Coordination Between Converter-Based Wind Turbines and Synchronous Generators During Inertia Control

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Abstract: Since the rotor speed of converter controlled wind turbines (WTs) is decoupled with system frequency, large-scale wind power integration into the power system reduces system inertia, and worsens system frequency response after disturbances. Although inertia control of the WT can improve the system frequency response by releasing kinetic energy stored in the rotor of the WTs, it masks the magnitude of the load disturbance and thus delays the response of the synchronous generators (SGs) during primary frequency control. Furthermore, due to the limited kinetic energy, WTs must terminate inertia control at some time, and this termination causes another system frequency drop. This paper proposes a coordination strategy between WTs and conventional SGs. By revising the input signal of the governing system of the SGs, and designing output power for the WTs during inertia control, the system frequency response can be improved. Case study results validate the efficacy of the proposed strategy.

1. INTRODUCTION

With the high penetration of the wind power, modern power systems are faced with more challenges. The system inertia declines because conventional SGs are phased out, and the converter-based WTs cannot naturally contribute to system inertia since their rotor speed is decoupled from the system frequency. The low inertia power system may experience a severe frequency drop after active power imbalance disturbances, and thus have higher risk of under frequency load shedding, or even cascading outages. Therefore, it is necessary to enhance the WTs with the ability to contribute to system inertia in order to guarantee system frequency stability.

Inertia control of WTs has been proposed in recent years [1]. Which can provide an emulated inertia after disturbances, and can improve frequency stability. Over the past years, the effect of inertial control on the power system and the way of improving the performance of inertial control have been widely investigated [2].

However, inertia control has some adverse effects to the power system. One of the most significant shortcomings of the existing inertial control is that WTs have fast active power response during system frequency regulation, and this could conceal the actual power imbalance of the system, leading SGs to delay their response when rejecting more mechanical power [3]. Another concern about the inertial control is that WTs have to suddenly switch back to the normal operating mode by decreasing the
output power during the system frequency regulation to recover the rotor speed. This causes a significant drop of the system frequency, which is called the Secondary Frequency Drop [4].

In [3], the incremental injected active power of WTs is communicated to the conventional SGs so that the governing system can increase the mechanical power more quickly based on the full load imbalance. However, in practice, the proposed method requires high investment on communication system and it is not economical for implementation.

To mitigate or eliminate the secondary frequency drop, some methods have been proposed aiming at smoothing the termination operation of WTs such as dynamic droop-based inertial control [5], and extended state observer (ESO)-based inertia emulation controller (InEC) [6]. Furthermore, it is also possible to mitigate secondary frequency drop by implementing energy storage devices [7]. It can be noticed that during inertia control, the mechanical power of the SGs increases and has an overshoot due to the dynamic of the governing system. This overshoot can be utilized as a compensation of the power drop caused by the termination of the inertia control, and mitigate secondary frequency drop efficiently.

Motivated by the above two aspects, this paper firstly analyses the characteristics of the output power of WTs and SGs, and the system frequency response during inertia control, and proposes a coordination strategy between converter-based WTs and conventional SGs. Applied with the strategy, during inertia control, the SGs can increase the mechanical power based on the full power imbalance of the system, and it is achieved without communication with WTs. Moreover, by designing the output power of WTs, the overshoot of the mechanical power of the SGs can be utilized to mitigate the secondary frequency drop.

2. MODELS AND PROBLEM STATEMENT

A. The simplified model of the SG-WT system

For the convenience of analysis, the SG-WT system model can be simplified as a model which is shown as Fig.1. The input mechanical power of the WT $P_{mw}$ is expressed by,

$$P_{mw} = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3$$

which is a function of air density $\rho$, the swept area $A$, the wind speed $v_w$ and the power coefficient $C_p$.

The value of $C_p$ is determined by the tip-speed ratio $\lambda$ and pitch angle $\beta$.

In normal operation mode, the output electrical power of the WT $P_{ew}$ is determined by maximum power point tracking (MPPT) control, and is calculated by,

$$P_{MPPT} = k \omega_r^3$$

where $\omega_r$ is the rotor speed of the WT, and $k$ is the coefficient of the MPPT curve.

![Simplified model of SG-WT system](image-url)

The model of the SG can be simplified as a low-order SFR model which is proposed in [8], where $P_{ms}$ is the mechanical power of the SG, $H_s$ and $D_s$ are the inertia constant and damping factor of the SG,
respectively. $K_m$, $R$ are the mechanical power gain factor and the regulation factor of the governor of the SG, respectively. $F_H$ is the fraction of total power generated by the High-Pressure turbine of the SG, and $T_R$ is the reheat time constant of the turbine of the SG.

After a disturbance, the system will experience a frequency drop, and the frequency deviation is expressed as $\Delta f$. After detects the frequency drop, the wind turbine activates the inertia control by adding an incremental power $\Delta P_{\text{add}}$ to $P_{\text{MPPT}}$. Synthetic inertia control is a common form of inertia control. It utilizes the system frequency deviation as the input of the control loop, and can replicate the behavior of synchronous generators after the disturbance. The output electrical power of the WT during inertia control is,

$$P_{\text{ew}} = P_{\text{MPPT}} + \Delta P_{\text{add}} = P_{\text{MPPT}} - \left( k_f \Delta f + k_d \frac{d\Delta f}{dt} \right)$$  \hspace{1cm} (3)

The simplified model of SG-WT system can be used for analyzing characteristics of output power of SGs and WTs during inertia control.

B. The output power of the SG and WF during inertia control

The output power of the SG and WT and the system frequency response after a disturbance with and without inertia control is compared and shown in Fig.2, respectively.

C. Problem Statement

It can be seen from Fig.2 that with inertia control, the system frequency nadir is improved. Nevertheless, the output power of the SG increases slower compared to the scenario without inertia control. The governing system of the SG increases the output power based on deviation of the rotor speed of the SG, which is coupled with the system frequency. With inertia control, the system frequency deviation is improved, but for the SG, the actual power imbalance is also concealed because its rotor speed deviation is also improved.

It is also shown from Fig.2 that the system has a significant secondary frequency drop, which is caused by the termination of the inertia control. It is observed from simulations that the magnitude of the secondary frequency drop is relevant with penetration of wind power, parameters of inertia control, and the magnitude of disturbance, etc. In some cases, the magnitude of secondary frequency drop may be even severer than the frequency drop caused by the disturbance.

To address the aforementioned two issues, this paper aims at designing a coordination strategy between WTs and SGs, which can avoid the delay of the governing system of the SG, and also mitigate the secondary frequency drop.
3. COORDINATION STRATEGY

The coordination strategy consists of two parts. Firstly, for the SG, the input signal of the governing system of the SG is replaced with “virtual” system frequency deviation which is calculated during inertia control; Secondly, for the WT, the output power of the WT is designed considering the characteristics of the output power of the SG.

A. SG: The “virtual” system frequency deviation

With inertia control, system frequency deviation is improved, thus it also conceals the actual power imbalance. To solve this problem, one approach is to communicate the WT’s incremental power to the SG, so that the governing system of the SG can “realize” the actual power imbalance and increase its output power based on that. This approach can effectively accelerate the response of the SG, but with high investment on communication system. Besides, the time delay of communication is also not negligible in large-scale power systems. Therefore, this paper proposes another approach which is free from communication.

The relation between initial rate of change of frequency (RoCoF) of the power system and the magnitude of the disturbance can be expressed as,

\[
\Delta P_i = 2H_s \frac{d\Delta f}{dt} \bigg|_{\omega^0} \quad (4)
\]

The initial RoCoF can be measured by the SG and its value is not affected by the inertia control of the WT since the activation of the inertia control has a time delay, thus the initial RoCoF of the system is only determined by the inherent inertia provided by the SG. After obtaining the initial RoCoF, the governing system will calculate the actual power imbalance using (4), and then calculate “virtual” system frequency deviation \( \Delta f_v \) using the low-order SFR system, that is,

\[
\Delta f_v(t) = \frac{\Delta P_i R}{D_j R + K_m} \left[ 1 + \alpha e^{-\Delta f v \sin(\Omega_s t + \phi)} \right] \quad (5)
\]

where,

\[
\Omega_s^2 = \frac{D_j R + K_m}{2H_s R T_R}, \quad \zeta = \left[ \frac{2H_s R + (D_j R + K_m) T_R^j}{2(D_j R + K_m)} \right] \Omega_s, \quad \alpha = \sqrt{\frac{1 - 2T_R \zeta \Omega_s + T_R^j \Omega_s^2}{1 - \zeta^2}}
\]

\[
\Omega_s = \Omega_s \sqrt{1 - \zeta^2}, \quad \phi = \arctan \left( \frac{\Omega_s T_R}{1 - \zeta^2 \Omega_s T_R} \right) - \arctan \left( \frac{\sqrt{1 - \zeta^2}}{1 - \zeta} \right) \quad (6)
\]

Essentially, this so-called “virtual” system frequency deviation is the system frequency deviation in a scenario where the system has the same disturbance, but the WT is not implemented with inertia control. By replacing the rotor speed with this “virtual” system frequency deviation as the input signal of the governing system of the SG, the SG will avoid the influence of the inertia control and its output power will increase likewise in the scenarios without inertia control.

B. WT: The Output Power During Inertia Control
The output power of the WT can be designed based on the objective of improving the system frequency response.

From the perspective of the system, the ideal output power of the WT is achieved if it can fully compensate the system power imbalance after the disturbance. In this way, the system will not experience any frequency drop. This ideal output power of the WT $\Delta P_{wi}$ can be expressed as,

$\Delta P_{wi} = \Delta P_l - \Delta P_{ms}$ \hspace{1cm} (7)

where $\Delta P_{ms}$ is the incremental mechanical power of the SG, and can be calculated by,

$$\Delta P_{ms} = \frac{K_m \Delta P_f}{D_J R + K_m} \left[1 + \alpha' e^{-\alpha' \varphi} \sin(\Omega_f + \varphi') \right], \quad \alpha' = \sqrt{\frac{1 - 2 T_J \xi \Omega_f + F_{ii} T_R^2 \Omega_f^2}{1 - \zeta^2}},$$

$$\varphi' = \tan^{-1} \left( \frac{\Omega_f F_{ii} T_R}{1 - \xi \Omega_f F_{ii} T_R} \right) - \tan^{-1} \left( \sqrt{\frac{1 - \xi^2}{-\xi}} \right) \quad (8)$$

For the convenience of calculation, the $\Delta P_{wi}$ can be approximated as a piecewise linear function (shown as Fig.3), that is,

$$\Delta P_{wi} = \begin{cases} \frac{\Delta P_{ms}}{t_1 - t_0}, & t_0 \leq t < t_1 \\ \Delta P_l - (\Delta P_{ms} + k_{wi} (t - t_1)), & t_1 \leq t < t_2 \\ 0, & t \geq t_2 \end{cases} \quad (9)$$

where $t_0$ is the time when the inertia control is activated, $t_1$ is the time when the maximum mechanical power of the SG occurs, and $t_2$ is the time when the mechanical power of the SG reaches its steady state value, $\Delta P_{ms}$ is the value of the maximum mechanical power of the SG. $t_1$, $t_2$ and $\Delta P_{ms}$ is given by,

$$t_1 = \frac{n \pi - \varphi'}{\Omega_f} = \frac{1}{\Omega_f} \tan^{-1} \left( \frac{\Omega_f F_{ii} T_R}{\Omega_f F_{ii} T_R - 1} \right), \quad t_2 = t_1 + \frac{\pi}{\Omega_f}, \quad \Delta P_{max} = \Delta P_{ms}(t_1) \quad (10)$$

The functionality of $\Delta P_{wi}$ is to provide a reference of the output power of the WT. Obviously, the output power of the WT cannot be set as $\Delta P_{wi}$ since the WT has its constraints on the electric torque and the available kinetic energy. Considering the constraints, the output power of the WT can be determined as,

$$\Delta P_{add} = \begin{cases} \Delta P_{wi} - \Delta P_{MPP}, & \Delta P_{wi} \geq \Delta P_{MPP} \& \omega_l > \omega_{l min} \\ \Delta P_{wi} \leq \Delta P_{MPP} \& \omega_l > \omega_{l min}, & \omega_l < \omega_{l min} \end{cases}$$

$$\Delta P_{ad} = \begin{cases} \Delta P_{wc} - \Delta P_{MPP}, & \Delta P_{wc} \geq \Delta P_{MPP} \& \omega_l > \omega_{l min} \\ \Delta P_{wc} \leq \Delta P_{MPP} \& \omega_l > \omega_{l min}, & \omega_l < \omega_{l min} \end{cases} \quad (11)$$
C. Overview of the Coordination Strategy
The schematic diagram of the proposed coordination strategy is shown as Fig.4.

4. CASE STUDY
To validate the performance of the proposed coordination strategy, case study is performed in a SG-WT system.

A. Low wind speed
   a) System frequency response

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To validate the performance of the proposed coordination strategy, case study is performed in a SG-WT system.

A. Low wind speed
   a) System frequency response
As shown in Fig. 6 and Fig. 7, in low wind speed zone, the system frequency nadir is improved with inertia control, but the response of the SG is delayed. With the proposed coordination strategy, the response of the SG is not delayed.

**B. Medium wind speed**

**a) System frequency response**
Fig. 8 Comparison of system frequency of the WT during frequency regulation in medium wind speed conditions (7.5m/s)

![Graph showing system frequency response with three different control strategies: no control, with inertia control, and with coordination control.]

![Graph showing the output power of the SG and WT with three different control strategies: no control, with inertia control, and with coordination control.]

It can be seen from Fig. 8 and Fig. 9 that, in medium wind speed zone, the frequency response is also enhanced with proposed coordination strategy, compared with the scenarios without inertia control and with traditional inertia control. Moreover, the delay of the SG’s response is also avoided effectively.

C. High wind speed

a) System frequency response

![Graph showing system frequency response with three different control strategies: no control, with inertia control, and with coordination control.]

Fig. 10 Comparison of system frequency of the WT during frequency regulation in high wind speed conditions (9.5m/s)
b) Output power of the SG and WT

Fig. 11 Comparison of output power of the WT and SG during frequency regulation in high wind speed conditions (9.5m/s)

The performance of the proposed coordination strategy is also validated in high wind speed zone, as is shown in Fig. 10 and Fig. 11. Furthermore, the secondary frequency drop was also improved with the proposed coordination strategy.

5. CONCLUSION

This paper analyzes the characteristics of the WT’s and SG’s output power as well as system frequency response during inertia control, and proposes a coordination strategy between converter-based WTs and conventional SGs based on the analysis. The proposed coordination strategy can let the SGs increase its mechanical power based on the full power imbalance of the system, and it is achieved without setting up communication between SGs and WTs. Moreover, the proposed coordination strategy can also mitigate secondary frequency drop caused by the termination of the inertia control. Simulation results show that the proposed coordination strategy has satisfactory performance in different wind speed conditions.

REFERENCES

[1] 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, 2006.

[2] M. Kayıkçı and J. V. Milanović, “Dynamic contribution of DFIG-based wind plants to system frequency disturbances,” *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 859–867, 2009.

[3] J. M. Mauricio, A. Marano, A. Gomez-Exposito, and J. L. Martinez Ramos, “Frequency Regulation Contribution Through Variable-Speed Wind Energy Conversion Systems,” *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 173–180, 2009.

[4] A. Bonfiglio, M. Invernizzi, A. Labella, S. Member, R. Procopio, and S. Member, “Design and Implementation of a Variable Synthetic Inertia Controller for Wind Turbine Generators,” *IEEE Trans. Power Syst.*, vol. 8950, no. c, pp. 1–1, 2018.

[5] M. Hwang et al., “Dynamic Droop – Based Inertial Control of a Doubly-Fed Induction Generator,” *Ieee Trans. Sustain. Energy*, vol. PP, no. 99, pp. 1–10, 2015.

[6] F. Liu, Z. Liu, S. Mei, W. Wei, and Y. Yao, “ESO-Based Inertia Emulation and Rotor Speed Recovery Control for DFIGs,” *IEEE Trans. Energy Convers.*, vol. 32, no. 3, pp. 1209–1219, Sep. 2017.

[7] L. Miao and C. District, “Coordinated Control Strategy of Wind Turbine Generator and Energy Storage Equipment for Frequency Support Jinyu Wen Wei-jen Lee,” *Ieee Trans. Ind. Appl.*, vol. 51, no. 50937002, pp. 1–7, 2014.

[8] P. M. Anderson and M. Mirheydar, “A low-order system frequency response model,” *IEEE Trans. Power Syst.*, vol. 5, no. 3, pp. 720–729, 1990.