Wind power grid-connected frequency regulation strategy based on ESO control and PI control

Maoda Xu 1, Hui Yang 2*, Wenbo Hao 1, Xiaoyang Zhao 2 and Siyao Yu 2

1 Electric Power Research Institute, State Grid Heilongjiang Electric Power Company, Harbin, Heilongjiang, 150030, China
2 Institute of electrical engineering, Northeast Electric Power University, Jilin, Jilin, 132012, China
*Corresponding author’s e-mail: yhneepu@163.com

Abstract: Frequency fluctuation of wind power grid-connected system is difficult to adjust, aiming at this problem, this paper proposed a control strategy based on the combination of inner loop control and outer loop to restrain frequency fluctuation. Extended state observer (ESO) is used as the outer loop. The error and disturbance which cannot be reflected directly in the system structure are estimated by linearization. The inner loop PI controller is designed through the parameters of proportional link and integral link to realize the reasonable allocation of internal model poles and achieve better damping effect. Simulation show that the control strategy can effectively suppress the system frequency fluctuation caused by load fluctuation and maintain frequency stable. The research results can be used to guide engineering practice.

1. Introduction
Large-scale wind power integration brings problems such as standby, inertia weakening and frequency stability to the power grid, making wind power auxiliary frequency adjustment a research hotspot [1]. At present, grid companies in many countries in the world require wind turbines to provide auxiliary services to grid frequency modulation like regular units, and participate in grid frequency adjustment [2-4]. Aiming at the support frequency control technology of large-scale new energy power stations, the literature [5] proposed a wind turbine multi-model predictive control (MMPC) FM control strategy based on model predictive control (MPC) technology. The control strategy of wind and thermal power bundling and characteristics of active power emergency control is given in [6]. The literature [7-8] using variable-gain linear quadratic Gaussian control to adjust the PI parameters. However, when wind speed changes, PI control cannot consider system-specific constraints and accommodate good coordinated control between active and rotational speeds. In view of this, the ESO control is used as the outer loop control, and the PI control is used as the inner loop control in this paper. The combination of the two controls the frequency control of the wind power grid-connected power system, to control system frequency.

2. the relationship between load balance and frequency
The P-Q decomposition method power flow calculation formula is:

$$\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
H & 0 \\
0 & L
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta U / U
\end{bmatrix}$$

(1)
Considering that the resistance component and the reactance component of the medium-high voltage power grid are far apart, the equation (1) can be decoupled as:

$$\Delta P = H \Delta \delta$$

(2)

Equation (2) includes both the power supply node and the non-power supply node, and the two are differentiated:

$$\begin{bmatrix}
\Delta P_G \\
\Delta P_L
\end{bmatrix} =
\begin{bmatrix}
H_{GG} & H_{GL} \\
H_{LG} & H_{LL}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_G \\
\Delta \delta_L
\end{bmatrix}$$

(3)

Where $\Delta P_G$ present the generator power increment, $\Delta P_L$ present the load active increment, $\Delta \delta_G$ present the generator node power angle, $\Delta \delta_L$ present the load node angle.

Assuming that the mechanical power of the generator is constant and ignoring the generator damper winding, the relationship between generator power and rotor angle can be derived from the rotor equation of the generator:

$$\Delta P_{gi} = \delta^2 T_{ji} \Delta \delta_{gi}$$

(4)

The expression of the matrix form of equation (4) is:

$$\Delta P_G = T_{ji} \Delta \delta_G$$

(5)

According to the first-row sub formula in the synthesis (5) and formula (3), it can be concluded that the relationship between the angle of the non-power supply node and the generator variable is as follows:

$$\Delta \delta_L = H_{GL}^{-1}(T_{ji} - H_{GG}) \Delta \delta_G$$

(6)

According to the second sub formula in the synthesis formula (6) and formula (3), it can be concluded that the relationship between the power increment of the load node and the generator variable is as follows:

$$\Delta P_L = [H_{LG} + H_{LL} H_{GL}^{-1}(T_{ji} - H_{GG})] \Delta \delta_G$$

(7)

Synthetic equations (6) and (7) can be concluded that the relationship between load node increments and non-power nodes is:

$$\Delta P_L = [H_{LG} + H_{LL} H_{GL}^{-1}(T_{ji} - H_{GG})] (T_{ji} - H_{GG})^{-1} H_{GG} \Delta \delta_L$$

(8)

Deriving the right side of equation (8) leads to the relationship between generator frequency and load disturbance.

It can be seen from equations (7) and (8) that after the grid load is disturbed, the grid frequency will change. When it is necessary to maintain the stability of the grid frequency, it is necessary to adjust the power output of the grid in time according to equation (7), so a reasonable control strategy is designed to achieve grid frequency stability.

3. Non-synchronous machine type electrical equipment equivalent inertia

The electrical equipment such as wind power, photovoltaic is different from the structure of the synchronous machine, and does not have a clear physical relationship between the rotor and the inertia. Therefore, the corresponding equivalent inertia $J_e$ is required, and the corresponding definition is:

According to the conservation of physics, the electrical power energy of electrical equipment over a period of time is equivalent to the energy released by the acceleration of the $J_e$ mass from angular frequency $\omega_{t_i}$ to $\omega_{t_f}$:

$$\Delta E = \int_{t_i}^{t_f} (P_{ie} - P_e) dt = \frac{1}{2} J_e \omega_{t_f}^2 (t) - \frac{1}{2} J_e \omega_{t_i}^2 (t)$$

(9)

Where $P_{set}$ and $P_e$ present the source side input power set value and the grid side output power value of the power electronic interface device, respectively. $\omega_{t_i}$ (t) is the angular speed corresponding to the voltage frequency of the electrical equipment access point.

The equivalent inertia time constant $He$ of the power electronic interface device can be defined as $1/2J_e$ (J_e is the standard value) by referring to the inertia time constant of the synchronous unit.
It must be pointed out that the differential form (10) does not necessarily exist. Because the inertia \( J_e \) of the power electronics interface is a variable control parameter. Considering that there will be a sudden change, and equation (10) will have parameter perturbation and model simplification neglect, extract the perturbed component of equation (10) and rewrite equation (10) as follows:

\[
\frac{1}{2} J_e \omega_e \frac{d\omega_e}{dt} = P_{set} - P_c + w
\]

Where: \( w \) is the disturbance caused by the parameter disturbance and the model correction part. Define the dummy variable \( v \) and rewrite equation (11) as:

\[
\frac{1}{2} J_e \omega_e \frac{d\omega_e}{dt} = v
\]

Referring to the common PI controller, the control variables are rewritten in the differential and integral form of \( \omega_e \) as follows:

\[
\frac{1}{2} J_e \omega_e \frac{d\omega_e}{dt} = K_p \Delta \omega_e + K_i \int_{0}^{t} \Delta \omega_e dt
\]

With the appropriate \( K_p \) and \( K_i \) parameters, \( \omega_e \) can obtain better damping effect and the frequency can be stabilized quickly.

The corresponding second-order ESO is constructed for equation (13) as shown in the following equation:

\[
\begin{align*}
\dot{m}_1 &= m_2 - \beta_0 f_e(m_1 - \omega_e, \alpha, \delta) + b_P \omega_e \\
\dot{m}_2 &= -\beta f_e(m_1 - \omega_e, \alpha, \delta)
\end{align*}
\]

Take the control amount: \( u = (-m_2 + v)/b_0 \), where \( m_1 \) is the estimated value of \( \omega_e \), \( m_2 \) present the expansion variable, which is used for estimate \(-P_c + w\).

The expression of the nonlinear function \( f_e \) in equation (12) is:

\[
f_e(e, \alpha, \delta) = \begin{cases} 
\frac{e}{\delta^{\alpha-1}}, & |e| \leq \delta \\
|e|^\alpha \text{sign}(e), & |e| > \delta
\end{cases}
\]

As shown in Figure 1, the control strategy designed in this paper is mainly divided into two parts, inner loop control and outer loop control. The outer ESO of the outer ring performs feedback linearization. The error and disturbance components in the system structure that cannot be directly reflected in equation (11) are estimated by ESO, and then feedback linearization is performed, so that mode (11) is directly converted to linear after ESO feedback model. The inner loop is a PI controller, which mainly realizes the rational configuration of the poles of the internal model through the parameter design of the proportional link and the integral link, thereby achieving better damping effect. The parameters of ESO, PI and other controllers need to be designed and adjusted when working in different conditions.

4. Simulation analysis
In order to verify the theoretical control effect of this paper, as is shown in figure 2, a 29-bus power system is built in matlab/Simulink.

The parameters of the PI controller are: integral link coefficient \( k_i = 1 \), proportional link coefficient \( k_p = 5 \). The main parameters of the ESO parameters are as follows:

\[
\beta_{01} = 3000, \alpha_1 = 0.25, \delta = 0.001; \beta_{02} = 3, \alpha_1 = 0.5, \delta = 0.001
\]
4.1 Short-circuit fault effect verification
A three-phase short-circuit fault is added to the 735kV grid line side near node 7, and the fault duration is 0.005s.

The control input signal is the 25kV bus frequency of the fan outlet, and the output is the active power of the fan. The effect of adding the controller and not adding the controller is verified. The specific effect is shown in Figure 2.

Figure 2 29-Bus power system

It can be seen from Fig. 3 that after adding the control method proposed in this paper, the 25kV voltage bus frequency fluctuation after the fault is improved, which is beneficial to the system frequency stability. However, since the wind farm has a capacity of only 9 MW, the space that can be improved is limited, and the system frequency oscillation cannot be quickly suppressed. For the actual power grid, the wind farm is distributed and the coordinated control of multiple wind turbines will play a more important role in system frequency stability.

4.2 Load fluctuation disturbance effect verification
At the time of 1 s, the load is cut off by 30 MW, the load is restored at 1.42 s, and the bus voltage frequency of the wind farm is extracted at 25 kV. The specific waveform is shown in Figure 3.
It can be seen from Fig. 4 that when the bus frequency changes greatly during load shedding and input, comparing the 25kV bus voltage frequency curve in the two cases, the curve of the method in this paper has less frequency fluctuation during load fluctuation, under load. The frequency drop curve after the fluctuation is also slower, indicating that the addition of the control strategy effectively suppresses the system frequency fluctuation caused by the load fluctuation and maintains the frequency stability of the system.

5. Conclusion
This paper considers the frequency control effect of ESO and wind power, and applies it to grid frequency regulation, which provides a new idea for system frequency research. The main conclusions of the article are as follows:

1) The input of the control strategy has a certain inhibitory effect on the system frequency fluctuation, and the design of a reasonable control strategy can suppress the system frequency oscillation.

2) Due to its adjustable range and speed, wind power is superior to synchronous generators, and has certain technical advantages in grid frequency regulation. Designing reasonable control strategies and control parameters is conducive to the reasonable adjustment of the grid frequency.

Acknowledgement
This work was supported by Scientific Research Project of Heilongjiang Academy of Electric Power Sciences of State Grid (SGHLDK00DWJS1800199) and Jilin Province Outstanding Young Talents Foundation Project of China (20180520067JH).

References
[1] Jiao, J. (2015) Research on response characteristics and control method of DFIG under grid frequency fluctuations [D] Yanshan University, 2015.
[2] Weng Y.X, Deng C.H, Huang W.T, et al. (2013) Research of CPS based on statistical theory for interconnected power grid with wind power [J]. Electric Power Automation Equipment, 33(12):79-84.
[3] Tang X.S, Miao F.F, Qi Z.P, et al. (2014) Survey on frequency control of wind power [J]. Proceedings of the CSEE. 34(25):4304-4314.
[4] Fu Y, Wang Y, Zhang X.Y, et al. (2014) Analysis and Integrated Control of Inertia and Primary Frequency Regulation for Variable Speed Wind Turbines [J]. Proceedings of the CSEE.34(27):4706-4716.
[5] Li C. (2015) Coordinated control strategy of weakly-synchronized grid containing large wind farms [D].Shandong University.
[6] Xing Z. (2014) Research on active power control among wind farms under emergency of power system [D].North China Electric Power University.
[7] Munteanu I, Bratcu A I, Cutululis N A, et al. (2008) Optimal Control of Wind Energy Systems: Towards a Global Approach[M]. Advances in Industrial Control, 2008.

[8] Liu X, Li K, Sun J, et al. (2015) Generalized predictive control based on extended state observer permanent magnet synchronous motor system [J]. Control Theory and Applications, 2015, 32(12):1613-1619.