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Frequency Control of Interconnected Power System via SBO assisted Simultaneous Tuning Strategy in Presence of DFIG

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Abstract: - To achieve the objectives of the automatic generation control (AGC) of wind integrated interconnected power system (WIIPS), better tuning and control strategies are required. This paper suggests simultaneous tuning strategy for the AGC and wind system controllers to improve the stability of the WIIPS. The bulk amount of wind is integrated into the grid using the doubly fed induction generator (DFIG) and its simplified model is used to simulate the WIIPS. Initially, classical controllers are opted in AGC mechanism to reduce the frequency disturbances caused by the load and wind generation uncertainties. Further, classical controllers of WIIPS are replaced with cascade controllers to enhance the system frequency profile during the disturbances. The optimal set of solutions of the classical and cascade controllers are examined by the satin bowerbird optimizer (SBO) with the help of integral square error as fitness function of the optimization problem. Comparisons are provided to show the merits of the WIIPS over normal interconnected power system, cascade controller over classical controller and simultaneous tuning strategy over regular tuning mechanism.

Keywords: Classical controller (CC), Frequency Control (FC), Automatic Generation Control (AGC), Satin Bowerbird Optimizer (SBO), Wind Energy (WE).

I. INTRODUCTION

The AGC mechanism of the electrical power system with conventional generation such as thermal, hydro, and nuclear etc. is different compared to the electrical grid integrated with bulk amount of renewable energy. Irrespective of the type of the system, the electrical power generation should meet the load demand. During load perturbations, the generation is controlled by the AGC along with the primary regulation of the conventional generating plants. In case of WIIPS, the generation also varies along with the demand and maintaining the power balance is challenging. However, the participation of renewables to meet the electrical power demand is inevitable and the scenario of renewables contribution is increasing in positive direction. Several solutions are provided in earlier studies to accomplish the objectives of AGC.

Among the existing renewable resources, wind and solar are significant contributors to generating electricity in order to meet the growing demand. The bulk amount of wind power is integrated to the grid using the doubly fed induction generators (DFIG). The volatile nature of the wind speed affects the system output along with load demand which imbalances the active power mechanism. Therefore, AGC mechanism is used to reduce such power imbalances in conventional systems since the power generation from the wind system is also participating to create power mismatches. The participation of wind energy through DFIG is presented in [3]. Apart from the AGC control mechanism, the strong primary frequency control of the DFIG impact the frequency regulation of the power system. The presence of REUs with such primary frequency control handles the issue of the frequency disturbances during the load and generation fluctuations. On the other side, the better AGC control strategies yields desired responses in both frequency and tie-line power. In [4], predictive cascade control strategy is adopted to reduce the frequency and tie-line disturbances in presence of the high penetration of the wind and solar. This cascade AGC controller handles system uncertainties better than the classical controllers. Furthermore, the power imbalances due to load fluctuations and renewable energy changes are minimized with intelligent controllers such as fuzzy [5], [9] etc. In [5], a combined fuzzy-particle swarm optimizer (PSO) tuning mechanism is adopted to minimize the frequency disturbances for a wind penetrated three area network. In [6], cuckoo search optimizer is used to control the DFIG in an interconnected power system with thermal, hydro and wind generating units. The study presented simultaneous tuning of controllers of AGC and DFIG units.

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Model predictive control (MPC) schemes are also suitable for the renewable integrated systems and robust in nature against the parameter variations and system uncertainties [7]. Due to wind power's erratic nature, the large-scale integration of its generation places an additional stress on frequency regulation. The active power control of wind turbines is necessary for the AGC to include wind turbines (WTs) and maintain a suitable frequency regulation performance. Traditionally, pitch angle control or rotor speed control, which exhibit delayed reaction and a constrained regulating range, respectively, are used to achieve the active power control of WTs. The study in [8] proposes a coordinated control technique to enhance the regulation performance of variable speed WTs that simultaneously activates control schemes [8].Optimal fuzzy control strategies in AGC reduces the impacts of the uncertainties in the WIIPS with the help of PID controller where the controller gains are adjusted by fuzzy [9]-[10]. Apart from the regular classical controllers, the modified architectures of the classical controllers reduces the disturbances to a great extent. In [11],a cascade-fractional order secondary controller is suggested to reach the goals of the AGC when the system integrated with renewables. A hybrid MPC is suggested in [12] to reach the goals of the AGC when the system integrated with renewables.

Under a variety of operating conditions, artificial intelligent techniques have the ability to build nonlinear controllers for higher dynamic performance in the AGC system. In [13]. support vector machines is used to regulate the frequency of a two-area linked power system with dynamic involvement from DFIG based wind turbines. In extension to the study of the renewables in AGC, effect of the storage units [14], transmission links [15], FACT devices [16], fractional controllers [16]-17] are also investigated in broad manner. Furthermore, the impact of electric vehicles is also investigated in presence of renewables [18]. The impact of the wind and solar uncertainties are addressed with better performance indices and literature review suggests ISE, IAE, ITSE, and ITAE as popular indicators to tune the AGC controllers [19]. These indicators are important to find the optimal gains of the controllers using heuristic algorithms. These performance indicators are also known as the cost functions of the optimizers to find the optimal tuning values of the AGC controllers.

This paper introduces simultaneous tuning strategy of the AGC and DFIG controllers to achieve the objectives of frequency control of WIIPS during the load, generation, and parameter uncertainties. PID and PI-PD controllers are used to study the impact of the AGC mechanism in presence of the high penetration of wind energy. The optimal gains of the supplementary controllers and DFIG speed controller are identified with the help of the SBO algorithm. Comparisons are provided to show the merits of the WIIPS over normal interconnected power system, cascade controller over classical controller and simultaneous tuning strategy over regular tuning mechanism. The rest of the article is organizing as follows: Section 2 provides the description of test system and secondary controller, section 3 provides details of fitness function and tuning algorithm, section 4 provides simulation results and section 5 provides comparisons. Conclusions are listed in final section of the paper.

II. TEST SYSTEM AND SC CONTROLLER

In case of the conventional power generating units (CPGUs) either in isolated or interconnected modes, the power generation is controlled initially by primary regulation and later secondary controller to balance the demand of the system. In such cases, design of the classical controllers in secondary AGC loops is acceptable since the load mismatches are balanced by the CPGUs by controlling its output power. However, frequency control is more challenging in presence of the renewable energy unit (REUs) since the power generations by REUs are also volatile in nature with time based on the input. In case of solar, the irradiance of the system is variable and affects the PV generation. In case of wind, the wind speed of the system is variable and affects the wind generation. The presence of renewable energy integrated with the CPGUs increases the need of the AGC and more attention is required to select proper control mechanism in the secondary control loop of AGC to minimize the tie-line disturbances and frequency deviations. In this work, a two-area test system is considered to study the AGC aspects. The test systems consist of one CPGU and one REU in each area. The secondary control AGC mechanism is provided to CPGU to minimize the frequency deviations of the system during the load perturbations. The block diagram of the test system is presented in Fig. 1. Furthermore, the DFIG is modeled as shown in Fig. 2 to integrate the effect of the wind generation into the grid. In the AGC secondary loop, the classical PID controller is used to control the generation output of the CPGU. The controller output is expressed as (1)

$$u_i = ACE_i(S)\left(k_{pi} + k_{ii}\cdot\frac{1}{S} + k_{di}S\right) \tag{1}$$

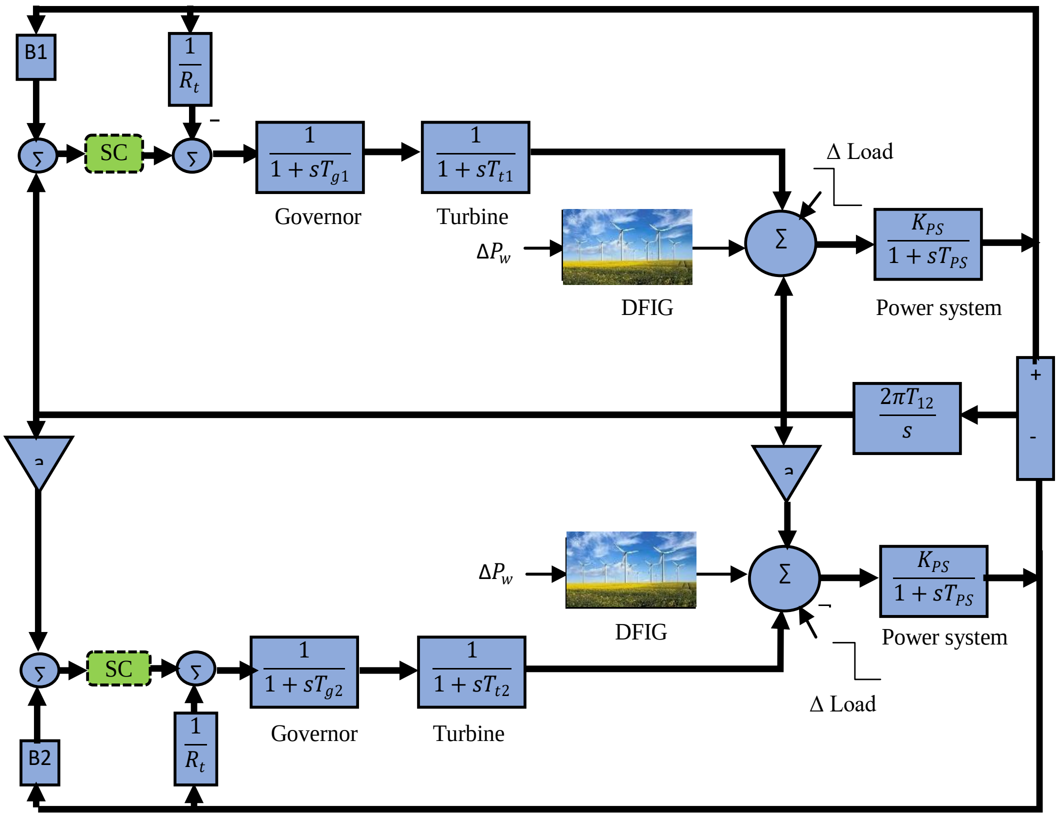

FIG. 1 WIND INTEGRATED INTERCONNECTED POWER SYSTEM BLOCK DIAGRAM MODEL.

The control output depends on the gains of the controller need to be selected carefully to meet the goals of the AGC. In case of the isolated system, the number of decision variables are 3 and increases to , where n is the number of the areas of the interconnected system. Identification of the best set of the gains is the main problem to reduce the frequency and tie-line power disturbances. This is achieved by search-based iterative techniques. This mechanism is suitable for both power system models with CPGUs and REUs as well. Furthermore, the proportional and integral gains of the speed controller of the DFIG unit are responsible for controlling the wind power variations. The output (2) of the speed controller with the optimal parameter gains are

$$u_{DFIG} = \Delta\omega_i\left(k_{wi}\cdot\frac{1}{S} + k_{wp}\right) \tag{2}$$

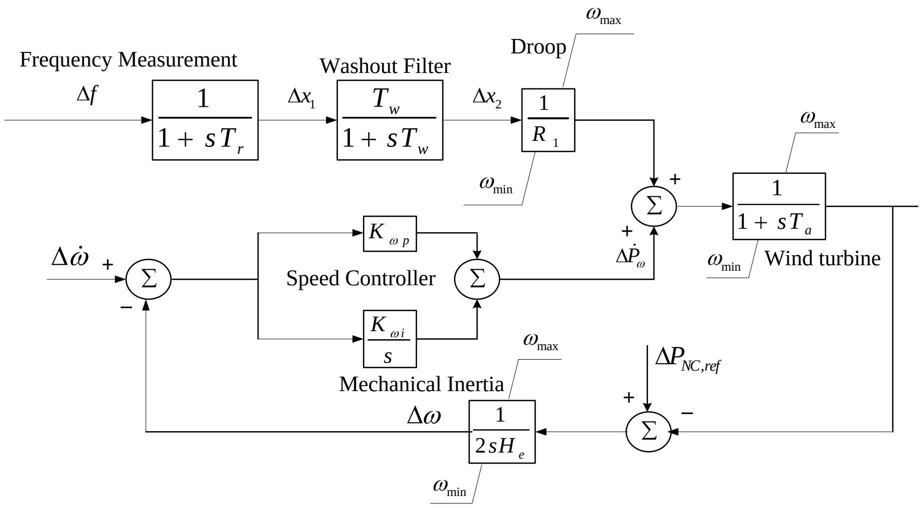

FIG. 2 SIMPLIFIED MODEL OF DFIG FOR AGC STUDIES.

Adopting optimal gains to speed controller of the DFIG unit becomes optimal DFIG enhances the output response. Along with the controller gains of the AGC network, the optimization problem need to identify the optimal gains of the speed controller of the DFIG unit then the number of the decision variables of the problem are

$$Decision\, variables = 3n + 2n, n\ is\ the\ number\ of\ areass \tag{3}$$

This tuning mechanism combined examines the controller gains of both CPGU and DFIG of individual areas with proper cost function

III. FITNESS FUNCTION AND TUNING ALGORITHM

The system performance is measured with performance metrices such as ISE, ITSE, IAE and ITAE. This performance indicators are framed to calculate the errors of the change in frequency and tie-line information. During the load perturbations, the change in frequency and tie-line power information is recorded and performance indicators are calculated to initiate the tuning strategies of the AGC controllers. The objective of the minimization of the performance indicators is nothing but to reduce the deviations of the signals. In fact, mitigation of the frequency disturbances and tie-line deviations is the preliminary goal of the AGC in an interconnected power system fulfilled by the optimization of the performance indicators. In case of the ISE, the objective function of the AGC problem is defined in (4) along with the search region provided by the upper and lower limits of decision variables of the process.

$$\left.\begin{array}{c} min\ J = \int_0^t \left((\Delta f_1(t))^2 + (\Delta f_2(t))^2 + (\Delta P_{tie}(t))^2\right)dt \\ S.To, k_{\min} < k_{pi,} k_{ii,} k_{di,} \alpha_{i,} \beta_i < k_{\max} \end{array}\right\} \tag{4}$$

In case of the IAE, the objective function of the AGC problem is defined in (5) along with the search region provided by the upper and lower limits of decision variables of the process.

$$\left.\begin{array}{c} min\ J = \int_0^t \left(|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{tie}(t)|\right)dt \\ S.To, k_{\min} < k_{pi,} k_{ii,} k_{di,} \alpha_{i,} \beta_i < k_{\max} \end{array}\right\} \tag{5}$$

These two performance indicators are considered to tune the controller gains with the help of population search algorithms. Literature provides a list of few algorithms used to tune the AGC controllers to reduce the frequency and tie-line disturbances.

In this work, SBO algorithm is suggested to tune the controller gains of the AGC during the power imbalance conditions. S.H.Moosavi and V.Bardsiri proposed SBO heuristic algorithm and applied it to computer network problems to check the benefits of the algorithm over other meta-heuristic algorithms. These birds' behavior is included in the design of the SBO starting from the process of the initiation to update mechanism. This algorithm used both male and female birds to implement the searching, courtship, and attraction strategies. To apply the SBO to solve the AGC problem where the optimal gains of the controllers are unknown, number of bowerbirds represents the solution of the problem. Therefore, the decision variables of the optimization problem are the controller gains referred by the position of the bowerbirds. In the initial step of searching the optimal gains of the controller, the values are randomly generated within the limits of the controller. The common parameters of the SBO to generate the number of solution in iteration are represented with NB known as number of bowerbirds. Mutation probability, spread factor and greatest step size (α) are the control parameters of the SBO. Before the initialization the feasible solutions generated randomly within the upper, lower limits of the decision variables, all the control and common parameters need to be specified. The search space of the SBO is decided by these decision variables boundaries. In the initialization, the solutions are randomly generated to represent the positions of the birds. To update these positions towards the optimal solution, the individual's probability is calculated using (6).

$$P_i = \frac{fit_i}{\sum_{p=1}^{NB} fit_p} \tag{6}$$

The solutions generated in SBO corresponding fitness values is evaluated with the help of the objective function provided in (4) represented with for the i^th number of the particle. The new positions are arrived with the help of (7) from the current positions with the help of the best solution represented with elites.

$$x_{ik}^{new} = x_{ik}^{old} + \lambda_k \left(\left(\frac{x_{jk} + x_{elite,k}}{2} \right) - x_{ik}^{old} \right) \tag{7}$$

In (7), x_i is i^th bower. indicates elite (best) position. Further, is the attraction power calculated using (8) given by

$$\lambda_k = \frac{\alpha}{1 + p_j} \tag{8}$$

Furthermore, the normal distribution of the solution set is used to update the positions of the birds from the old positions with the help of the mechanism provided in (9).

$$x_{ik}^{new} \sim N\left(x_{ik}^{old}, \sigma^2\right) = x_{ik}^{old} + (\sigma * N(0,1)) \tag{9}$$

However, the new position should be in the search region after updating it from the old position. The proportion of the space width ( ) is inserted in the (9) to keep the decision variables updated values in the upper and lower limits of variables. The new solutions generated using the mechanism provided from the (7) to (9) evaluate the cost function to find the best elite in the new generation set. This updating mechanism of the solutions is carried out until convergence occurs. In general, the number of iterations of the SBO is the termination criterion to stop the SBO. The solution set available at the end of the final iteration is the best solution in the feasible solution region of optimization. The testing of the controllers in AGC environment is carried out with this best solution at the final iteration.

IV. Simulation Results

The impact of both DFIG-wind farm and optimal DFIG-wind farm are investigated in AGC of interconnected power system during the simple, random, and stochastic load variations. Furthermore, wind generation changes are considered to extend the study to check the performance of the classical and cascade controllers along with the generic DFIG and optimal DFIG models. The optimal parameter gains of the controllers are presented in Table 1.Additionally, the sensitivity analysis was also carried out to validate the effects of the parameter uncertainties.

Table 1. Optimal PID parameter gains of WIIPS

Controller	Area-1			Area-2		
	k_p	k_i	k_d	k_p	k_i	k_d
Without DFIG	0.38318	0.9445	0.2784	0.05447	0.77466	0.2994
With DFIG	0.99795	0.945	0.999	0.99974	0.924	0.998
Optimal DFIG	0.9996	0.9998	0.9983	1	0.9998	0.9677

A. WIIPS load perturbations in case of classical controllers

In case of the classical PID as secondary controller of the WIIPS, the effect of the simple load perturbations are studied on the system and comparisons are provided with the interconnected system with CPGUs only. The step load change of -0.1 p.u is simulated in area 1 and corresponding frequency changes of same area are presented in Fig. 3.a. However, the frequency of area 2 also deviates from its nominal value since both areas are connected to transfer electrical power. Therefore, the deviations of the frequency in area 2 along with the tie-line power changes are presented in Fig. 3.b and Fig. 3.c. In each plot, the comparisons are provided for the conventional system without REUs, WIIPS and WIIPS with optimal speed controller tuning. Furthermore, when the load perturbations in area 2 (0.01 p.u), Fig. 4 shows the response of the system.

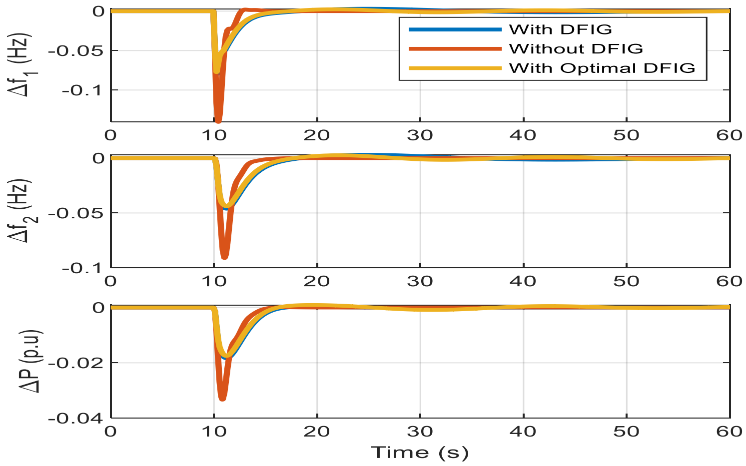

Fig. 3 a. , b. , c. during the simple load changes in area 1.

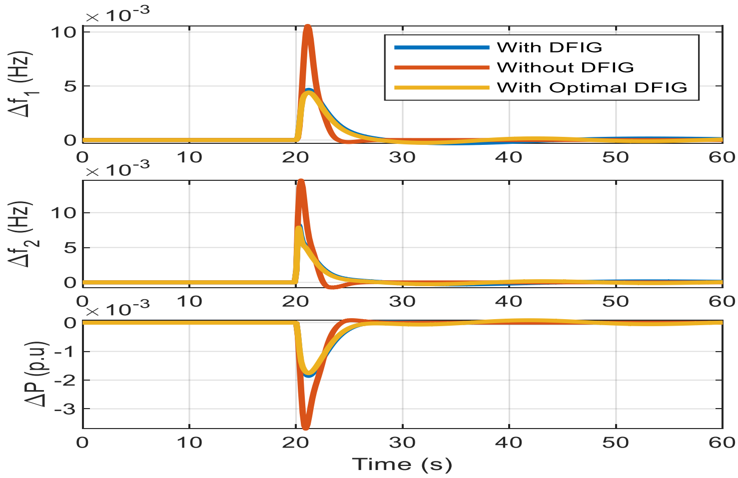

FIG. 4 A. , B. , C. DURING THE SIMPLE LOAD CHANGES IN AREA 2.

B. Effect of random demand variations in case of classical controllers

The load perturbations continuously with time and effects the AGC of the WIIPS. To study the effect of such random load perturbations, a simulation case is investigated in presence of the classical PID controller. The load perturbations are initiated at times of 10, 30, 50 and 80 with per unit variations of 0.1, -0.2, 0.15 and -0.05 as shown in Fig. 5. The outputs of the conventional system without REUs, WIIPS and WIIPS with optimal speed controller tuning are presented in Fig. 6.The tuning values extracted from the SBO search mechanism under simple load changes are used to evaluate the performance of the systems during the random load perturbations. In fact, the WIIPS with optimal speed controller provided better control to minimize the disturbances of the signal's frequency and tie-line power.

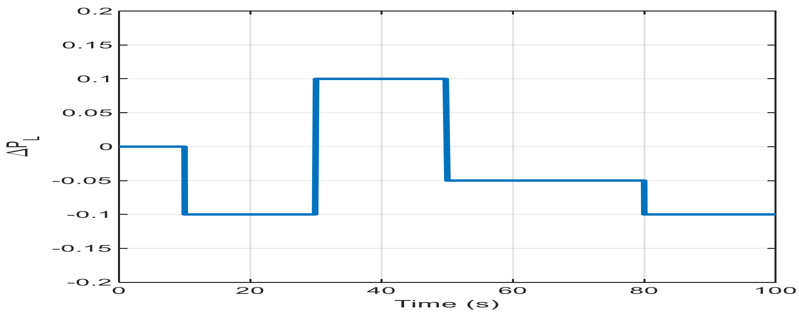

FIG. 5 RANDOM LOAD PERTURBATIONS INITIATED IN AREA 1.

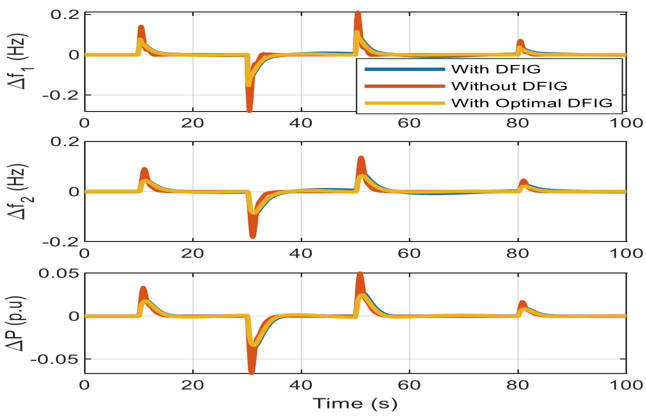

FIG. 6 A. , B. , C. DURING THE RANDOM LOAD PERTURBATIONS.

The impact of both DFIG-wind farm and optimal DFIG-wind farm are investigated in AGC of interconnected power system during the simple, random, and stochastic load variations. Furthermore, wind generation changes are considered to extend the study to check the performance of the classical and cascade controllers along with the generic DFIG and optimal DFIG models. The optimal parameter gains of the controllers are presented in Table 1.Additionally, the sensitivity analysis was also carried out to validate the effects of the parameter uncertainties.

C. Impact of wind generation changes on WIIPS in presence of PID controller

Apart from the CPGU assisted interconnected power system, the AGC challenges are more in case of the WIIPS due to integration of REUs. The power generation outputs of these REUs are continuously varying with time in similar way like electrical demand. The impacts of such generation changes are investigated in presence of PID controller as supplementary AGC controller to mitigate the disturbances in both frequency and tie-line power. During these wind uncertainties, the system outputs are presented in Fig. 7.

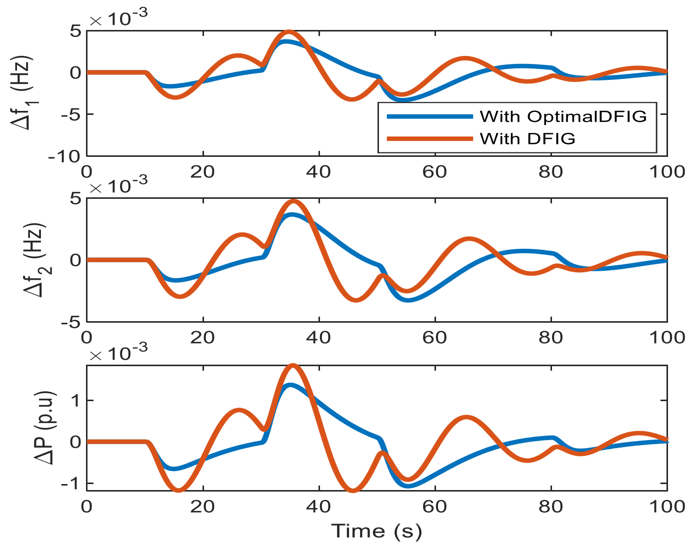

FIG. 7 A. , B. , C. DURING THE RANDOM WIND PERTURBATIONS.

D. Load+ generation changes in WIIPS

When the simultaneous changes of both load and generations are simulated in the system, the response of the WIIPS with and without optimal speed controller are provided in Figure 8. The optimal speed controller based DFIG model is reliable to reduce the frequency changes in the power system during the simultaneous disturbances in both generation and demand.

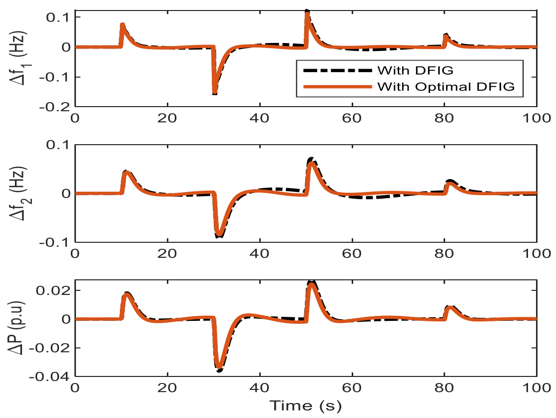

FIG. 8. A. , B. , C. DURING THE RANDOM WIND PERTURBATIONS.

E. WIIPS load perturbations in case of cascade controller

In case of the cascade PI-PD as secondary controller of the WIIPS, the effect of the simple load perturbations are studied on the system and comparisons are provided with the conventional interconnected power system. The step load change of 0.01 p.u is simulated in area 1 and 2, corresponding frequency changes of same area are presented in Fig. 9. Comparisons are provided for the conventional system without REUs, WIIPS and WIIPS with optimal speed controller tuning. (1% in area 1 and -1% in area 2).

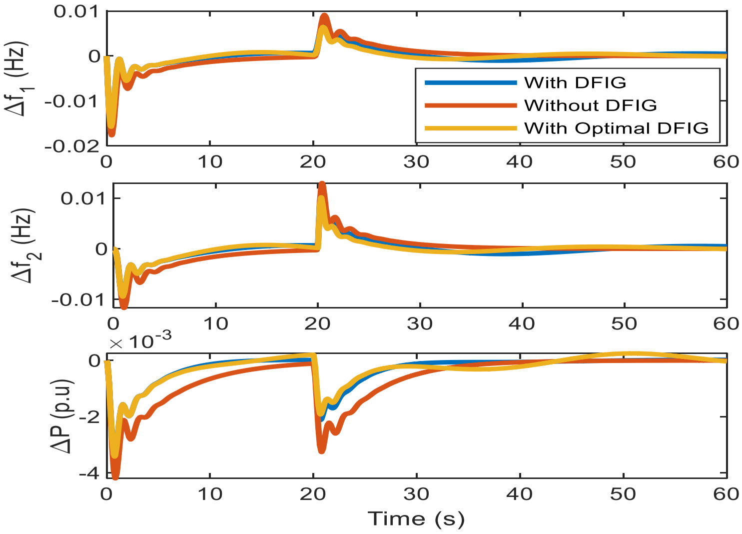

FIG. 9 A. , B. , C. DURING THE SIMPLE LOAD CHANGES.

F. Effect of random demand variations in case of cascade controllers

The load perturbations continuously with time and effects the AGC of the WIIPS. To study the effect of such random load perturbations, a simulation case is investigated in presence of the cascade controller. The load perturbations are initiated at times of 10, 30, and 50 with per unit variations of 0.1, -0.2, and 0.15 in area 1. The outputs of the conventional system without REUs, WIIPS and WIIPS with optimal speed controller tuning are presented in Fig. 10. The tuning values extracted from the SBO search mechanism under simple load changes are used to evaluate the performance of the systems during the random load perturbations. In fact, the WIIPS with optimal speed controller provided better control to minimize the disturbances of the signal's frequency and tie-line power.

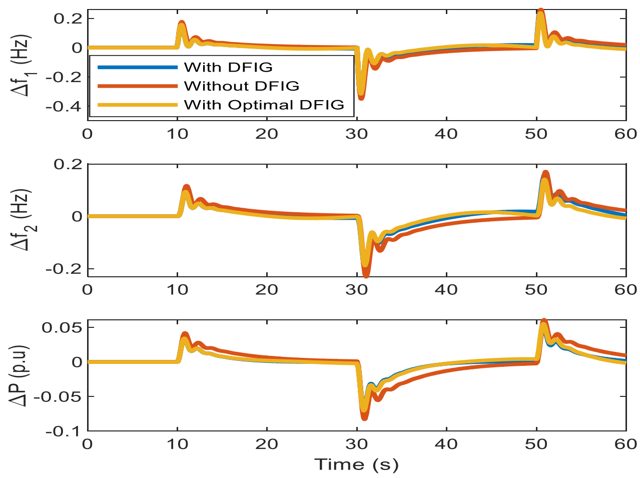

FIG. 10 A. , B. , C. DURING THE RANDOM LOAD PERTURBATIONS.

G. *Parameter sensitivities*

The parameter variations are another possible event occurring in the interconnected power system. To check the behavior of the optimal controller in presence of the parameter variations, a power system gain value is opted. The nominal system gain value is 120 and 4 different values are taken (100, 110and 130) to check the performance of the cascade controller. The change in frequency of area 1, tie-line power and change in area 2 frequencies are shown from Fig. 11.a to Fig. 11.c provided the handling capacity of the proposed controller in such parameter variations.

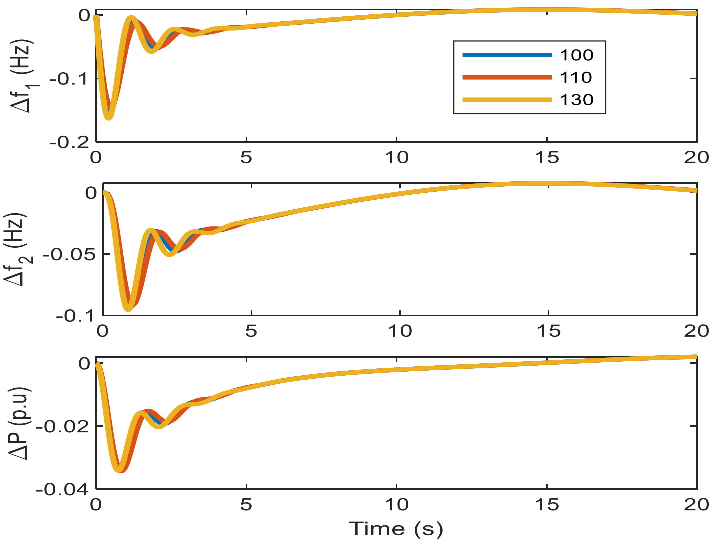

FIG. 11 A. , B. , C. DURING THE PARAMETER UNCERTAINTIES.

V. CONCLUSION

A simultaneous optimal control strategy was proposed in this work to minimize the frequency deviations of the interconnected power system integrated with sufficient amount of wind power. A simplified DFIG model is included in the test system to study the impact of the wind power with and without optimal controller. First, PID controller was used as secondary AGC to minimize the active power imbalance between the load and generation. The controller performance was compared in three strategies known as system without DFIG, with DFIG and with optimal DFIG. Later, PI-PD cascade controller was adopted to improve the stability of the system during random load perturbations. In both cases, the optimal DFIG based model produced good results to meet the objectives of the AGC in presence of wind power.

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