

Effect of Wind Power on Load Frequency Control

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Abstract—The integration of wind power into power systems has been gaining momentum in the global energy industry due to its environmental benefits and abundance of supply. However, the natural intermittent and non-dispatchable features of wind negatively impact the system's frequency regulation capability. Wind power not only injects additional fluctuations to the already variable nature of frequency deviation, it also decreases frequency stability by reducing the inertia as well as the regulation capability. This reduction causes the decrease of overall system frequency response characteristic. These effects of wind integration will be examined closely in this paper. In addition, the effect of wind power on tie-line power flows and area control error will be investigated. The analytical and simulation model of load frequency control are utilized to show the impact of wind on system frequency regulation. Additionally, a range of wind penetration levels is considered to determine the 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

Renewable energy (RE) resources are being utilized all over the world to address environmental concerns and the depletion of fossil fuel reserves. According to [1] and [2], approximately 20% of RE is expected in the US and European countries by 2020, and half of that comes from wind power. With steady growth and decreasing cost, wind power is considered a very promising renewable energy resource. Although wind power offers advantages in environmental impact and abundance of supply, its integration causes a lot of technical challenges. With zero or low inertia and intermittent characteristics, wind power negatively affects the stability and reliability of power systems [3], [4]. One of the main concerns with wind integration is frequency stability. Once wind power connects to the main grid and replaces conventional generators, it causes the frequency to deviate to a larger degree. Moreover, due to the reduction of inertia, the frequency deviation takes longer to return to its nominal value. In normal operation, the quality of power supplied must satisfy several conditions as required by the balancing authority. One of these conditions is the limit of frequency deviation. To ensure that the frequency deviation remains within a safe limit, a minimum amount of inertia is vital. If the main grid does not have sufficient regulation capacity, the frequency deviation might violate the safe limit, which directs to load shedding or even causes the system to collapse. For this reason, it is important to investigate not only the change of system frequency regulation capability with

different wind power penetration levels but also the maximum acceptable level of wind that penetrates into the grid.

While examining the negative influence of wind power on the load frequency control (LFC), previous works generally considered wind power output uncertainty (or intermittence), inertia reduction [5]–[8], and the increase of equivalent regulation constant [7], [9]. Several papers have made an effort to identify the maximum penetration level of wind power based on thermal limit [10] or constraint value of frequency deviation [11]. The work presented in this paper extends previous work by adding the following contributions: (i) model the effect of wind integration on the system frequency response characteristic (β); (ii) model the effect of wind integration on the area control error (ACE) and on tie-line interchanges in an interconnected system; (iii) model the relationship between the system frequency regulation and wind penetration levels; (iv) determine the limit of wind penetration given a frequency deviation limit.

The remainder of this paper is organized as follows. Section II presents the elemental concepts of load frequency control and mathematical model of one control area in the presence of wind power. This model will be the starting point to define the limitation of wind penetration in the grid. A simulation model and results are presented in section III to verify the mathematical model. In this section, some observations and recommendations are also included to clarify the main idea of the paper. Finally, section IV provides some concluding remarks.

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

The function of load frequency control is to return the frequency to its nominal value after the system is subjected to a disturbance. Once there is an imbalance between supply and demand, LFC is implemented via four stages [12]: inertial, primary, secondary and tertiary response. In the first stage, frequency deviation is immediately inhibited by inertia, governor action, load and other damping mechanisms. In the second stage, the governor regulates generator output by changing prime mover input. These stages are attributed to the farthest frequency deviation point and a part of the frequency recovery duration. To remove the remaining frequency error, it is required to have the Automatic Generation Control (AGC) change the generator set point in the third stage. The last stage reschedules system reserves to prepare for the future

disturbance.

When wind generators are installed in the system and replace conventional generators, the effectiveness of LFC decreases due to the relative reduction in inertia and in the ability to regulate the generation output of the entire system. As a result, the frequency deviates to a larger magnitude and the recovery is prolonged. The combination of governor, generator, turbine, rotating mass and load damping control model produces the load frequency control model, which is shown in Fig. 1 below [13]. The wind included in the control model by $\Delta P_L(s)$ is based on the notion that wind power is considered as a negative load. In Fig. 1, the notations used are as follows:

ΔP_C = supplementary control action
 $K(s)$ = LFC controller
 ΔP_{load} = non-frequency-sensitive load change

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

T_{ij} = synchronizing torque coefficient
 H = equivalent inertia constant
 Δf = frequency deviation
 D = load damping constant
 $TG_{ki}(s)$ = turbine-governor transfer function
 $\Delta P_{tie,i}$ = total tie-line power change between area i and other areas [13]

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

B_i = frequency bias factor and its suitable value can be calculated as follows [17]:

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

Once wind generators 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 [14]), and 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. In addition to 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, two types of conventional turbines will be considered in the LFC model: non-reheat turbine and reheat turbine. The dynamic models of turbine-governor systems for these generators are as follows [13]:

$$TG_{non-reheat}(s) = \frac{1}{1 + T_t s} \frac{1}{1 + T_g s} \quad (8)$$

$$TG_{reheat}(s) = \frac{1}{1 + T_t s} \frac{1}{1 + T_g s} \frac{1 + F_{HP} T_{RH} s}{1 + T_{RH} s} \quad (9)$$

In equations (8) and (9), the notations used are as follows:

T_g = speed governor time constant
 T_t = steam turbine time constant
 T_{RH} = time constant of reheater
 F_{HP} = fraction of turbine power generated by HP unit

During the disturbance, the frequency deviation and tie-line power signal are the inputs to calculate area control error (ACE). The system frequency deviation is given as follows:

$$\begin{aligned} \Delta f_i(s) &= \frac{1}{2H_{new,i}s + D_i} \left(\sum_{k=1}^N TG_{ki}(s) [\Delta P_{Cki}(s) \right. \\ &\quad \left. - \Delta P_{ki}(s)] - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s) \right) \end{aligned} \quad (10)$$

where

$$\begin{aligned} \Delta P_{Cki}(s) &= K(s)(\Delta P_{tie,i}(s) + B_{new,i} \Delta f_i(s)) \\ \Delta P_{ki}(s) &= \frac{\Delta f_i(s)}{R_{new,i}} \end{aligned}$$

Equation (10) can be rewritten as follows:

$$\begin{aligned} \Delta f_i(s) &= \frac{\sum_{k=1}^N TG_{ki}(s) K(s) \Delta P_{tie,i}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i - \sum_{k=1}^N TG_{ki}(s) K(s) B_{new,i} + \frac{\sum_{k=1}^N TG_{ki}(s)}{R_{new,i}}} \end{aligned} \quad (11)$$

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

$$\begin{aligned} \Delta f_{iss} &= \lim_{s \rightarrow 0} s \Delta f(s) = \lim_{s \rightarrow 0} s \cdot \left(\frac{\sum_{k=1}^N TG_{ki}(s) K(s) \Delta P_{tie,i}(s) - \Delta P_{tie,i}(s) - \Delta P_{L,i}(s)}{2H_{new,i}s + D_i - \sum_{k=1}^N TG_{ki}(s) K(s) B_{new,i} + \frac{\sum_{k=1}^N TG_{ki}(s)}{R_{new,i}}} \right) \end{aligned} \quad (12)$$

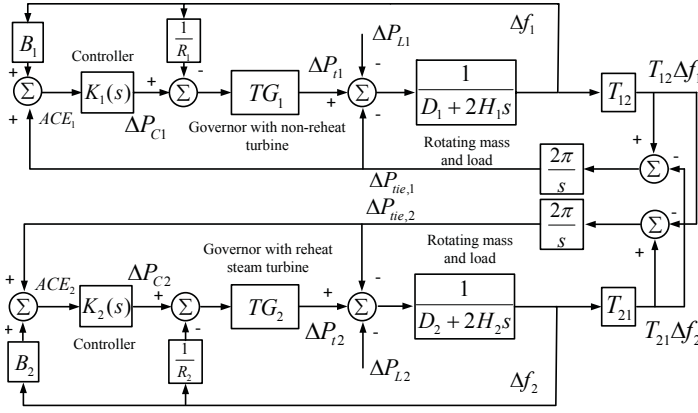


Fig. 3. Simulation model of two interconnected control areas.

between areas in an interconnected system. The simulation model of two interconnected control areas is presented in Fig. 3. The maximum frequency deviation, the maximum tie-line power, the maximum ACE results when changing wind penetration levels are shown in figures 5, 6, and 7 respectively. The simulation was implemented with and without the effect of wind on the frequency response characteristic and equivalent regulation constant to show the differences between them.

In the simulation results, we can see the following:

- 1) The more wind power that is integrated into the system, the higher the frequency deviation due to a larger reduction in total system inertia and a higher increase in the equivalent regulation constant which lead to a decrease in the area frequency response characteristic. This is shown clearly in Fig. 4 and Fig. 5: maximum frequency deviation increases from 0.14 Hz to 0.32 Hz (in the first case) and from 0.075 Hz to 0.135 Hz (in the second case) while the reduction of inertia varies from 0% to 60%. It is also obvious in Fig. 4 and Fig. 5 that if the effect of wind on the frequency response characteristic and equivalent regulation constant is taken into account, maximum frequency deviation gets worse. In addition to the further variation in frequency, the duration of frequency recovery is also extended due to the presence of wind power.
- 2) In an interconnected system, control areas have the ability to assist each other when the system is subjected to disturbances. In simulation results, the assistance from area 2 alleviates the frequency deviation in area 1. Frequency deviation is much smaller in the second case (0.075 to 0.135 Hz falling range) compared to the first case (0.14 to 0.32 Hz). For this reason, it is better that control areas collaborate to get the highest benefit when wind generation is integrated into power system.
- 3) Following the increase of penetration levels, the maximum tie-line power flow increases and the maximum area control error decreases as shown in Fig. 6 and Fig. 7. These are outcomes of wind power impact on β and on the frequency which have been discussed in

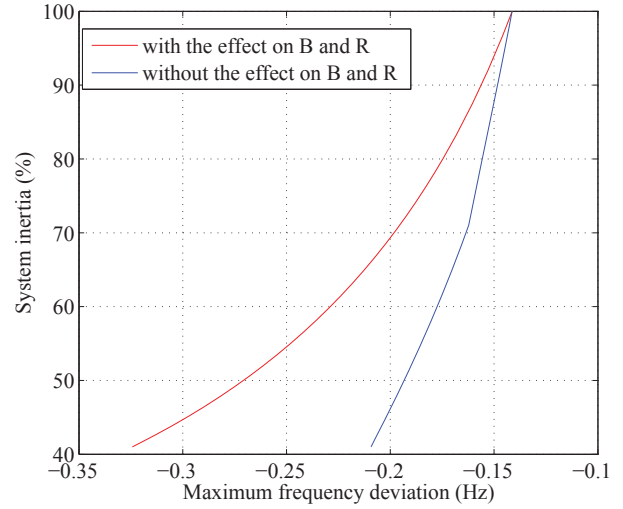


Fig. 4. Maximum frequency deviations of the stand-alone control area with and without considering the effect of wind on β and R.

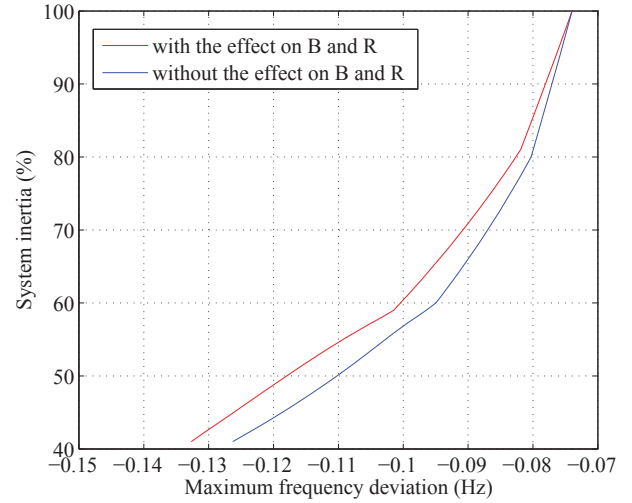


Fig. 5. Maximum frequency deviations of area 1 in an interconnected system with and without considering the effect of wind on β and R.

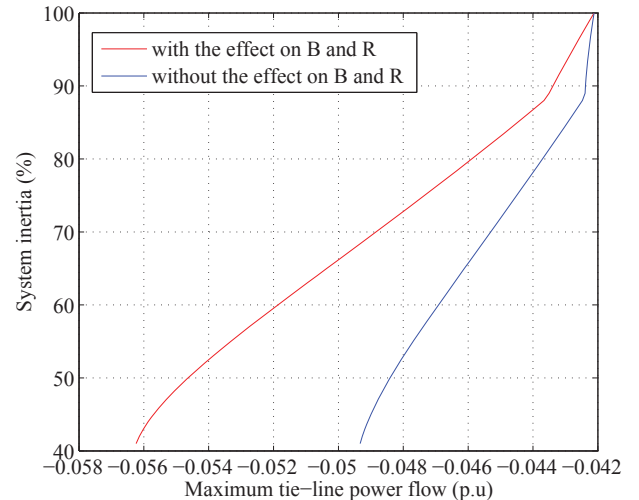


Fig. 6. Maximum tie-line power flows of area 1 in an interconnected system with and without considering the effect of wind on β and R.

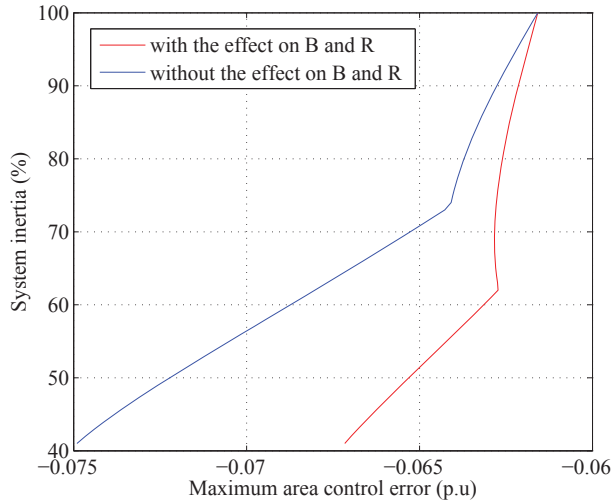


Fig. 7. Maximum ACE in an interconnected system with and without considering the effect of wind on β and R.

the foregoing section.

- 4) By combining the mathematical model, the maximum predictable load disturbance, frequency stability standard and simulation results, it is possible to identify the penetration limit of wind generation into the main grid. This idea can be illustrated in the simulation that has been made: if the safe range of frequency deviation is $\pm 0.2\text{Hz}$ [15], [16], and 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% if the control area has strong interconnections with neighboring control areas. However, the congestion in the tie-lines that connect areas, the ability to maintain stability of one control area when it is isolated by an inadvertence, and maximum inertia and reserve of the system should all be taken into account. If the inertia and reserve of the system is not sufficient, high values of frequency deviation might compromise the system stability.

IV. CONCLUSION

This paper has presented and examined the effect of wind power on load frequency control at different penetration levels. The mathematical model proves that wind power leads to reduction of not only the overall system inertia but also the frequency response characteristic due to an increase of regulation constant. This has covered the drawback that most previous papers did not appropriately mention while investigating load frequency control in the presence of wind. The analysis also provides necessary information to decide the maximum level of wind generation in the grid based on the configuration of the system, the maximum load disturbance and the safe range of frequency excursion. The investigation results show that replacing a certain capacity of conventional generators by wind

power has a negative impact on system frequency stability. The simulation results support the hypothesis presented and show the importance of considering the impact on the frequency response characteristic. The well-known benefits of interconnected operation are also supported by the studies reported.

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