Load-Frequency Control Strategy of Power Grid with High Penetration Wind Power Based on Active Disturbance Rejection Control

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Abstract. After large-scale wind power is integrated to the grid, the randomness and uncertainty of wind power will cause problems of active power imbalance and frequency fluctuations, which puts forward higher requirements for load-frequency control of power grids with wind power integrated. Based on the analysis of the load-frequency control system of power grids with wind power integrated, a novel load-frequency control model based on active disturbance rejection control considering random fluctuating wind energy is proposed. The simulation results show that not only the proposed model can effectively maintain the system frequency, but also the control effect is significantly better than the conventional PI load-frequency controller.

1. Introduction
As the fast growing of clean energy, the use of large-scale wind power has shown obvious social and environmental benefits[1-2]. Wind power output has strong uncertainties and is difficult to predict, making large-scale wind power integration into grids a challenge to the safety and stability of power system operation[3]. The system frequency based on active power balance is most significantly affected by the uncertainty of the wind turbines’ active power output, which also places higher requirements on the load frequency control of the power grids with wind power[4-5]. Different from the traditional power generation form, the controllability of wind power active power output is poor. Although studies have shown that the control of wind power active output can be achieved through paddle angle control[6-7], it is difficult to accurately predict and control the motive power of wind turbine, which makes the adjustment range of wind turbine active power output very limited. At the same time, the active decoupling control is often adopted on existing main wind turbines (dual-fed induction wind turbines and permanent magnet synchronous wind turbines), which cannot effectively track the frequency change on the grid side. Reference [8] superimposed the wind turbines’ active power output into the regional control deviation signal, and reflected the influence of wind power uncertainty on the system load frequency control through the change of Area Control Error (ACE) signal. It makes the design of load-frequency controller based on this model more difficult. In [9], based on the dynamic trajectory of a conventional generator set, the automatic power generation control of a high-penetration wind power integrated power grid based on full-state time-domain simulation is designed and implemented, but the proposed control method does not take into account the ACE signal, which has certain limitations.

Active Disturbance Rejection Control (ADRC) is a theory that is a combination of nonlinear PID, tracking differentiator, and extended state observer. ADRC has better performance and stability than the classic feedback control[10].
The wind farm active power fluctuation is introduced as a random term into the load-frequency control model of wind power integrated power grid in this paper. Based on that, a load-frequency control model for a typical independent power grid that takes the wind farm active power output fluctuation into account is proposed. The simulation of the control model for a power system with high-penetration wind power is carried out to demonstrate the effectiveness of the model.

2. Load-frequency control model for power grid with wind power integrated
A complete power grid Load-Frequency Control (LFC) dynamic model includes governor, prime mover, generator set and load. Based on this, a LFC model for an independent power grid is established. The system hybrid dynamic model is shown in Figure 1. This system is mainly powered by steam power plants with wind farms as supplement.

![Figure 1. Load-frequency control model of an independent grid with wind power.](image)

The power system load model are shown in the figure. Its output is the frequency. The wind farm is introduced into the power system as a randomly varying load, merged with different prime movers, and finally acts on the power system. In order to stabilize the output power-frequency, feedback is added to the controller, and the power frequency of the system is stabilized through the design of the controller.

In an independent power grid system, frequency control only needs to control the frequency deviation of the region itself. Usually, the area control error (ACE) is used as the input of the power-frequency controller. Its linear combination formula is:

$$ACE = \beta \Delta f$$  \hspace{1cm} (1)

3. Optimized design of secondary frequency modulation controller
For the power frequency control of most power grids, multi-channel PID control is still used to ensure the stability of the frequency. However, the traditional multi-channel method has many limitations on performance, such as low control efficiency and slow response speed[11-12].

3.1. Linearized Active Disturbance Rejection Control
In order to overcome the shortages of low control efficiency and slow response speed, new control technology should be employed in the load-frequency control system for wind turbine integrated power system. The application of ADRC theory can effectively improve the control frequency response, meanwhile, it has strong anti-interference ability and finer control.

There are many uncertainties and disturbances in the control system for the wind power integrated power grid. The state of uncertainty, and disturbances as well as other states can be estimated in real time through the extended state observer, and fed back to the controller for further controlling the system to eliminate disturbances. In this way, grid output frequency can be stabilized[13].

However, in general ADRC theory, there are many control parameters which are difficult to be adjust. In order to meet the power frequency control requirements of the grid, ADRC can be simplified with linearization. The simplified ADRC framework with Linearized Extended State Observer (LESO) and controller, named as Linearized Active Disturbance Rejection Control (LADRC), is shown in Figure 2, where \(b_0\) is the compensation coefficient.
3.2. Model integration
With LADRC, the complete specific models of the controlled object and the disturbance are not necessary. The only requisite three related parameters are observer bandwidth, controller bandwidth and system gain estimates. The controlled object with disturbances in the wind power integrated grid can be expressed as:

\[ Y(s) = G(s) \cdot U(s) + D(s) \]  

where \( Y(s) \) is the system output, \( U(s) \) is the system input, \( D(s) \) is the aggregate of uncertainty and internal and external disturbances, and \( G(s) \) is the system transfer function.

According to [14], a second-order time-domain model is adopted:

\[ \dot{y} = -a\dot{y} + by + w_e + bu \]  

where \( u \) and \( y \) represent the input and output of the whole system respectively, \( w_e \) is the sum of all external disturbances, parameters \( a \) and \( b \) are designed parameters, and \( b=b_0 \) is generally set. Then rewrite equation (3) as:

\[ \dot{y} = -a\dot{y} + by + w_e + (b-b_0)u + b_0u \equiv f + b_0u \]  

Among them, \( f = -a\dot{y} + by + w_e + (b-b_0)u \) is recorded as the aggregate of system uncertainty and internal and external interference

Take state \( x = [x_1 \ x_2 \ x_3]^T = [y \ \dot{y} \ f]^T \). Then \( x = [y \ \dot{y} \ f]^T \) is the extended state including the disturbance, so one gets a continuous extended state space description:

\[
\begin{aligned}
\dot{x} &= Ax + Bu + E \dot{f} \\
y &=Cx
\end{aligned}
\]  

Among them, \( A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix} \), \( E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \), \( C = [1 \ 0 \ 0] \).

3.3. Linearized Extended State Observer (LESO)
The equation of the second-order LESO is:

\[
\begin{aligned}
\dot{z}_1 &= z_2 - \beta_1(z_1 - y) \\
\dot{z}_2 &= z_3 - \beta_2(z_2 - y) + b_0u \\
\dot{z}_3 &= -\beta_3(z_3 - y)
\end{aligned}
\]  

where \( L = [\beta_1 \ \beta_2 \ \beta_3] \) is the gain vector of LESO. The characteristic equation of the system is:
The parameters $\beta_1$, $\beta_2$, and $\beta_3$ are set to $3\omega_0$, $3\omega_1^2$, and $\omega_0^3$, so that the characteristic equation of the system is rewritten as $(s + \omega_0)^3 = 0$, which makes the system stable and quickly adjustable. The value of $\omega_0$ needs to be set according to the system bandwidth.

3.4. Linear state error feedback

Although non-linear state error feedback control may perform better in general, based on the ADRC method, the linear state error feedback control, namely PID technology, can also achieve good results[13]. Therefore, in order to simplify the design of the ADRC controller, the classic PID combination can be used to implement the controller design. Since extended state observer can estimate and compensate for external and internal disturbances in real time, traditional PID are used to eliminate static differences under constant disturbances. The integrator is no longer necessary, and the linear state error feedback control is further simplified to the design of the PD combination. For a second-order system with LESO, the linear ADRC can use a PD controller as:

$$u_0 = k_p (r - z_1) - k_d z_2$$

(8)

In the above formula, $r$ is a given value, $k_p$ is the proportional coefficient in PD control, and $k_d$ is a differential coefficient in PD control, $Z_1$ and $Z_2$ are the observer states from LESO.

4. Simulation analysis

4.1. Simulation parameters

In order to verify the effectiveness of the proposed ADRC-based control method in the control of wind power frequency, a simulation study is performed in this paper. The block diagram of the load-frequency control model of the independent grid shown in Figure 1 is simulated. The parameters of this grid are shown in Table 1.

| Generator | G |
|-----------|---|
| rated power/MW | 800 |
| $R/(\text{Hz} \cdot \text{p.u.}^{-1})$ | 2.4 |
| $T_t$ | 0.36 |
| $T_g$ | 0.06 |
| $\beta/(\text{p.u.} \cdot \text{Hz}^{-1})$ | 0.8675 |

In this paper, the control effect of the proposed ADRC controller is compared with that of a Proportional Integral (PI) controller.

4.2. Example analysis

4.2.1. Wind power fluctuates randomly. Considering the random fluctuation of wind power, the wind power deviation value used is the wind power deviation generated according to the generation method in [8]. The deviation between the generated wind power and the predicted value is shown in Figure 3.
Using the power grid frequency control deviations and LADRC control strategies that take into account the wind power fluctuations established in this paper to simulate the dynamic frequency process of the system under the random fluctuations of wind power shown in Figure 3, the power and frequency control response deviations are shown in Figure 4.

It can be seen from Figure 4 that when the wind active output fluctuates randomly in the power grid, the ADRC control strategy proposed in this paper can well estimate and eliminate wind power fluctuations, provide a better control effect for the AGC unit in this area, and can effectively suppress power frequency deviation caused by wind rate deviation. However, in the conventional PI control strategy, the system frequency recovery speed is slow and the system frequency variation range is large. The PI control strategy cannot keep the system frequency within the safe operating limit and cannot guarantee scale safe and stable operation of the system after the wind farm / group is connected to the grid.

4.2.2. Wind power and load fluctuations coexist. In order to further verify the effectiveness of the LADRC control strategy for power-frequency control of the power grid, the system frequency fluctuations under the conditions of both wind power fluctuations and load fluctuations were analyzed through simulation.

In this working condition, a step load of 0.02 is added to the independent grid at 80s, and the standard deviation of the load deviation is shown in Figure 5. The grid wind power deviation standard value is as shown in Figure 3. The simulation results in this case is shown in Figure 6.

The simulation results show that under the simultaneous input of wind power deviation and load surge mixed disturbance, the grid frequency fluctuates little under the action of ADRC, and the control effect of the conventional PI controller cannot guarantee that the frequency is within the safe operating range. From the simulation results shown in Figure 6, it can be seen that the ADRC control strategy proposed in this paper is also effective for load surge disturbances, and the control effects such as frequency deviation amplitude are significantly better than conventional PI control strategies.

5. Conclusion
Aiming at the problem of load-frequency control of the power grids with large-scale wind farms, an
independent load-frequency control model considering wind power fluctuations was established. Considering wind power fluctuations as a random term injecting into the traditional grid model, a control strategy based on the ADRC control algorithm was proposed.

The Simulation results show:

1) An independent grid load-frequency control model considering wind power fluctuations can truly reflect the impact of wind power fluctuations on the grid

2) ADRC-based power-frequency control strategy can effectively maintain the system frequency and power in a relatively small range, and its control effect is significantly better than the traditional PI control strategy.

Improving wind power prediction accuracy is another effective method to optimize the power-frequency control effect of large-scale wind farms integrated power grids. The ADRC load-control strategy proposed in this paper is based on wind power forecasting accuracy that can meet application requirements. The research and establishment of a high-precision wind power forecasting model suitable for the control strategy in this paper is a future research work.

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