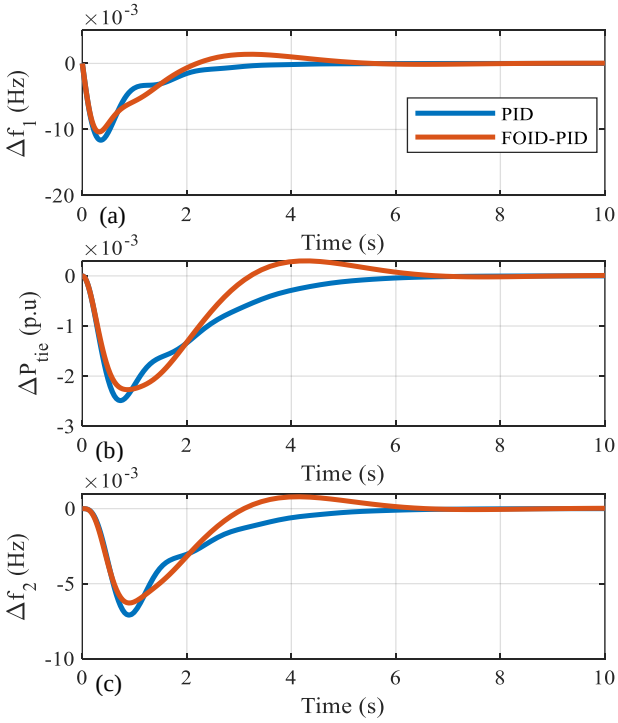


Fig. 3a. Δf_1, **b**. ΔP_{tie}, **c**. Δf_2 during the simple load changes.

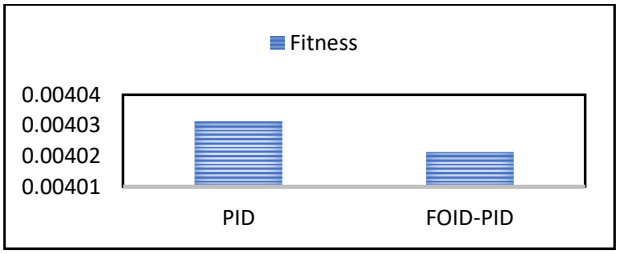


Fig. 4. ITAE measures for PID and FOID-PID controllers during simple load changes.

4.2. Random Load Changes

The comparative response of the FOID-PID controller over PID controller is investigated with random load pattern variations as shown in Figure 5. These patterns are generated using the step and random functions initiated at times of 0, 20, 40 and 70 sec. These load variations are initiated in area-1 and frequency deviations of the same area are presented in Figure 6.a. Figure 6.b shows the tie line power fluctuations between the two locations, whereas Figure 6.c shows the changes in frequency for area 2. These observations are made at the same tuning values mentioned in Table 1. In line with the simple load changes, the FOID-PID cascade controller is adaptable to minimize the random load variations compared to PID controller. The wind generation variations of this simulated case are treated as zero. Because the increase or decrease in wind generation does not contribute to the power balancing under load disruptions, the analyzed situations in sections 4.1 and 4.2 fall within a regular two-area linked power system. Therefore, separate cases are required to test the FOID-PID controller performance in such generation variations. Interestingly, the ZOA algorithm provided the best tuning values of the controllers since the outputs of the system during the severe random load disturbances are really good as shown in Figure 6.

4.3. Continuous Wind Generation Changes

Wind generation, like electrical demand, is erratic in nature, increasing power imbalance in the linked power system. In area 1, random wind power fluctuations are launched to test the effectiveness of the two PID & FOID-PID controllers. These random fluctuations of the wind speed or power are created with the help of either stochastic equations or with random function blocks of Simulink. Figure 7.a-c depicts the frequency change of area 1, tie-line power, and change in frequency of area 2. The random wind input variations are provided in Figure 8. For these variations, the response of both controllers are acceptable to minimize the frequency and tie line power deviations. Overall merits are compared with ISTE metrices.

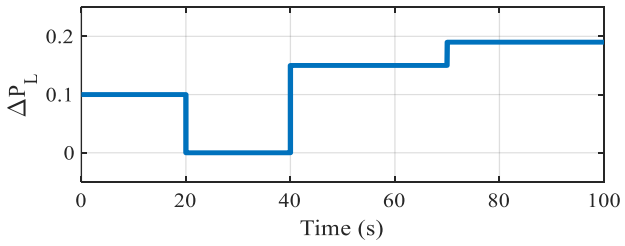


Fig. 5. Random load perturbations initiated in area 1.

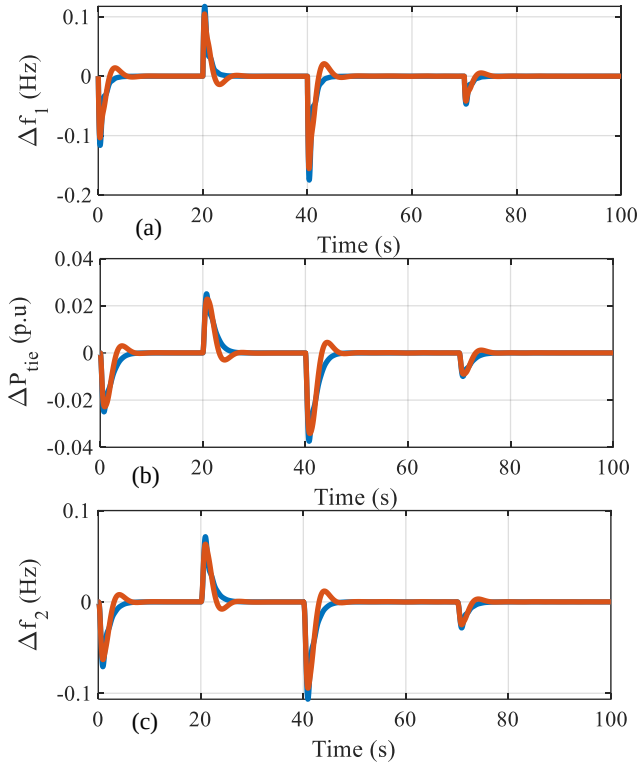


Fig. 6a. Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 during the random load perturbations .

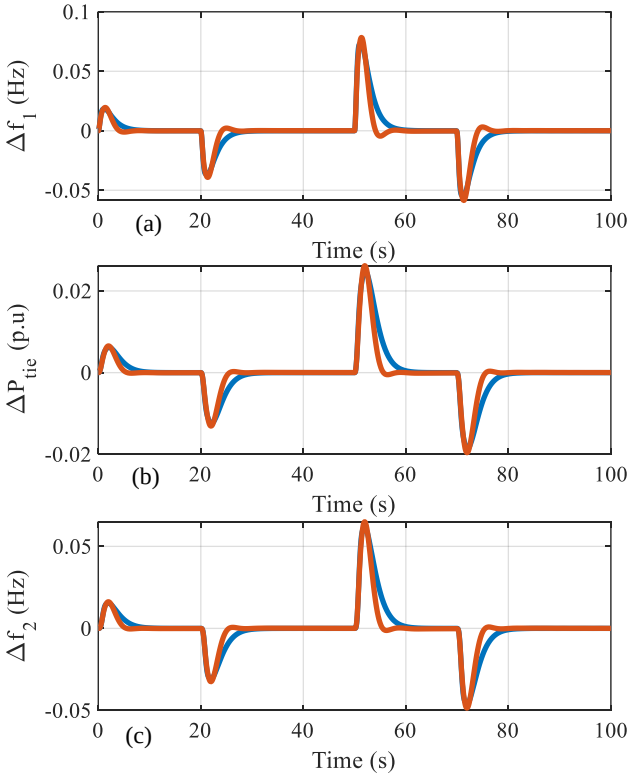


Fig. 7a. Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 during the random wind perturbations.

4.4. Changes in Load and Generation Simultaneously

Preferably, the system experiences both load and generation fluctuations at the same time. Area 1 is used to

examine the effects of PID & FOID-PID controllers as SCs. In this instance, Figures 9.a through 9.c display the changes in area 1 frequency, tie-line power, and area 2 frequency. The performance metrices of cases 4.3 and 4.4 are provided in Figure 10 to show the improvements with FOID-PID controller over the PID controller.

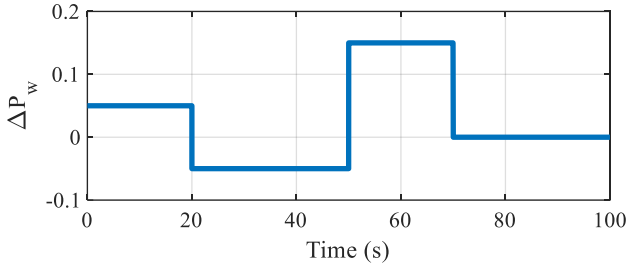


Fig. 8. Wind input uncertainties in the area 1.

4.5. Parameter Sensitivities

Another potential event within a linked power system is parameter fluctuations. A power system gain value is chosen in order to examine the behaviour of the FOID-PID controller when parameter changes are present. The nominal system gain value is 120 and 4 different values are taken (100, 110, 130, and 140) to check the performance of the cascade controller. Figures 11.a through 11.c illustrate the changes in area 1 frequency, tie-line power, and area 2 frequency, as well as the FOID-PID controller's ability to handle these parameter fluctuations. Although, the variations of the parameter changes are considerable, no significant changes are observed on the results as depicted in Figure 11.

4.6. Impact of TCSC

TCSC is positioned in the tie-line to increase the linked power system's capacity for power transmission. Figures 12.a, 12.b, and 12.c show the responses to a 1% load change that is implemented in area 1 to assess the effect of the TCSC. Every graphic matches a test system that has a FOID-PID controller. The deviation in frequency of area 1 with and without TCSC are shown in Figure 12.a. It is noted that the addition of TCSC improves the steady state settling time and lowers peak errors, which increases system stability.

5. Comparisons

ZOA is used to adjust the PID & FOID-PID controllers' optimum controller gains. In simulation studies, these values are used to reduce tie-line power variances & frequency variations. Additionally, the suggested tuning algorithm's advantages are contrasted with those of the PSO [4], differential evolution (DE) [22], & bio-geography-based optimizer (BBO) [23]. PSO, DE, and BBO adjust the FOID-PID controller gains using the same ITAE metric. Figure 13 shows the system's outcomes in terms of tie-line power variations and frequency deviations. These comparisons are provided after taking the optimal tuning values of the aforementioned techniques at their best runs.

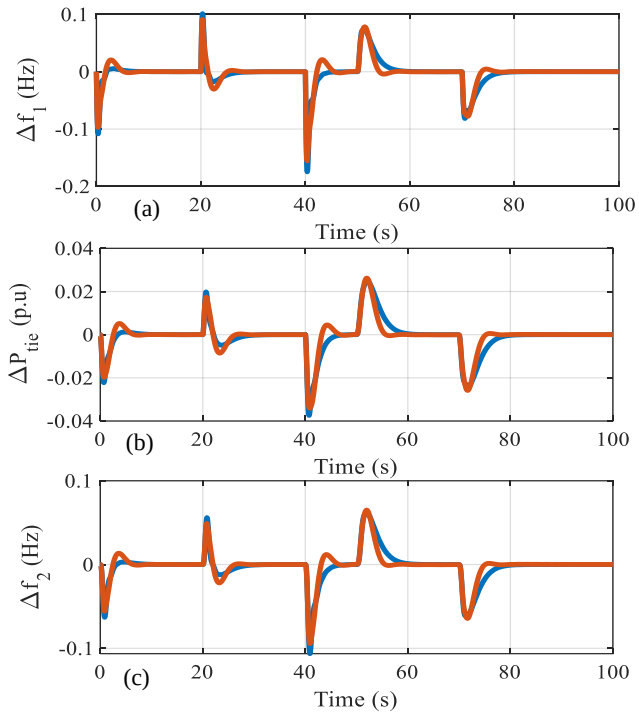


Fig. 9a. Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 during the random wind perturbations.



Fig. 10. ITAE measures for PID and FOID-PID controllers during simultaneous disturbances.

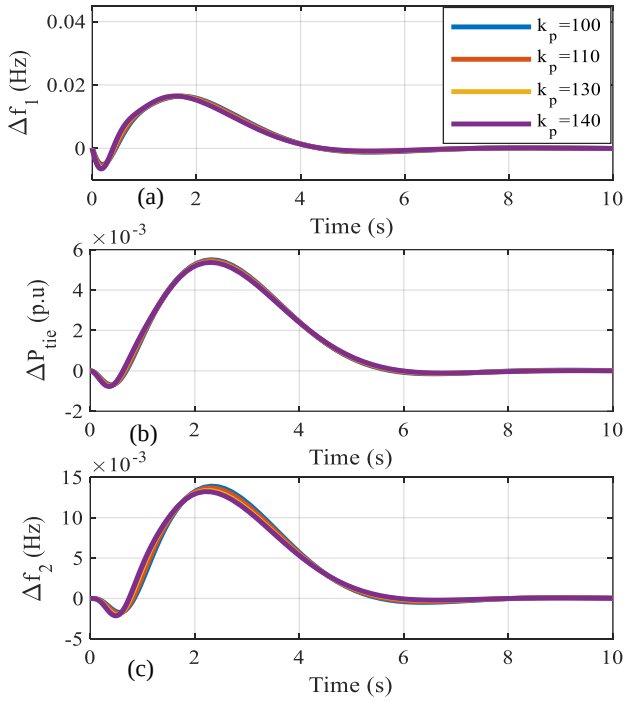


Fig. 11a. Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 during the parameter uncertainties.

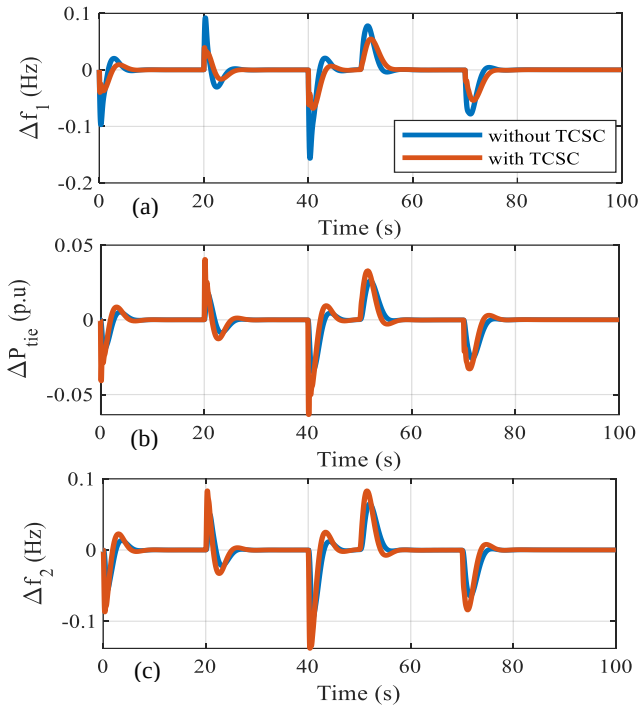


Fig. 12a. Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 in presence of TCSC.

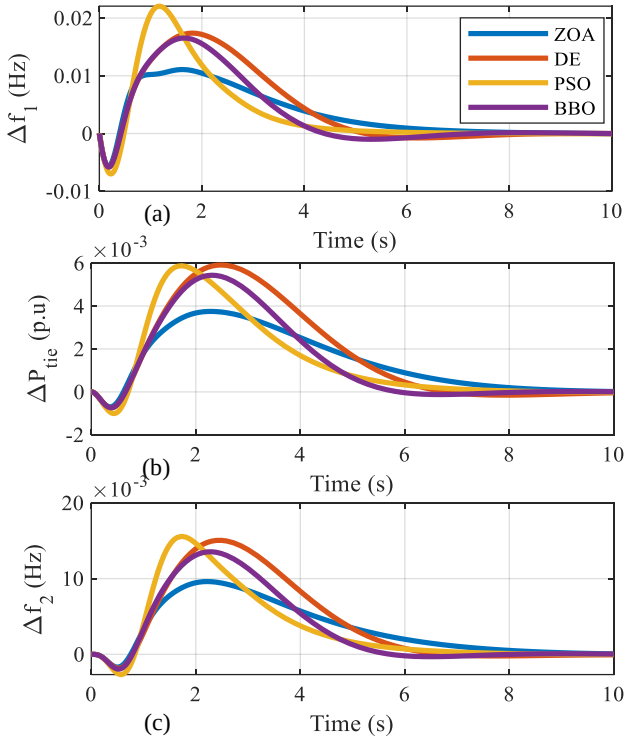


Fig. 13. Comparative assessment for **a.** Δf_1, **b.** ΔP_{tie}, **c.** Δf_2 when tuning is carried out with different optimization algorithms.

6. Conclusion

This work proposes the FOID-PID cascade controller as the SC of AGC to manage frequency during load and generation perturbations. To assess the efficacy of the FOID-PID controller, a two-area linked power system with a significant degree of wind penetration is used. Advantages are shown by contrasting the controller's output with that of the conventional controller. In the study, ZOA is utilized to adjust the cascade controller's optimum gains, yielding better outcomes than PSO, DE, and BBO. The investigations carried out at simple, random, and simultaneous load and generation changes extracts the benefits of the proposed work. Additionally, the impact of TCSC was also verified during the load perturbations in presence of the FOID-PID controller. This controller provide better results compared to the system without TCSC

Appendix

Thermal generation unit: $T_{t1} = T_{t2} = 0.3$; $T_{g1} = T_{g2} = 0.08$; $R_t = 2.4$; Wind unit: $K_{WTG1} = K_{WTG2} = 1$; $T_{WTG1} = T_{WTG2} = 1.5$; TCSC: $K_{TCSC} = 1$; $T_{TCSC} = 0.015$; System: $K_{PS} = 120$; $T_{PS} = 20$; $Ps = 0.545$;

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