

An Analysis of the Effects and Dependency of Wind Power Penetration on System Frequency Regulation

Nga Nguyen, *Student Member, IEEE*, and Joydeep Mitra, *Senior Member, IEEE*

Abstract—The integration of renewable energy sources into power systems has gathered significant momentum globally because of its unlimited supply and environmental benefits. Within the portfolio of renewable energy, wind power is expected to have a soaring growth rate in the coming years. Despite its well known benefits, wind power poses several challenges in grid integration. The inherent intermittent and non-dispatchable features of wind power not only inject additional fluctuations to the already variable nature of frequency deviation, they also decrease frequency stability by reducing the inertia and the regulation capability. This paper closely examines these effects as well as the effect on tie-line flows and area control error, which causes a larger and longer frequency deviation in the integrated system. Further, the effect of wind power on frequency regulation capability at different penetration levels is also examined. The analytical and simulation results presented here provide some guidance on determining maximum wind power penetration level given a frequency deviation limit.

Index Terms—Area control error, equivalent regulation constant, frequency deviation, frequency response characteristic, inertia, tie-line power, wind power.

I. INTRODUCTION

WITH technological and economic growth, the need for energy has been on the rise worldwide. However, this substantial growth faces two major concerns: the reduction of fossil fuel reserve and the impact on the environment. In order to deal with these issues, renewable energy is being increasingly utilized all over the world. According to [1], renewable energy is expected to provide 40% of total electricity in the US by 2030, and half of that comes from wind power. Wind farms have been growing steadily throughout the US both in turbine size and in wind farm capacity. Furthermore, the cost of wind generators has decreased dramatically over the past decade. These have promoted wind power as a promising renewable energy technology. However, the application of wind power has been confronted with a host of technical and economical problems. Although the leveled cost of wind production has been gradually growing competitive with respect to conventional technologies, the integration of wind power can negatively affect the stability of a power system if there are not enough appropriate measures to deal with the intermittency and low or zero inertia [2], [3] that characterize this resource. One of these undesirable effects is frequency disturbance. In normal operation, as system frequency deviation must be maintained within a specified range, a minimum inertial frequency response is vital for frequency stability. Therefore, by contributing to a reduction

of the system's inertia response, high wind power penetration level can endanger the stable operation of the system. Once wind power sources are connected to the main grid and replace conventional generators, they will cause a larger and faster frequency deviation. If the main grid does not have sufficient regulation capability, frequency deviation might direct to load shedding or even cause the whole system to collapse. The North American Electric Reliability Corporation (NERC) as well as Electric Reliability Council of Texas (ERCOT) and Western Interconnect (WECC) have all reported a reduction in frequency response due to an increase of variable generation [4]–[8]. Hydro-Québec TransÉnergie (HQT) is dealing with this problem by requiring their wind power plants to be equipped with an inertia emulation system [9]. Therefore, it is important to investigate not only the effects of different wind power penetration levels on frequency regulation capability of power systems but also the maximum acceptable level of wind power that can be integrated into the grid.

While examining the undesirable influence of wind power on the load frequency control (LFC) of power system, previous works mostly consider wind power output uncertainty (i.e. intermittency) and inertia reduction [8], [10]–[19], reserve requirement [20]. In [18] and [21], the effect of wind power on equivalent regulation constant was also investigated. Besides, several papers have made an effort to identify the maximum penetration level of wind power based on thermal limit [22] or constraint on frequency deviation [23], [24]. The work presented in this paper extends the prior art by adding the following contributions: (i) it models the effect of wind integration on the system frequency response characteristic (β); (ii) it models the effect of wind integration on the area control error (ACE) and on tie line interchanges in an interconnected system; and (iii) it provides guidance to the limit on wind penetration for a given limit on frequency deviation.

The remainder of this paper is organized as follows. Section II explains load frequency control and the mathematical modeling of one control area in the presence of wind power. This model provides the basis to define the limitation of wind penetration to the grid. A simulation model and result are presented in section III to verify the computation obtained from the mathematical model. In this section, some observations and recommendations are also included to clarify the salient aspects of the contribution. Finally, section IV provides some concluding remarks on the work presented.

II. MATHEMATICAL LFC MODELING FOR ONE CONTROL AREA IN THE PRESENCE OF WIND

A. Load frequency control

The main objective of LFC is to return frequency excursion to the nominal value whenever a mismatch between generation

This work has been supported in part by the US Department of Energy under award no. DE-OE0000625. The authors are with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, 48823 USA e-mail: (nguye301@msu.edu, mitraj@msu.edu).

and demand appears. Frequency disturbance is immediately inhibited by inertia, governor action, load and other damping mechanisms. Motor loads resist disturbance by adjusting their speed in direct proportion to frequency deviation while governor regulates generator output by changing prime mover input. These actions are attributed to the furthest frequency deviation point and a part of frequency recovery duration. They stabilize system frequency rather than restore frequency to its nominal value. To remove the remaining frequency error, it is required to have the Automatic Generation Control (AGC) change the generator set point.

When wind generators are installed into the main grid and replace conventional generators, the governor response will be less effective due to the decline of inertia and of ability to regulate the generation output of the entire system. As a result, the frequency deviates at a larger magnitude and the recovery is prolonged. These effects are considered in the mathematical model in the next sub-section.

B. LFC mechanism of one control area in the presence of wind power

Traditionally, mechanical power, which is created from rotational energy, is fed to the conventional generator via turbine to produce electrical power. Once an imbalance occurs between input and output, rotor speed will experience a deviation. The governor plays the role of sensing the disturbance that causes unbalance and sends a control signal to recover frequency by adjusting the turbine input. The combination of governor, turbine, rotating mass and load damping control model is represented in the load frequency control model as shown in Fig. 1 [25]. The disturbance caused by wind power is captured in the control model by $\Delta P_L(s)$ based on the assumption that wind power is considered to be a negative load. In Fig. 1, the notations used are as follows:

ΔP_C = supplementary control action
 $K(s)$ = LFC controller

$$K(s) = \frac{K}{s}$$

ΔP_{wind} = disturbance caused by wind power
 ΔP_{load} = non-frequency-sensitive load change
 ΔP_L = disturbance

$$\Delta P_L = \Delta P_{load} - \Delta P_{wind} \quad (1)$$

T_{ij} = synchronizing torque coefficient
 H = equivalent inertia constant
 Δf = frequency deviation
 D = load damping constant
 $TG_{ki}(s)$ = turbine-governor transfer function
 $\Delta P_{tie,i}$ = tie-line power exchange between area i and other areas [25]

$$\begin{aligned} \Delta P_{tie,i} &= \sum_{\substack{j=1 \\ j \neq i}}^N \Delta P_{tie,ij} \\ &= \frac{2\pi}{s} \left(\sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} \Delta f_i - \sum_{\substack{j=1 \\ j \neq i}}^N T_{ji} \Delta f_j \right) \end{aligned} \quad (2)$$

B_i = frequency bias factor which is calculated as below [27]:

$$B_i = \beta_i = \frac{1}{R_i} + D_i \quad (3)$$

Although the nature of wind power is intermittent, it is said that fixed-speed wind turbines can contribute to LFC by its spinning inertia [30]–[32]. On the other hand, DFIG wind turbines cannot provide spinning inertia because they are decoupled from the grid by power electronic converters. However, with improved control strategies, DFIG turbine is able to provide partial inertia to support the grid by performing some operations similar to these in conventional generators [18], [33]–[40]. As stated in [41]–[43], wind turbine can also have a droop characteristic with speed up/down averaging control. In another point of view, the application of synchronverters [44] can make the wind generators mimic the behavior of synchronous generators. However, the wind inertia is limited by the available output of wind generators and the type of wind turbines. Once wind generators gradually replace conventional generators, the total inertia of the system decreases while the equivalent regulation constant increases. This effect yields a reduction of the area frequency response characteristic. Assuming that the fraction of inertia that wind power contributes to the grid is r_w (which is determined based on wind generation output [45]), the fraction of conventional generation inertia that is reduced in the presence of wind is r_r , the new inertia constant of the system can be calculated as follows:

$$H_{new,i} = H_{old,i}(1 + r_w - r_r) \quad (4)$$

The term r_w includes both the actual inertia provided by fixed-speed wind turbines as well as any artificial inertia that may be synthetically emulated at other wind turbines. It should also be noted that r_r is not always the fraction of wind power that takes the place of conventional power. The following example will illustrate the difference between these two definitions (power replacement and inertia replacement):

Consider a small power system with three conventional generators of 50 MW output and 0.02 pu.s inertia each. Assuming that the system has a total output of 150 MW, let us consider three possibilities as below:

- If the total integrated wind power is 40 MW (which is smaller than output of one conventional generator) and constitutes approximately 26.7% total power, the total power output of the conventional generators will reduce. However, the total inertia constant of the integrated system does not change because none of the conventional generators is decommitted.
- If the total integrated wind power is 50 MW (which equals to the output of one conventional generator) and constitutes approximately 33.3% total power, both the total power output of the conventional generators and the total inertia of the integrated system reduce because one of the conventional generators will be completely decommitted. The inertia constant reduction in this case equals 0.02 pu.s. The fraction of replaced power and the fraction of inertia reduction are the same.

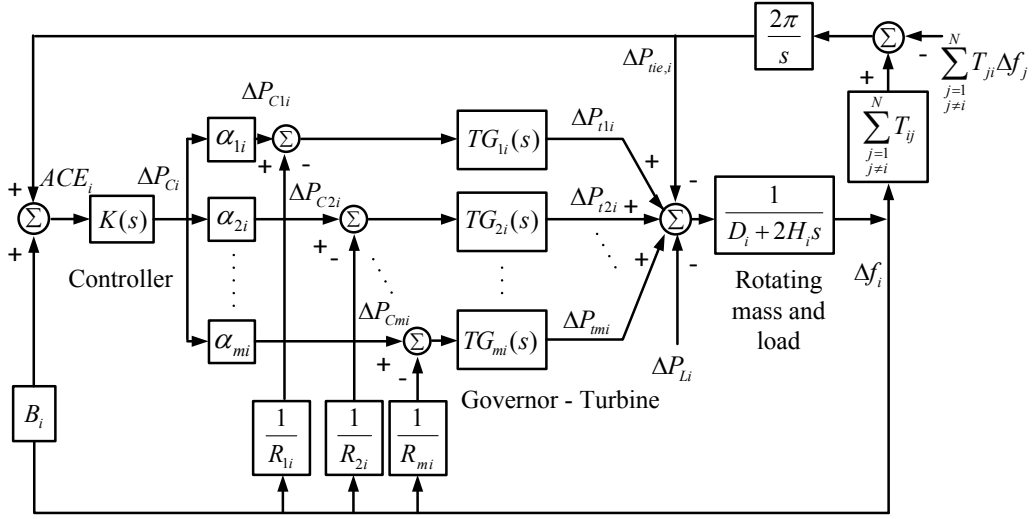


Fig. 1. Control area i in an interconnected system in the presence of wind power.

- If the total integrated wind power is 60 MW (which is larger than the output of one conventional generator) and constitutes 40% total power, both the total power output of the conventional generators and the total inertia of the integrated system reduce. However, the inertia constant reduction in this case equals 0.02 pu.s which is approximately 33.3% total inertia.

Besides the change in the inertia constant, the equivalent regulation constant is also modified:

$$R_{new,i} = \frac{R_{old,i}}{1 + r_w - r_r} \quad (5)$$

Because of the change in equivalent regulation constant, the new area frequency response characteristic is determined as follows:

$$\beta_{new,i} = B_{new,i} = \frac{1}{R_{old,i}}(1 + r_w - r_r) + D_i \quad (6)$$

The change in R and β leads to the variation in the area control error in the interconnected system:

$$ACE_{new,i} = \Delta P_{tie,i} + \beta_{new,i} \Delta f_i \quad (7)$$

While investigating the effect of wind power on interconnected systems, three types of conventional turbine will be considered in LFC model: non-reheat turbine, reheat turbine and gas turbine. The dynamic models of turbine-governor systems for these three generators are shown in Fig. 2, Fig. 3 [27] and Fig. 4 [28], [29].

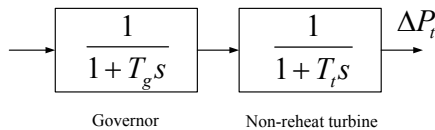


Fig. 2. Block diagram of governor with non-reheat turbine.

In Fig. 2, Fig. 3 and Fig. 4, the notations used are as follows:

T_g = speed governor time constant
 T_t = steam turbine time constant

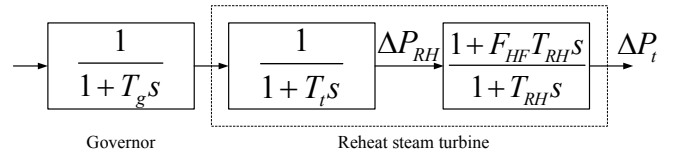


Fig. 3. Block diagram of governor with reheat steam turbine.

T_{RH} = time constant of reheater
 F_{HP} = fraction of turbine power generated by HP unit
 ΔP_{RH} = intermediate (reheat) power signal
 ΔP_v = intermediate valve positioner signal
 T_v = valve positioner time constant
 T_f = gas fuel time constant
 W_m = minimum fuel flow
 W_f = fuel flow
 a_f, b_f = gas turbine constant

The state-space of LFC dynamic model for control area i that includes m reheat steam turbine generators in the presence of wind power can be presented as follows:

$$\dot{x}_i = \hat{A}_i x_i + \hat{B}_i u_i + \hat{C}_i n_i \quad (8)$$

$$y_i = \hat{D}_i x_i \quad (9)$$

where

$$\begin{aligned} x_i &= [\Delta f_i \ \Delta P_{ti} \ \Delta P_{gi} \ \Delta P_{tie,i} \ \Delta P_{RH,i}]^T \\ \Delta P_{ti} &= [\Delta P_{t1i} \ \Delta P_{t2i} \ \dots \ \Delta P_{tmi}] \\ \Delta P_{gi} &= [\Delta P_{g1i} \ \Delta P_{g2i} \ \dots \ \Delta P_{gmi}] \\ \Delta P_{RH,i} &= [\Delta P_{RH1i} \ \Delta P_{RH2i} \ \dots \ \Delta P_{RHmi}] \\ y_i &= [\Delta f_i \ ACE_i]^T \\ u_i &= [\Delta P_{C1i} \ \Delta P_{C2i} \ \dots \ \Delta P_{Cmi}]^T \\ n_i &= [\Delta P_{Li} \ \sum_{j=1, j \neq i}^N T_{ji} \Delta f_j]^T \end{aligned}$$

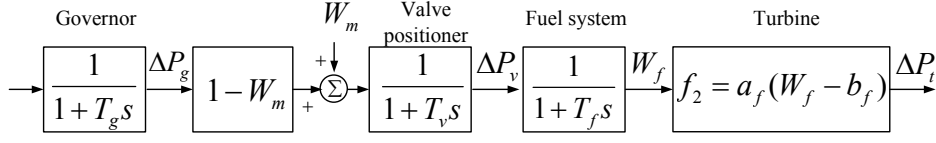


Fig. 4. A simplified block diagram of single-shaft gas turbine.

For simplicity, matrices $\hat{A}_i$, $\hat{B}_i$, $\hat{C}_i$ and $\hat{D}_i$ of a control area with one reheat steam turbine can be expressed as shown in (10):

$$\hat{A}_i = \begin{pmatrix} \frac{-D_i}{2H_i} & \frac{1}{2H_i} & 0 & \frac{-1}{2H_i} & 0 \\ 0 & \frac{-1}{T_{RH_i}} & \frac{F_{HP_i} T_{RH_i}}{T_{ti} T_{RH_i}} & 0 & \frac{T_{ti} - F_{HP_i} T_{RH_i}}{T_{ti} T_{RH_i}} \\ \frac{-1}{R_i T_{gi}} & 0 & \frac{-1}{T_{gi}} & 0 & 0 \\ 2\pi \sum_{j=1, j \neq i}^N T_{ij} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{T_{ti}} & 0 & \frac{-1}{T_{ti}} \end{pmatrix} \quad (10)$$

$$\hat{B}_i = (0 \ 0 \ \frac{1}{T_{gi}} \ 0 \ 0)^T$$

$$\hat{C}_i = \begin{pmatrix} \frac{-1}{2H_i} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -2\pi & 0 \end{pmatrix}^T$$

$$\hat{D}_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \beta_i & 0 & 0 & 1 & 0 \end{pmatrix}$$

In case of non-reheat turbine, the state variables are similar to those in reheat turbine except that the entries corresponding to ΔP_{RH} are omitted and the entries corresponding to ΔP_t are modified. The state-space of the gas turbine is different from that of the reheat and non-reheat turbines and has been described in the Appendix of this paper.

As is evident from Fig. 1, the frequency deviation can be expressed as follows:

$$\Delta f_i(s) = \frac{\sum_{k=1}^m TG_{ki}(s) \Delta P_{Cki}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i + \frac{\sum_{k=1}^m TG_{ki}(s)}{R_{new,i}}} \quad (11)$$

Using the final value theorem to get the steady state value of the frequency deviation Δf_{iss} :

$$\Delta f_{iss} = \lim_{s \rightarrow 0} s \Delta f_i(s) = \lim_{s \rightarrow 0} s \cdot \left(\frac{\sum_{k=1}^m TG_{ki}(s) \Delta P_{Cki}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i + \frac{\sum_{k=1}^m TG_{ki}(s)}{R_{new,i}}} \right) \quad (12)$$

Following the assumption that $\Delta P_{tie,i}(s)$ approaches zero at steady state [25] and the system has enough reserve to match the disturbance $\Delta P_{Ci} = \Delta P_{Li}$, equation (12) gives the result:

$$\Delta f_{iss} = 0 \quad (13)$$

However, the frequency deviates farther from the scheduled value and the recovery duration is lengthened. Due to the change in frequency, the power flow on the tie line increases, which is a negative impact on each area. This can be inferred easily from equation (2).

When a stand-alone system is considered, power exchange in the tie-line between control areas does not exist and $\Delta P_{tie,i}(s)$ vanishes in equation (11).

From the above analysis, the maximum excursion of frequency can be identified. As a consequence, it is possible to evaluate the wind penetration limit. The maximum excursion is compared with the safe range of frequency deviation ± 0.2 Hz [26] to define how much wind power should be integrated into the main grid. Based on the theoretical examination in this section, a simulation model is implemented in the following section in order to verify the effect of wind power on frequency deviation, tie-line power flow, and area control error.

III. SIMULATION AND RESULTS

For the purpose of illustrating the aforementioned influence of integrating wind power into power system, the Matlab/Simulink model of the system explained in section II is developed. Three scenarios are evaluated, as described below. These scenarios examine the behavior of a single area, the interaction of two interconnected areas, and the impact of gas turbines that are being increasingly deployed to provide ramping capability. The test cases are constructed as follows:

- All generators in one area are chosen to be the same type and combined into one single unit.
- Only area 1 includes wind power.
- Load disturbance is simulated by a 0.04 pu step function.
- Only area 1 is subjected to a load disturbance in order to observe the assistance of area 2 to area 1.
- Wind penetration level will be adjusted with different values of inertia reduction: 0%, 10%, 20%, 30%, 40%, 50% and 60%.
- The effects of wind power on LFC with and without considering the change in frequency response characteristic and equivalent regulation constant will be compared.

Scenario 1: A stand-alone control area.

The simulation model of a stand-alone control area (area 1) is presented in Fig. 5. The parameters of the study system are derived from [25] and reported in Table I in the Appendix. These parameters are the typical parameters for a small system and converted to per unit. Using initial values in Table I and applying equations (4), (5) and (6), simulation parameters are calculated and shown in Table II in the Appendix.

Scenario 2: Two interconnected control areas.

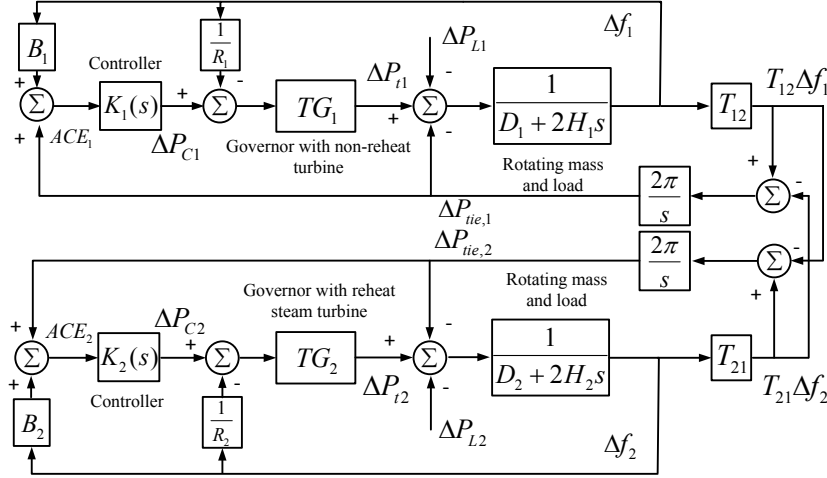


Fig. 6. Simulation model of two interconnected control areas.

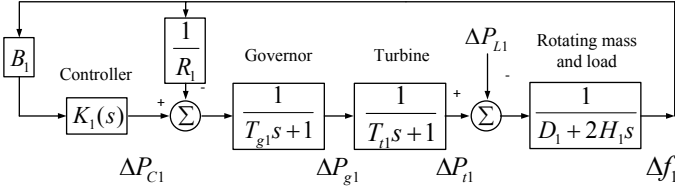


Fig. 5. A stand-alone control area with non-reheat turbine unit.

In this scenario, parameters of control area 1 are kept the same as those in the first scenario. Parameters of area 2 are derived from [46] and reported in Table III in the Appendix. The load disturbance is applied only to area 1 to examine the mutual frequency assistance between the areas in an interconnected system and the change of ACE due to the adjusted R and β . The simulation model of the two interconnected control areas is presented in Fig. 6.

Scenario 3: A stand-alone control area with a combination of a gas turbine and a non-reheat turbine.

This scenario is similar to Scenario 1 except that it includes a gas turbine. This helps illustrate the impact of gas turbines, which are being increasingly integrated in systems with wind generation to provide ramping capability. The parameters of the non-reheat turbine are kept the same as those in the first scenario. The parameters of the gas turbine are derived from [28] and reported in Table IV in the Appendix. Ramp rate limits are applied for all turbines with a higher ramp rate limit for the gas turbine. In particular, the ramp rate limit for the non-reheat turbine (RR_{nr}) is 0.029 while the ramp rate limit for the gas turbine (RR_g) is varied from 0.045 to 0.062 in order to observe the impact of the gas turbine. Due to the presence of wind, the 10% and 30% reduction of inertia are applied. The simulation model of this scenario is presented in Fig. 7.

In the first two scenarios, the simulation is implemented with and without the effect of wind on the frequency response characteristic and equivalent regulation constant to compare the differences between them. Frequency deviation obtained

from scenario 1 and 2 with different wind penetration levels are shown in Figures 8, 10, 12 and 16. The rate of change of frequency (ROCOF) is presented in Fig. 9, Fig. 11, Fig. 13 and Fig. 17. Also, the power flows in the tie lines and the ACE in scenario 2 are illustrated in Fig. 14, Fig. 15 and Fig. 18, Fig. 19. The frequency deviations obtained from the third scenario are shown in Figures 20 and 21.

From the simulation results, several observations can be made:

- 1) The more wind power is integrated into the system, the larger the frequency deviation that occurs in case of disturbance. The reason is that when a greater amount of wind power substitutes conventional generators, a larger reduction in total system inertia and a higher increase in equivalent regulation constant occur. This leads to a deeper decrease in area frequency response characteristic. As a result, frequency deviates farther from the scheduled value. This is evident in Fig. 10 and Fig. 16: the largest frequency deviation increases from 0.14 Hz to 0.32 Hz (in the first scenario) and from 0.075 Hz to 0.125 Hz (in the second scenario) while inertia reduction augments from 0% to 60%. It is also obvious that if the effect of wind on frequency response characteristic and equivalent regulation constant is taken into account, frequency deviation gets worse value. From Fig. 8 to Fig. 16, these values fall into the range 0.14 to 0.32 Hz (in the first scenario) and 0.075 to 0.125 Hz (in the second scenario) instead of 0.14 to 0.22 Hz (in the first scenario) and 0.075 to 0.115 (in the second scenario) if these effects are not considered. In addition to the farther variation in the frequency, the rate of change of frequency as shown in Fig. 9, Fig. 11, Fig. 13 and Fig. 17 proves that the duration of frequency recovery has been extended due to the effect (the derivatives of frequency with respect to time change more slowly). Besides, the more wind power is integrated, the lower the ROCOF is. These changes can cause serious consequences if the system employs

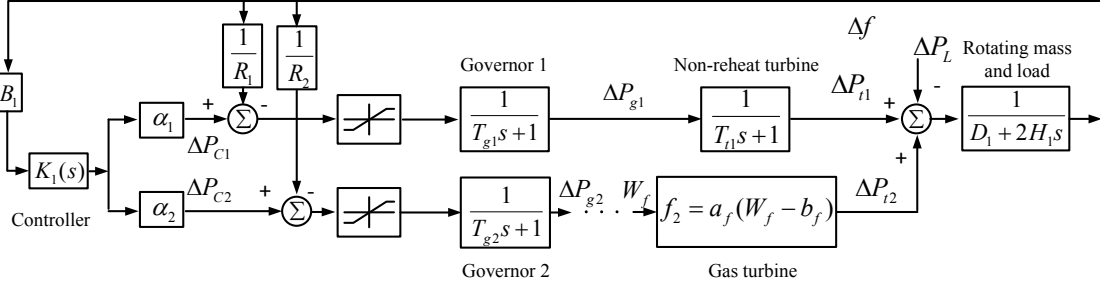


Fig. 7. Simulation model of a control area including a gas turbine and a non-reheat turbine.

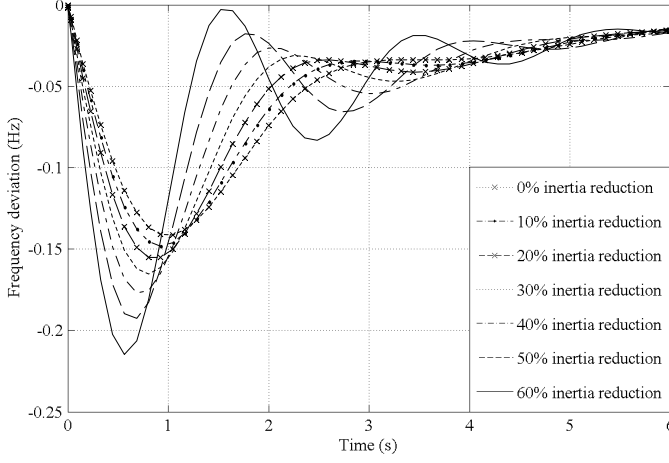


Fig. 8. Scenario 1: Frequency deviations in the stand-alone control area 1 without considering the effect of wind on β and R .

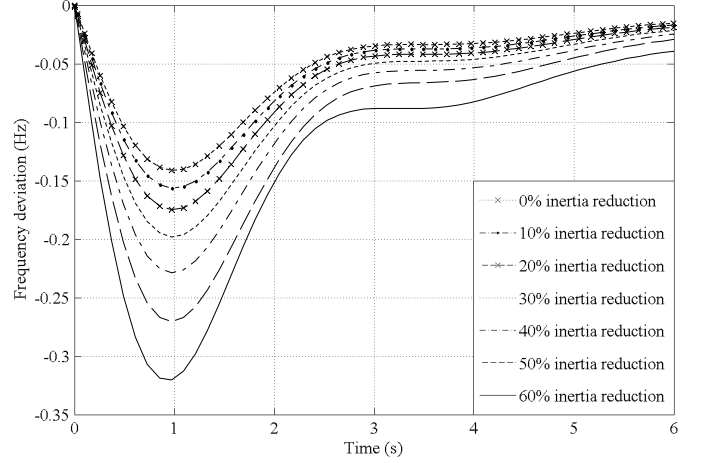


Fig. 10. Scenario 1: Frequency deviations in the stand-alone control area 1 considering the effect of wind on β and R .

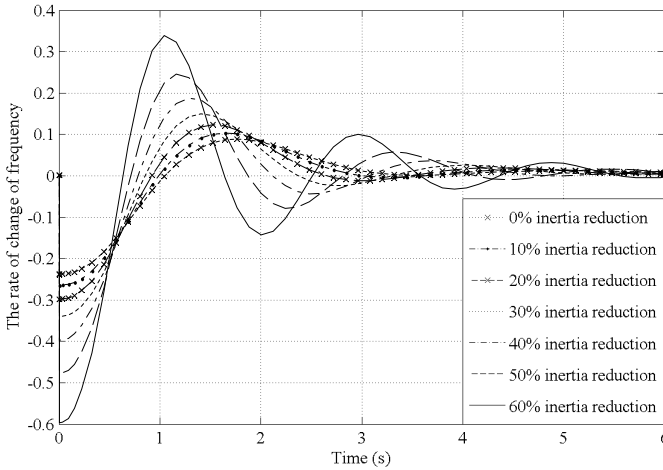


Fig. 9. Scenario 1: ROCOF in the stand-alone control area 1 without considering the effect of wind on β and R .

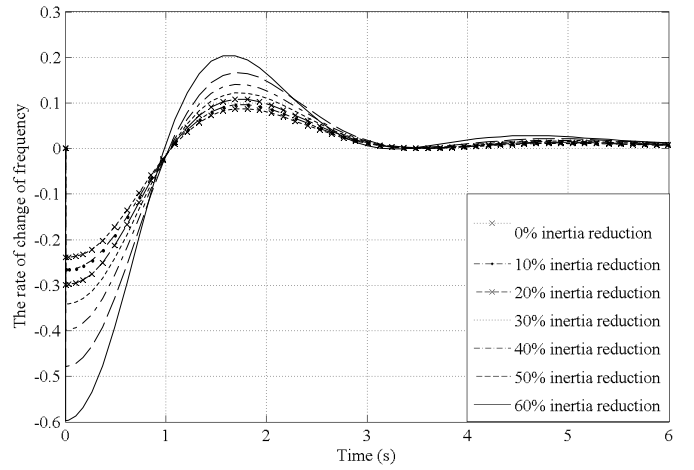


Fig. 11. Scenario 1: ROCOF in the stand-alone control area 1 considering the effect of wind on β and R .

protective df/dt relays.

- 2) In an interconnected system, control areas are able to assist each other when the system is subject to disturbances. In simulation results, assistance from area 2 to area 1 has prevented frequency deviation from growing up. Frequency deviation is much smaller in the second scenario (0.075 to 0.125 Hz falling range) compared to the first scenario (0.14 to 0.32 Hz) as shown in Figures 10 and 16. For this reason, it is recommended that

control areas collaborate to get the most benefit when wind generation is integrated into power system.

- 3) Following the increase of penetration levels, the tie-line power flow and the area control error get larger absolute values and longer time to recede as shown in Fig. 14, Fig. 15, Fig. 18 and Fig. 19. These are negative consequences due to the effect of wind power on β and on frequency which have been discussed in the foregoing section.

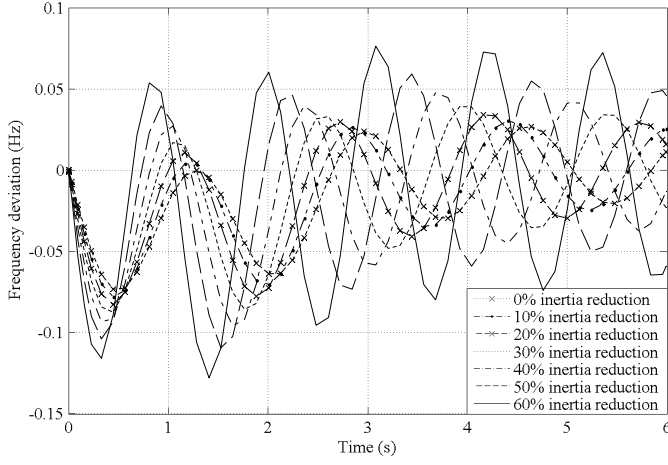


Fig. 12. Scenario 2: Frequency deviations of area 1 in an interconnected system without considering the effect of wind on β and R .

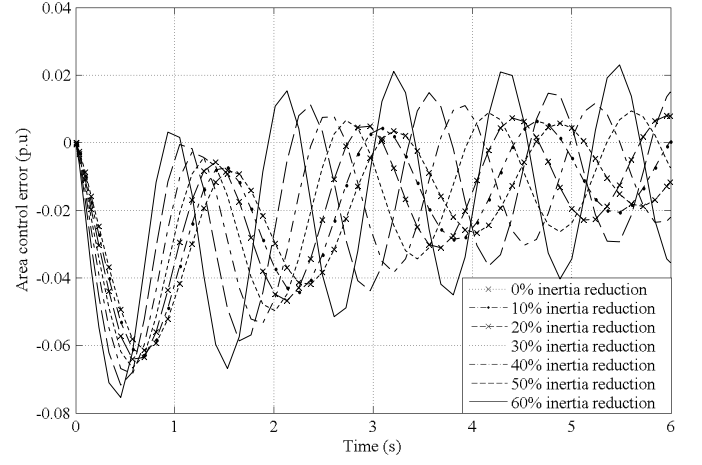


Fig. 15. Scenario 2: Area control error of area 1 in the interconnected system without considering the effect of wind on β and R .

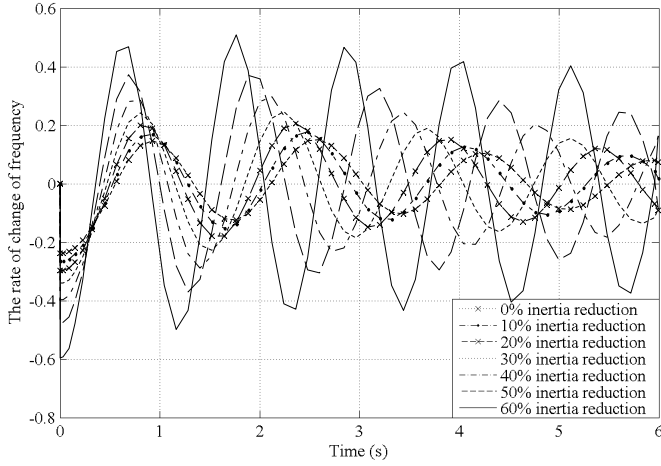


Fig. 13. Scenario 2: ROCOF of area 1 in an interconnected system without considering the effect of wind on β and R .

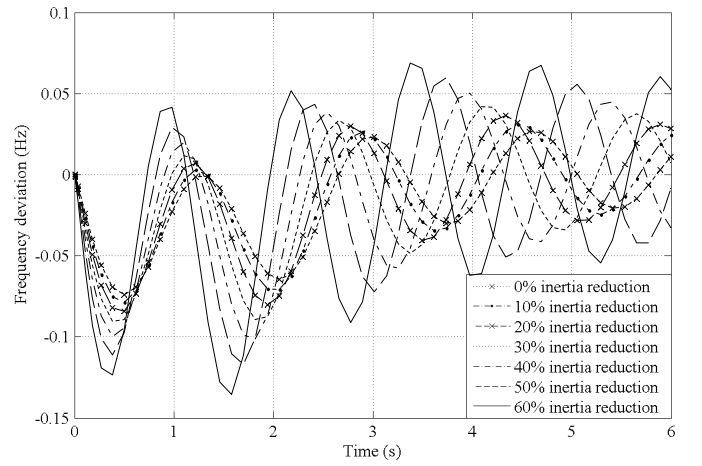


Fig. 16. Scenario 2: Frequency deviations of area 1 in an interconnected system considering the effect of wind on β and R .

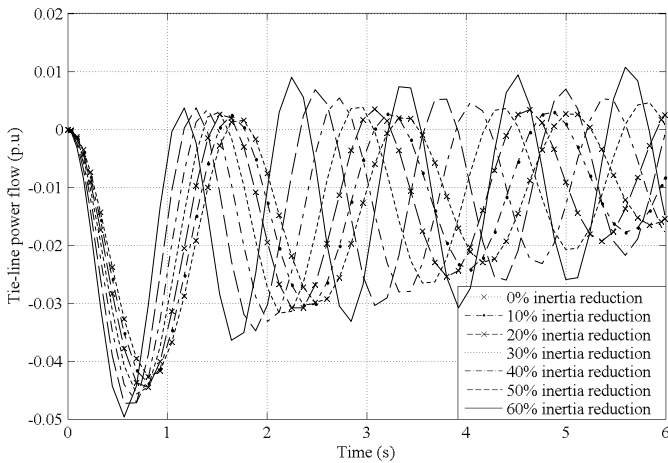


Fig. 14. Scenario 2: The tie-line power flow of area 1 in an interconnected system without considering the effect of wind on β and R .

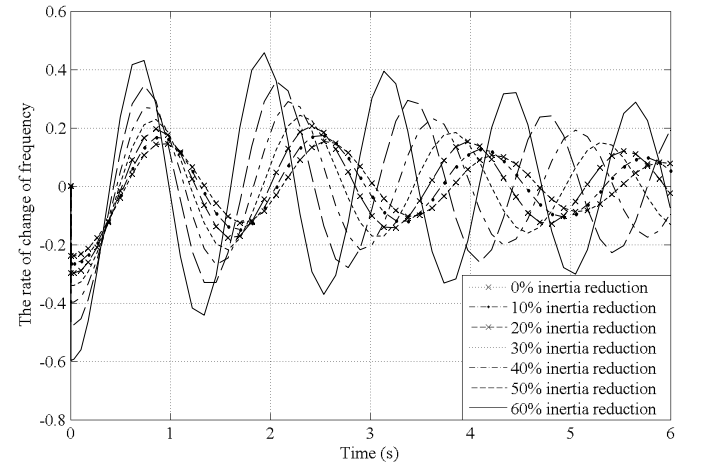


Fig. 17. Scenario 2: ROCOF of area 1 in an interconnected system considering the effect of wind on β and R .

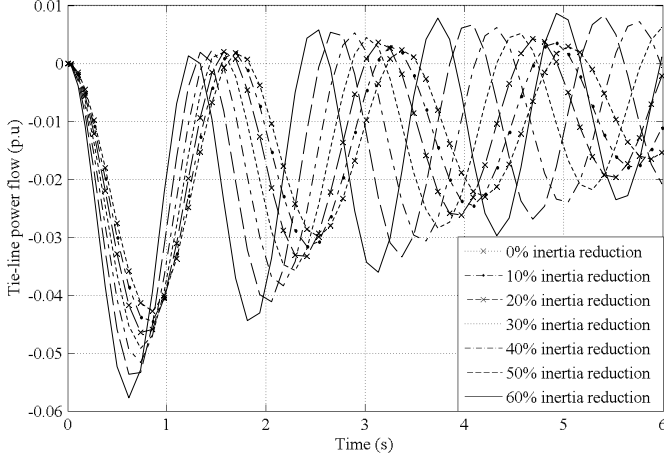


Fig. 18. Scenario 2: The tie-line power flow of area 1 in an interconnected system considering the effect of wind on β and R .

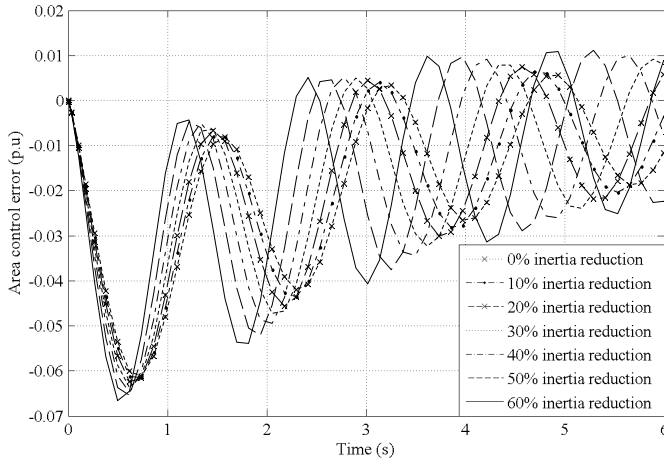


Fig. 19. Scenario 2: Area control error of area 1 in the interconnected system considering the effect of wind on β and R .

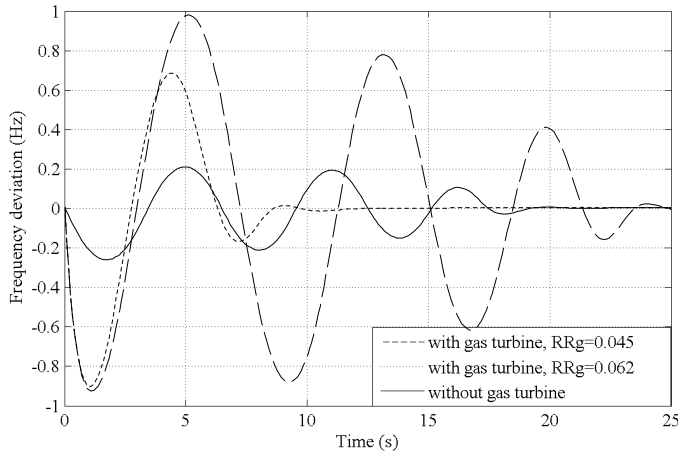


Fig. 20. Scenario 3: Frequency deviations in the stand-alone control area considering the effect of gas turbine with 10% inertia reduction.

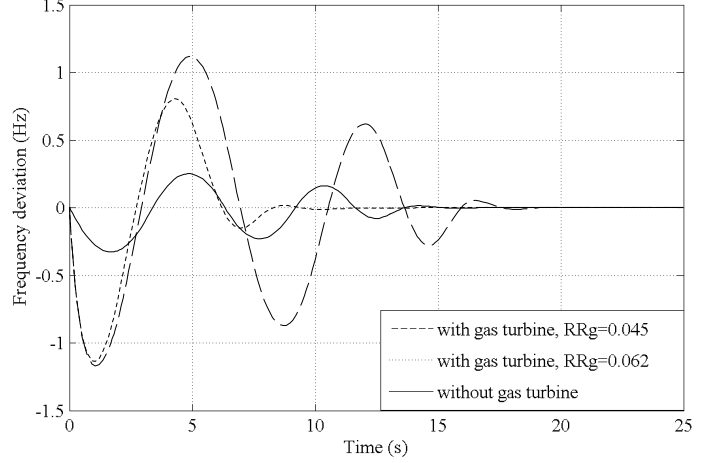


Fig. 21. Scenario 3: Frequency deviations in the stand-alone control area considering the effect of gas turbine with 30% inertia reduction.

4) From the first two scenarios, by combining the mathematical model, the maximum predictable load disturbance, frequency stability standard, and simulation results, it is possible to estimate the penetration limit of wind generation into the main grid. This idea is illustrated in the simulation that has been presented: if the safe range of frequency deviation is ± 0.2 Hz [26], and if maximum predicted load disturbance is 0.04 pu, the penetration of wind power in a stand-alone control area should not be higher than the level that creates 30% reduction in inertia. This level can be higher than 30% of total generator inertia in the area if it has strong interconnections with neighboring control areas. However, planning and operation processes should take the following into account.

- The effect of tie-line loading and congestion.
- The effect of inadvertent islanding.
- The proportion of inertia and regulating capability to the total system load.

5) Depending on the relationship between the ramp rate limits of two types of turbine, the gas turbine shows different impacts on frequency deviation. This is shown in Figures 20 and 21. If the ramp rate limit of the gas turbine is high (0.062), the system with gas turbine recovers faster. When this value decreases to 0.045, the system with gas turbine recovers slower. In the first case, the gas turbine benefits the frequency recovering speed clearly. However, the gas turbine makes the frequency nadir worse in both cases. This is consistent with the results reported in [47]–[49]. It is clear that while gas turbines benefit systems with wind generation through ramping capability, they are generally detrimental to frequency regulation.

IV. CONCLUSION

In this paper, the effect of wind power on load frequency control has been presented and examined at different penetration levels. The mathematical model and simulation

results indicate that wind power leads to reduction in not only the overall system inertia but also frequency response characteristic due to an increase of regulation constant. As a consequence, the frequency deviation, the tie-line power flow and the area control error increase. This contribution of our paper addresses a factor that is often overlooked when investigating load frequency control in the presence of wind generation. The analysis also provides guidelines toward estimating the allowable level of wind generation based on the configuration of system, maximum load disturbance and safe range of frequency excursion. The analyses presented here provide important information to the grid operator when considering wind power integration while ensuring the system stability. In the illustrations reported here, the control areas include gas turbine, reheat and non-reheat turbines. It is not difficult to extend this approach to include hydraulic turbine to more appropriately model the frequency response.

APPENDIX

The parameters of LFC dynamic model state space for the gas turbine are shown as follows:

$$\begin{aligned}
 x_i &= [\Delta f_i \ \Delta P_{gi} \ \Delta P_{tie,i} \ \Delta P_{vi} \ W_{fi}]^T \\
 \Delta P_{gi} &= [\Delta P_{g1i} \ \Delta P_{g2i} \ \cdots \ \Delta P_{gmi}] \\
 \Delta P_v &= [\Delta P_{v1i} \ \Delta P_{v2i} \ \cdots \ \Delta P_{vmi}] \\
 W_{fi} &= [W_{f1i} \ W_{f2i} \ \cdots \ W_{fmi}] \\
 y_i &= [\Delta f_i \ ACE_i]^T \\
 u_i &= [\Delta P_{C1i} \ \Delta P_{C2i} \ \cdots \ \Delta P_{Cmi}]^T \\
 n_i &= [\Delta P_{Li} \ \sum_{\substack{j=1 \\ j \neq i}}^N T_{ji} \Delta f_j \ b_{fi} \ W_{mi}]^T
 \end{aligned}$$

Matrices $\hat{A}_i$, $\hat{B}_i$, $\hat{C}_i$ and $\hat{D}_i$ of a control area with one gas turbine are provided as follows:

$$\begin{aligned}
 \hat{A}_i &= \begin{pmatrix} \frac{-D_i}{2H_i} & 0 & \frac{-1}{2H_i} & 0 & \frac{a_{fi}}{2H_i} \\ \frac{-1}{R_i T_{gi}} & \frac{-1}{T_{gi}} & 0 & 0 & 0 \\ 2\pi \sum_{\substack{j=1 \\ j \neq i}}^N T_{ij} & 0 & 0 & 0 & 0 \\ 0 & \frac{1-W_{mi}}{T_{vi}} & 0 & \frac{-1}{T_{vi}} & 0 \\ 0 & 0 & 0 & \frac{1}{T_{fi}} & \frac{-1}{T_{fi}} \end{pmatrix} \\
 \hat{B}_i &= [0 \ \frac{1}{T_{gi}} \ 0 \ 0 \ 0]^T \\
 \hat{C}_i &= \begin{pmatrix} \frac{-1}{2H_i} & 0 & 0 & 0 & 0 \\ 0 & 0 & -2\pi & 0 & 0 \\ \frac{-a_{fi}}{2H_i} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{T_{vi}} & 0 \end{pmatrix}^T \\
 \hat{D}_i &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \beta_i & 0 & 1 & 0 & 0 \end{pmatrix}
 \end{aligned}$$

The model data used in the simulations are reported in Tables I–IV below.

TABLE I
SIMULATION PARAMETERS OF A STAND-ALONE CONTROL AREA FOR SCENARIO 1

K	D (pu/Hz)	2H (pu.s)	R (Hz/pu)	T_g (s)	T_t (s)	B (pu/Hz)	T_{ij} (pu/Hz)
−0.3	0.015	0.1667	3.00	0.08	0.4	0.3483	0.2

TABLE II
SIMULATION PARAMETERS FOR A STAND-ALONE CONTROL AREA WITH WIND EFFECT ON β AND R

Inertia reduction (%)	K	D (pu /Hz)	2H (pu.s)	R (Hz /pu)	T_g (s)	T_t (s)	B (pu /Hz)	T_{ij} (pu /Hz)
0	−0.3	0.015	0.1667	3.00	0.08	0.4	0.3483	0.2
10	−0.3	0.015	0.1500	3.333	0.08	0.4	0.315	0.2
20	−0.3	0.015	0.1334	3.75	0.08	0.4	0.2817	0.2
30	−0.3	0.015	0.1167	4.286	0.08	0.4	0.2483	0.2
40	−0.3	0.015	0.1000	5	0.08	0.4	0.215	0.2
50	−0.3	0.015	0.0834	6	0.08	0.4	0.1817	0.2
60	−0.3	0.015	0.0667	7.5	0.08	0.4	0.1483	0.2

TABLE III
SIMULATION PARAMETERS OF CONTROL AREA 2 FOR SCENARIO 2

K	D (pu /Hz)	2H (pu.s)	R (Hz /pu)	T_g (s)	T_t (s)	B (pu /Hz)	T_{ij} (pu /Hz)	T_{RH} (s)	F_{HP}
−0.4	0.008	0.167	2.4	0.08	0.3	0.42	0.087	10	0.5

TABLE IV
SIMULATION PARAMETERS OF A GAS TURBINE FOR SCENARIO 3

K	D(pu/Hz)	T_g (s)	T_v (s)	T_f (s)	W_m	a_f	b_f
−0.3	0.015	0.05	0.05	0.4	0.23	1.3	0.23

REFERENCES

- [1] Y. V. Makarov, R. Diao, P. V. Etingov, S. Malhara, N. Zhou, R. T. Guttromson, J. Ma, P. Du, N. A. Samaam, C. Sastry, "Analysis methodology for balancing authority cooperation in high penetration of variable generation," Final report, Feb. 2010.
- [2] M. Benidris, S. Elsaiah, S. Sulaeman and J. Mitra, "Transient stability of distributed generators in the presence of energy storage devices," in *North American Power Symposium (NAPS)*, pp.1–6, champaign, IL, USA, 9–11 Sept. 2012.
- [3] M. Benidris, J. Mitra, "Enhancing stability performance of renewable energy generators by utilizing virtual inertia," in *IEEE Power and Energy Society General Meeting*, pp.1–6, San Diego, CA, USA, 22–26 July 2012.
- [4] North American Electric Reliability Corporation, "Operating practices, procedures and tools," NERC IVGTF Task 2.4 Report, Mar. 2011.
- [5] J. Conto, "Grid challenges on high penetration levels of wind power," *IEEE Power and Energy Society General Meeting*, pp. 1–3, Jul. 2012.
- [6] H. Shun-Hsien, D. Maggio, K. McIntyre, V. Betanabhatla, J. Dumas and J. Adams, "Impact of wind generation on system operations in the deregulated environment: ERCOT experience," *Power and Energy Society General Meeting*, pp. 1–8, Jul. 2009.
- [7] N. W. Miller, M. Shao, S. Venkataraman, C. Loutan, M. Rothleder, "Frequency response of California and WECC under high wind and solar conditions," *Power and Energy Society General Meeting*, pp. 1–8, Jul. 2012.
- [8] S. Sharma, H. Shun-Hsien, and N. D. R. Sarma, "System inertial frequency response estimation and impact of renewable resources in ERCOT interconnection," in *Power and Energy Society General Meeting, 2011 IEEE*, pp. 1–6, 2011.

- [9] J. Brisebois and N. Aubut, "Wind farm inertia emulation to fulfill Hydro-Québec's specific need," *Power and Energy Society General Meeting*, pp. 1–7, Jul. 2011.
- [10] H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy sources and frequency regulation: Survey and New Perspectives," *IET Renewable Power Generation*, vol. 4, no. 5, pp. 438–457, Sep. 2010.
- [11] I. Erlich, K. Rensch and F. Shewarega, "Impact of large wind power generation on frequency stability," *Power Engineering Society General Meeting, 2006 IEEE*, 2006.
- [12] Wei Li, G. Joos and C. Abbey, "Wind power impact on system frequency deviation and an ESS based power filtering algorithm solution," *Power Systems Conference and Exposition, 2006 IEEE PES*, pp. 2077–2084, 2006.
- [13] E. Muljadi, V. Gevorgian, M. Singh, S. Santoso, "Understanding inertial and frequency response of wind power plants," *Power Electronics and Machines in Wind Applications (PEMWA), 2012 IEEE*, pp. 1–8, 2012.
- [14] L. Changling, O. Boon-Teck, "Frequency deviation of thermal power plants due to wind farms," *Energy Conversion, IEEE Transactions on*, vol. 21, no. 3, pp. 708–716, Sep. 2006.
- [15] H. D. Mathur, L. B. F. Leite, H. Siguerdidjane, Y. K. Bhateshvar, "Study impact of wind power penetration on frequency stabilization in multi-area power system," *Advanced Topics in Electrical Engineering (ATEE), 2013 8th International Symposium on*, pp. 1–6, 2013.
- [16] M. Johan, P. Jan, W. H. de Haan Sjoerd, "Inertial response of variable speed wind turbines," *Electric Power Systems Research*, vol. 76, no. 11, pp. 980–987, Jul. 2006.
- [17] L. Meegahapola, D. Flynn, "Impact on transient and frequency stability for a power system at very high wind penetration," *Power and Energy Society General Meeting, 2010 IEEE*, pp. 1–8, 2010.
- [18] N. R. Ullah, T. Thiringer and D. Karlsson, "Temporary primary frequency control support by variable speed wind turbines–Potential and Applications," *IEEE Trans. Power Systems*, vol. 23, no. 2, pp. 601–612, May. 2008.
- [19] H. Ahmadi, H. Ghasemi, "Maximum penetration level of wind generation considering power system security limits," *IET Generation, Transmission and Distribution*, vol. 6, no. 11, pp. 1164–1170, Nov. 2012.
- [20] G. Strbac, A. Shakoor, M. Black, D. Pudjianto and T. Bopp, "Impact of wind generation on the operation and development of the UK electricity systems," *Electric Power Systems Research*, vol. 77, no. 9, pp. 1214–1227, Jul. 2007.
- [21] P. Bhatt, R. Roy, S. P. Ghoshal, "Dynamic contribution of DFIG along with SMES for load frequency control of interconnected restructured power system," *Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on*, pp. 1–5, 2011.
- [22] E. Vittal, J. D McCalley, V. Ajjarapu, and T. Harbour, "Wind penetration limited by thermal constraints and frequency stability," *Power Symposium, 2007. NAPS'07. 39th North American*, pp. 353–359, 2007.
- [23] L. Changling, H. G. Far, H. Banakar, P. K. Keung and O. Boon-Teck, "Estimation of wind penetration as limited by frequency deviation," *IEEE Trans. Energy Conversion*, vol. 22, no. 3, pp. 783–791, Sep. 2007.
- [24] H. Ahmadi, H. Ghasemi, "Security-Constrained unit commitment with linearized system frequency limit constraints," *IEEE Trans. Power Systems*, vol. 29, no. 4, pp. 1536–1545, Jun. 2014.
- [25] H. Bevrani, *Robust Power System Frequency Control*, Springer, 2009.
- [26] I. A. Erinmez, D. O. Bickers, G. F. Good, W. W. Hung, "NGC experience with frequency control in England and Wales-Provision of frequency response by generator," *Power Engineering Society 1999 Winter meeting, IEEE*, vol. 1, pp. 590–596, 1999.
- [27] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill, 1993.
- [28] W. I. Rowen, "Simplified mathematical representations of heavy-duty gas turbines," *ASM J. Eng. Power*, vol. 105, pp. 865–869, 1983.
- [29] Soon Kiat Yee, J. V. Milanovic, F. M. Hughes, "Overview and comparative analysis of gas turbine models for system stability studies," *Power Systems, IEEE Transaction on*, vol. 23, no. 1, pp. 108–118, Feb. 2008.
- [30] J. Ekanayake, N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *IEEE Trans. Energy Conversion*, vol. 19, no. 4, pp. 800–802, Dec. 2004.
- [31] J. M. Kennedy, B. Fox, T. Littler, D. Flynn, "Validation of fixed speed induction generator models for inertial response using wind farm measurements," *Power Systems, IEEE Transactions on*, vol. 26, no. 3, pp. 1454–1461, Aug. 2011.
- [32] L. Holdsworth, J. B. Ekanayake, N. Jenkins, "Power system frequency response from fixed speed and doubly fed induction generator-based wind turbines," *Wind Energy*, vol. 7, no. 1, pp. 21–35, Mar. 2004.
- [33] Y. Xue and N. Tai, "Review of contribution to frequency control through variable speed wind turbine," *Renewable Energy*, vol. 36, no. 6, pp. 1671–1677, Jun. 2011.
- [34] X. Zhang, L. Heming, W. Yi, "Control of DFIG-based wind farms for power network frequency support," *Power System Technology (POWER-CON)*, pp. 1–6, 2010.
- [35] Z. S. Zhang, Y. Z. Sun, J. Lin, G. J. Li, "Coordinated frequency regulation by doubly fed induction generator-based wind power plants," *Renewable Power Generation, IET*, vol. 6, no. 1, pp. 38–47, Jan. 2012.
- [36] N. W. Miller, K. Clark, and M. Shao, "Frequency responsive wind plant controls: Impacts on grid performance," *Power and Energy Society General Meeting*, pp. 1–8, 2011.
- [37] I. A. Gowaid, A. El-Zawawi, M. El-Gammal, "Improved inertia and frequency support from grid-connected DFIG wind farms," *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES*, pp. 1–9, 2011.
- [38] M. F. M. Arani, E. F. El-Saadany, "Implementing virtual inertia in DFIG-Based wind power generation," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1373–1384, Aug. 2013.
- [39] J. Morren, S. W. H. de Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 433–434, Feb. 2006.
- [40] R. G. de Almeida, J. A. Peas Lopes, "Participation of doubly fed induction wind generators in system frequency regulation," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 944–950, Aug. 2007.
- [41] Y. Wang, K. Y. Lee, "A control configuration of wind farm for load-following and frequency support by considering the inertia issue," *Power and Energy Society General Meeting, 2011 IEEE*, pp. 1–6, 2011.
- [42] M. Wang-Hansen, R. Josefsson, H. Mehmedovic, "Frequency controlling wind power modeling of control strategies," *Sustainable Energy, IEEE Transactions on*, vol. 4, no. 4, pp. 954–959, Oct. 2013.
- [43] L. Wu, D. Infield, "Investigation on the interaction between inertial response and droop control from variable speed wind turbines under changing wind conditions," *Universities Power Engineering Conference (UPEC), 2012 47th International*, pp. 1–6, 2012.
- [44] Z. Qing-Chang and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *Industrial Electronics, IEEE Transactions on*, vol. 58, no. 4, pp. 1259–1267, Mar. 2011.
- [45] R. Doherty, A. Mullane, G. Nolan, D. J. Burke, A. Bryson, M. O'Malley, "An assessment of the impact of wind generation on system frequency control," *Power Systems, IEEE Transactions on*, vol. 25, no. 1, pp. 452–460, Oct. 2009.
- [46] K. P. S. Parmar, S. Majhi and D. P. Kothari, "Optimal load frequency control of an interconnected power system," *MIT International Journal of Electrical and Instrumentation Engineering*, vol. 1, no. 1, pp. 1–5, Jan. 2011.
- [47] G. Lalor, M. O'Malley, "Frequency control on an island power system with increasing proportions of combined cycle gas turbines," *Power Tech Conference Proceedings, 2003 IEEE Bologna*, vol. 4, pp. 7–pp, 2003.
- [48] G. Lalor, J. Ritchie, D. Flynn, M. J. O'Malley, "The impact of combined-cycle gas turbine short-term dynamics on frequency control," *Power Systems, IEEE Transactions on*, vol. 20, no. 3, pp. 1456–1464, Aug. 2005.
- [49] M. A. Hanley, "Frequency instability problems in North American Interconnections," *DOE/NETL, Rep. DOE/NETL-2011/1473*, May 2001.

Nga Nguyen (S'11) received the Bachelor and Master degrees in electrical engineering from Hanoi University of Science and Technology, Hanoi, Vietnam in 2005 and 2008, respectively.

She is a Ph.D. student and a research assistant at the Energy Reliability & Security (ERISE) Laboratory at Michigan State University, East Lansing. Her research interests include stability, reliability and control of power systems in the presence of renewable energy.

Joydeep Mitra (S'94–M'97–SM'02) received the B. Tech. (Hons.) degrees in electrical engineering from Indian Institute of Technology, Kharagpur, India, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA.

He is Associate Professor of Electrical Engineering at Michigan State University, East Lansing, Director of the Energy Reliability & Security (ERISE) Laboratory, and Senior Faculty Associate at the Institute of Public Utilities. His research interests include reliability, planning, stability and control of power systems.