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# Frequency Regulation Analysis of Power Systems with High Penetration Wind Power

F.F. Miao, X.S. Tang, Z.P. Qi
Institute of Electrical Engineering
Chinese Academy of Sciences
Beijing, China

***Abstract--*****The integration of large-scale Variable-Speed Wind Turbine Generators (VSWTGs) will challenge power systems frequency stability due to the lack of inertia response and reserve capacity in their control system, which are important for power system stability and power quality. This paper deduced quantitatively power systems frequency regulation indexes considering high penetration wind power integration, including Rate Of Change Of Frqeuncy (ROCOF), Maximum Frequency Deviation (MFD), and Steady State Frequency Deviation(SSFD). Then the dominant parameters effect on frequency stability were analyzed. The improvement on frequency stability with wind plants participating in Inertia Response (IR) and Primary Frequency Regulation (PFR) services was analyzed with the choice basis for wind plants ancillary frequency regulation controller parameters provided. Finally, a regional power grid was used to verify the the oreitcal analyses, and the results indicated that wind plants with frequency regulation services can improve power systems frequency stability and power quality.**

***Keywords-wind power; frequency stability; frequency regulation***

## I. INTRODUCTION

Frequency stability is one of importance aspects for power systems reliable and stable operation, and the evaluation indexes are ROCOF, MFD and SSFD[1, 2]. Wind power penetration level is increasing, which takes a threat to power systems frequency stability: 1) VSWTGs cannot provide frequency regulation services due to through power converter integrate into grid and Maximum Power Point Track (MPPT) operation[3]; 2) large-scale wind plants replace the traditional generators, which decreases the capability of inertia response and primary frequency regulation in power systems[4]. Therefore, frequency regulation of power systems with high penetration wind power is need to research topic.

In recent years, frequency regulation of power systems with wind power has been analyzed in several papers. Simulations on EMTDC/PSCAD package were used to compare frequency characteristics of power systems with Double Fed and Fixed-speed Induction generator wind turbines[5]. In [6], several simulations using a two-area test systems are performed to analyze frequency stability with VSWTG providing frequency support in the program PSS/E. Analysis and impacts of systems stability with implementing droop control in VSWTGs were simulated in Matlab/Simulink in [7].These papers almost focused on qualitative analysis in time-domain simulation, lack of quantitative expression of power systems frequency regulation indexes.Although the probabilistic of power systems frequency regulation evaluation indexes with wind power is quantitative analysis inreference [8], the frequency regulation of wind plants is not considered.

This paper deduces thefrequency regulation indexes quantitative equation of power systems with wind power providingfrequent regulation services, and provides the choice basis of wind power frequency regulation parameters. The remainder of this paper is organized as follows: first, the frequency control model of power systems is simple introduced; followed by the quantitative expressions and analysis of power systems frequency regulation indexes with wind power; on this basis, wind plants with auxiliary frequency regulation services is proposed to improve frequency characteristics, and the choice basis of frequency regulation controller parameters are analyzed. Finally, a province power grid datais used toverify the theoreitcal analyses, the results indicate that wind power with frequency regulation ensures frequency stability, and improves wind power penetration level in power systems.

## II. FREQUENCY CONTROL MODEL OF POWER SYSTEMS WITH WIND POWER

Frequency control model of power systems is the basis of frequency regulation analysis [9]. This paper takes steam turbine generators as example to analyze frequency regulation of power systems with wind power, frequency control model contains traditional generators, wind plants and load, as shown in figure 1.

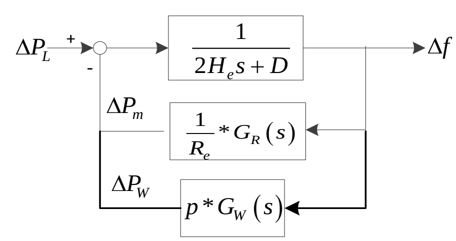



FIGURE I. FREQUENCY CONTROL MODEL OF POWER SYSTEMS WITH WIND POWER

where, $\Delta P_L$ is load disturbance power, $\Delta P_m$ is steam generators frequency regulation power, $\Delta P_W$ is wind plants frequency regulation power, $H_e$ is inertia constant, $R_e$ is droop coefficient, $D$is damping factor, $p$ is penetration level of wind power, $G_R(s)$ is steam generators frequency control model and $G_W(s)$ is wind plants frequency control model.

With wind power increasing, traditional generators are replaced by wind plants, the VSWTG cannot response the change of frequency, the equivalent inertia constant ($H_e$)and droop coefficient ($R_e$) are shown eqn. (1) and (2).

$$H_e = (1-p)H \tag{1}$$

$$R_e = R/(1-p) \tag{2}$$

where, $H$ and $R$ are the inertia constant and droop coefficient of power system without wind power.

Without considering the effect of primary frequency regulation, the frequency characteristic model of power systems is given below.

$$G(s) = \frac{\Delta f}{\Delta P_L} = \frac{1}{2H_e s + D} \tag{3}$$

When the frequency deviate from the rated normal, due to wind plants without inertia response and primary frequency regulation, the $\Delta P_W$ =0, the frequency control model of power systems with wind power is shown eqn. (4).

$$\frac{\Delta f}{\Delta P_L} = -\frac{G(s)}{1+\frac{1}{R_e}G(s)G_R(s)} \tag{4}$$

The characteristic of traditional generotor governor is based on first order intertial loop, as shown eqn. (5) [9]. where, $T$is the governor time constant.

$$G_R(s) = \frac{1}{1+sT} \tag{5}$$

## III. FREQUENCY REGULATION INDEXES OF POWER SYSTEMS WITH WIND POWER

Power systems Frequency regulation indexes consist of maximum ROCOF, MFD and SSFD, and each index expression is deduced.

### A. *Rate of Change of Frequency (ROCOF)*

In order to ensure the safe operation of wind turbine generators, which equips with ROCOF relay protection device. When frequency events is occur, the ROCOF over limit value causes the WTGs out of operation, which further deteriorates frequency stability. Therefore, ROCOF of power systems under high penetration wind power must lower than the limit value.

As the primary frequency response slowly, maximum ROCOF occurs the moment of power imbalance, systems frequency in frequency domain is shown eqn.(6), when the load power is step increase.

$$\Delta f(s) = \frac{1}{2H(1-p)s+D}\cdot\frac{-\Delta P_L}{s} \tag{6}$$

The ROCOF is deduced by deviating eqn.(6), as follows:

$$\frac{df(t)}{dt} = -\frac{\Delta P_L}{2H(1-p)}e^{-\frac{D}{2H(1-p)}t} \tag{7}$$

When t=0+, the maxmium ROCOF is obtained as

$$\left|\frac{df}{dt}\right|_{\max} = -\frac{\Delta P_L}{2H(1-p)} \tag{8}$$

Eqn. (8) indicates that power systems ROCOF is proportional to load disturbance $\Delta P_L$, inversely proportional tosystems equivalent inertia $H$ and penetration level $p$. From eqn. (8), wind power maxmium penetration level in power systems in the index of ROCOFis expression as

$$p < 1 - \frac{\Delta P_L}{2H\left|df/dt\right|_{\max}} \tag{9}$$

### B. *Steady State Frequency Deviation(SSFD)*

In order to ensure stablilty operation of the power systems, power grid operation guide in China[10]: frequency deviation of power systems under normal operating conditions below the limit value of 0.2Hz; when the systems capacity is small (<3000MW), deviation limit value is relaxed to 0.5Hz. Therefore, SSFD of power systemswith high penetration wind power must lower than the limit value.

From eqn. (5), using the final value theorem, SSFD of power systems under load disturbance $\Delta P_L$ is calculated as

$$\Delta f_{ss} = \lim_{s\to 0} s\Delta f(s) = \frac{R}{(1\text{-}p)+DR}\Delta P_L \tag{10}$$

Eqn. (10) indicates that SSFD is proportional to load disturbance $\Delta P_L$ and penetration level $p$, inversely proportional to droop coefficient $R$ and damping factor $D$, no relative to inertia canstant $H$. From eqn. (10), wind power maxmium penetration level in the index of SSFD is expression as

$$p < 1 + DR - \frac{R}{\Delta f_{ss}}\Delta P_L \tag{11}$$

### C. *Maximum Frequency Deviation(MFD)*

When MFD is larger than 1Hz, the power systems automatic under-frequency load sheddingact[12], which reduces the reliability of power supply. Therefore, MFD of power systems under high penetration wind power must lower than the limit value.

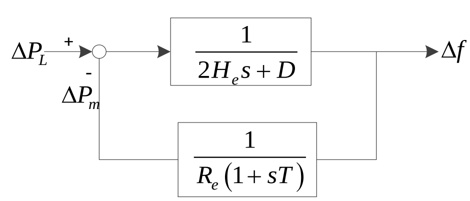



FIGURE II. FREQUENCY CONTROL MODEL OF POWER SYSTEMS WITHOUT WIND POWER FREQUENCY REGULATION

The eqn.(4) is substituted into figure 1, the simplified model of power systems frequency response is obtained[11], as shown in figure 2.the equations in the systems are:

$$2H_e\frac{d\Delta f(t)}{dt} + D\Delta f(t) = \Delta P_L - \Delta P_m(t) \tag{12}$$

$$TR_e \frac{d\Delta P_m(t)}{dt} + R_e \Delta P_m(t) = \Delta f(t) \quad (13)$$

The solution of eqn.(12) and (13) is:

$$\Delta f(t) = -\frac{\Delta P_L}{K}\left[1 - 2Ae^{-\alpha t}\cos(\omega t + \varphi)\right] \quad (14)$$

where,

$$K = D + \frac{1}{R_e} \quad ; \quad T_e = \frac{2H_e}{D} \quad ; \quad \alpha = \frac{1}{2}\left(\frac{1}{T_e} + \frac{1}{T}\right) \quad ;$$

$$\omega = \sqrt{\frac{K}{2H_e T} - \alpha^2} \; ; A = \frac{1}{4\omega H_e}\sqrt{\frac{K}{R_e}} \; ; \varphi = \tan^{-1}\left(\frac{K - 2H_e\alpha}{2H_e\omega}\right).$$

In order to found extreme point, the derivation of $\Delta f(t)$ is as follows:

$$\frac{d\Delta f(t)}{dt} = 0 \to t_{\min} = \frac{1}{\omega}\tan^{-1}\left(\frac{2\omega}{1/T_e - 1/T}\right) \quad (15)$$

The maximum frequency deviation occured at $t_{min}$, MFD is obtained as:

$$\Delta f_{\min} = -\frac{\Delta P_L}{K}\left[1 + 2Ae^{-\alpha t_{\min}}\cos(\omega t_{\min} + \varphi)\right] \quad (16)$$

To sum up, the maximum ROCOF depends on power systems equivalent inertia constant $H_e$, the SSFD depend on equivalent droop coefficient $R_e$, and the MFD with relative to the $H_e$and $R_e$. To improve wind power penetration level, the IRand PFR should be increased through other methods, such as wind plants or energy storage systems provide frequency regulation services.

## IV. Frequency Regulation Analysis of Power Systems with Wind Power Frequency Regulation

To improve frequency stability ofpower systems with high penetration wind power, VSWTGs provide short-time frequency regulation services through inertia control, which increases/decreases rotor speed to store /release kinetic energy to rapid response systems frequency change[13, 14]. The frequency regulation of wind plants as follows:

$$\Delta P_W = -2k_{df}\frac{d\Delta f}{dt} - k_{pf}\Delta f \quad (17)$$

where, $k_{df}$ is wind plants inertia constant, $k_{pf}$ is wind plants droop coefficient.

The wind plants frequency regulation power in laplace is

$$\Delta P_W(s) = -\left(2k_{df}s + k_{pf}\right)\Delta f(s) \quad (18)$$

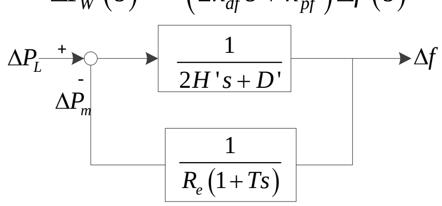



FIGURE III. FREQUENCY CONTROL MODEL OF POWER SYSTEMS WITH WIND POWER FREQUENCY REGULATION

The eqn.(18) is substituted into figure 1, and simple frequency control model of power systems with wind power frequency regulation is shown in figure 3.where

$$H' = H_e + p * k_{df} \quad (19)$$

$$D' = D + p * k_{pf} \quad (20)$$

The frequency regulation characteristics of power systems with wind power frequency regulation is obtained through substituting eqn.(19) and (20) into eqn. (9) and (11).

$$p < 1 - \frac{-H + \frac{1}{2}\Delta P_L / \left|df/dt\right|_{\max}}{\left(H - k_{df}\right)} \quad (21)$$

$$p < \frac{1 + RD}{1\text{-}Rk_{df}} - \frac{R\Delta P_L / \Delta f_{ss}}{1\text{-}Rk_{df}} \quad (22)$$

In order to integrate wind power penetration level $p$ in power systems, the wind plants frequency regulation controller parameters should be choosed as follows:

$$k_{df} > \frac{H(1-p) + \Delta P_L / \left|df/dt\right|_{\max}}{2p} \quad (23)$$

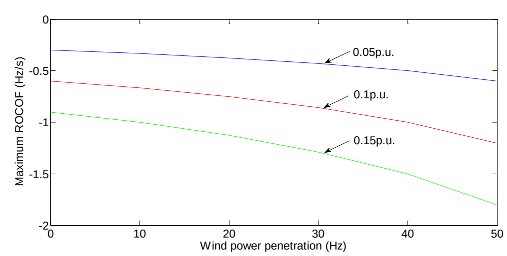
$$k_{pf} > -\frac{1 - p + RD}{Rp} + \frac{R\Delta P_L / \Delta f_{ss}}{Rp} \quad (24)$$

## V. Analysis and Validation

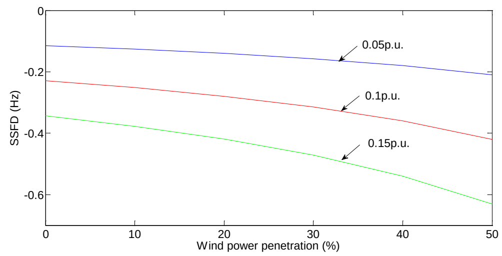
This paper takes a regional power grid in China in 2011 as an example to validate the theoretical analysis, the data package of the province power grid includes: H=4.16s, R=0.05, T=5.3s, D=1.9, $f_0$=50Hz. Frequency regulation indexes of power systems with/without wind power providing frequency regulation services is analyzed under a sudden load disturbance.

### *A. Frequency Regulation Analysis of Power Systems with Wind Power*

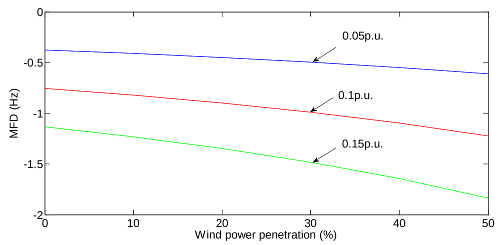
With wind power penetration level increasing, traditional generators are replaced by VSWTG without inertia response and primary frequency regulation, which deteriorates power systems frequency stability.Frequency regulation indexes (ROCOF, SSFD, MFD) of power systems with different wind power penetrations and load disturbance are shown in figure 4.




(a) Maximum ROCOF




(b) Steadystate frequency deviation(SSFD)



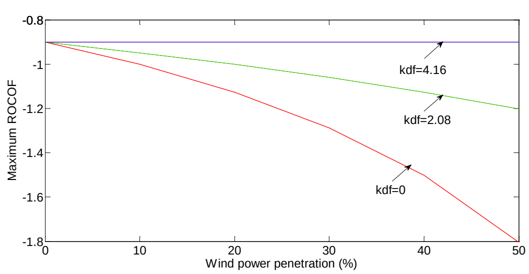

(c) Maximum frequency deviation

FIGURE IV. FREQUENCY REGULATIONANALYSIS OF POWER SYSTEMS WITH DIFFERENT WIND POWER PENETRATIONS AND LOAD DISTURBANCE

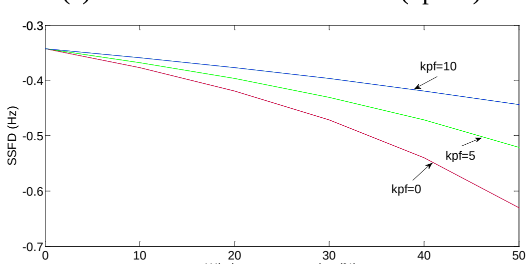
The ROCOF and frequency deviation are limited by Transmission Systems Operator (TSOs) to avoid generators equipped with ROCOF relay out of operation and UFSD action, such as the maximum ROCOF is 1Hz/s and the maximum frequency deviation is 1Hz. As seen from figure 4, the maximum wind power penetration is estimated about 30%, when the load disturbance is 0.10p.u.

### *B. Frequency Regulation Analysis of Power Systems with Wind Power Participating in Frequency Regulation*

In order to increase the wind power penetration, improve frequency stability of power systems, the wind plants are expected to providing short-term frequency regulation services.




(a) ROCOF with different kdf (kpf=0)




(b) SSFD with differentkpf (kdf=0)

FIGURE V. FREQUENCY REGULATION ANALYSIS OF POWER SYSTEMS WITH WIND POWER PARTICIPATING IN FREQUENCY REGULATION

The frequency indexes are improved by the wind plants providing inertia response and primary frequency regulation, when the load disturbance is 0.15p.u, asshown figure 5. According to the index of maximum ROCOF, Figure 5(a) indicates that the penetration level increases from 10% to 25%, when wind plants provide inertia response kdf=2.08s, which is half of traditional generators. Similarly, according to the index of SSFD, Figure 5(b) indicates that the penetration level increases from 35% to 45%, when wind plants provide primary frequency regulation kpf=5, which is a quarter of traditional generators.

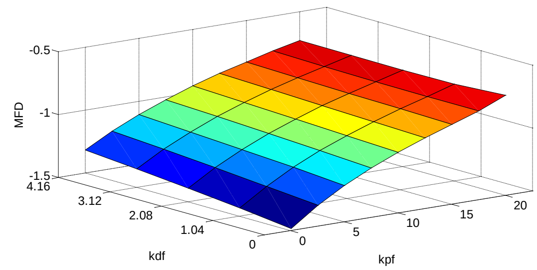



FIGURE VI. MFD WITH DIFFERENT VALUES OF KDF AND KPF

When load disturbance is 0.15p.u and the wind power penetration is 30%, the MFD with different values of kdf and kpf is shown figure 6. As the parameters of kdf and kpf increasing, the MFD is decreasing. When kdf is 2.08 and kpfis 10, the MFD is -0.981Hz (<-1Hz), which indicates the wind power penetration level reaches 30%, with wind plants providing half of frequency regulation capability of traditional generators, although the load disturbance is 0.15p.u..

## VI. CONCLUSION

This paper established power systems frequency control model considering high penetration level of wind power integration. The frequency regulation indexes such as maximum ROCOF, SSFD and MFD were compared with and without wind plants providing inertia response and primary frequency regulation services.Then the choice basis of wind plants frequency regulation parameters is obtained by the limit value of ROCOF and frequency deviation required by TSOs. A regionalpower grid wastakento verify the theoretical analyses, and the results indicate that wind plants with frequency regulation can improve power systems frequency stability and power quality.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] TANG Xisheng, MIAO Fufeng, QI Zhiping, Survey on frequency of wind power[J]. *Proceedings of the Chinese Society for Electrical Engineering*, 34 (25): 4304-4314, 2014.

[2] F. Díaz-González, M. Hau, A. Sumper, O. Gomis-Bellmunt, Participation of wind power plants in systems frequency control: Review of grid code requirements and control methods. *Reviews Renewable and Sustainable Energy*, 34(6), pp. 551-564, 2014.

[3] A. B. T. Attya, T. Hartkopf, Control and quantification of kinetic energy

released by wind farms during power systems frequency drop. *IET Renewable Power Generation*, 7(3), pp. 210-224, 2013.
[4] I. D. Margaris, S. A. Papathanassiou, N. D. Hatziargyriou, A. D. Hansen, P. Sorensen, Frequency Control in Autonomous Power Systems With High Wind Power Penetration. *IEEE Transactions on Sustainable Energy*. 3(2), pp. 189-199, 2012.
[5] J. Ekanayake, N. Jenkins, Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. *IEEE Transactions on Energy Conversion*, 19(4), pp. 800-802, 2004.
[6] M. F. M. Arani, Y. A. R. I. Mohamed, Analysis and Impacts of Implementing Droop Control in DFIG-Based Wind Turbines on Microgrid/Weak-Grid Stability. *IEEE Transactions on Power Systems*, 30(1), pp. 385-396, 2015.
[7] J. M. Mauricio, A. Marano, A. Gomez-Exposito, J. L. Martinez Ramos, Frequency Regulation Contribution Through Variable-Speed Wind Energy Conversion Systems. *IEEE Transactions on Power Systems*, 24(1), pp. 173-180, 2009.
[8] DING Li, QIAO Ying, LU Zongxiang. Impact on frequency regulation of power systems from wind power with high penetration [J]. Automation of Electric Power Systems, 38(14), pp. 1-8, 2014.
[9] P. Kunder. Power Systems Stability and Control. McGraw-Hill, 1994.
[10] GB/T 15945-2008, Power Quality Frequency Deviation for power systems.
[11] P. M. Anderson, M. Mirheydar, A low-order systems frequency response model. *IEEE Transactions on Power Systems*, 5(3), pp. 720-729, 1990.
[12] DL/T 428-2010, Technical rules for power systems automatic under-frequency load shedding.
[13] J. Morren, S. W. H. de Haan, W. L. Kling, J. A. Ferreira, Wind turbines emulating inertia and supporting primary frequency control. *IEEE Transactions on Power Systems*, 21(1), pp. 433-434, 2006.
[14] Y. Wang, G. Delille, H. Bayem, X. Guillaud, B. Francois, High Wind Power Penetration in Isolated Power Systems- Assessment of Wind Inertial and Primary Frequency Response. *IEEE Transactions on Power Systems*, 28(3), pp. 1-9, 2013.