Research on Intelligent Control of Photovoltaic Power Generation Fluctuation Based on Linear Active Disturbance Rejection

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Abstract: Nowadays, the output power of photovoltaic power generation fluctuates greatly, which endangers the safe and stable operation of the power grid. Therefore, a method for eliminating photovoltaic power generation volatility based on linear active disturbance rejection control is proposed in the paper. Moreover, through establishing the "anti-disturbance paradigm" model of the photovoltaic power generation system, the frequency scale transformation is introduced to design the linear expansion state observer is. Meanwhile, the linear expansion state observer output is converted too. Besides, proportional calculus controller is used for control, and parameter tuning is achieved through linear auto-disturbance rejection control technology to obtain optimal parameters, thereby completing the elimination of photovoltaic power generation volatility. The simulation experiment results show that when LADRC control is added, the phase A voltage fluctuation is small and the output current is relatively stable, which can effectively reduce the active power output by the photovoltaic power generation unit and improve the execution efficiency.

1 Introduction
Nowadays, the most important component of new energy is photovoltaic power generation. In actual operation process, if the grid line [1-2] fails, in order to effectively prevent the grid-connected inverter from being damaged, a trawling operation will be required. Moreover, with the continuous increase of the penetration rate in the photovoltaic power generation system, if the traditional control method is used, the voltage of the grid connection point will fluctuate greatly, and the stability of the system will be poor. Therefore, the grid-connected power system in the new grid code is required to have low voltage ride-through capability, which can provide support for the grid-connected point voltage during the system failure.

The traditional photovoltaic grid-connected power generation system mainly uses PID or an improved PID control method [3] for control. Although it can effectively eliminate fluctuations and reduce errors, it still has the following defects. For example,

(1) Assuming that the error is obtained by comparing the system output and the given value, the resulting error will be too large and it will be easy to cause overshoot;

(2) In the integral feedback link, the response speed of the system is greatly reduced, and PID control is a simple linear weighted control, which is not the best linear weighted combination.

The defects mentioned above will lead the photovoltaic power generation system to malfunction, which affects the overall performance of the system [4-5]. What is worse, it even destroys the protection device of the system, causing the system to go offline.
In order to overcome the shortcomings of linear PID, a method is proposed in the paper to eliminate the volatility of photovoltaic power generation according to linear active disturbance rejection control. Additionally, the specific simulation experiment data effectively verifies the effectiveness and superiority of the proposed method.

2 Linear Active Disturbance Rejection Control Strategy
The grid voltage $d$ axis is set as vector orientation [6], then the mathematical model in the grid-side converter $dp$ coordinate system can be expressed in the following form:

\[
\begin{align*}
C_{dc} \frac{du_{dc}}{dt} &= \frac{3}{2} \left( i_d s_d + i_q s_q \right) - i_0 \\
L_g \frac{di_d}{dt} + R_g i_d - \omega L_g i_q &= e_d - u_d \\
L_g \frac{di_q}{dt} + R_g i_q + \omega L_g i_d &= e_q - u_q
\end{align*}
\]

In the formula, $i_d$ refers to the current component of the $d$ axis; $i_q$ represents the $q$ axis current component; $e_d$ is the $d$ axis grid voltage component; $e_q$ indicates the $q$ axis grid voltage component; $u_d$ represents the $d$ axis converter side terminal voltage component; $u_q$ refers to the voltage component of converter side; $s_d$ indicates the switching function component of the $d$ axis; $s_q$ is the switching function component of the $q$ axis.

Linear active disturbance rejection control, instead of PI regulating controller is used in the paper to get better control effect and anti-disturbance. The following is a specific analysis.

3 Method for Eliminating Photovoltaic Power Generation Volatility Based on Linear Active Disturbance Rejection Control

3.1 Establishment of the "Anti-disturbance Paradigm" Model of Photovoltaic Power Generation System
According to the linear active disturbance rejection control strategy, the research on the "disturbance rejection paradigm" of the photovoltaic power generation system is focused on in the following content. What is more, the total disturbance of the system is set as an unknown state variable, and the ESO (Expanded State Observer) is used for estimation and testing. Meanwhile, the modeling problem is transformed into state estimation.

In order to facilitate the establishment of the anti-interference paradigm, the mathematical model of the three-phase photovoltaic grid-connected inverter is required to be transformed in the $dp$ coordinate system, then:

\[
\begin{align*}
C_{dc} \frac{du_{dc}}{dt} &= i_{dc} - \frac{u_{dc}}{R_L} \\
L_g \frac{di_d}{dt} + R_g i_d - \omega L_i q &= e_d - u_d \\
L_g \frac{di_q}{dt} + R_g i_q + \omega L_i d &= e_q - u_q
\end{align*}
\]

Since LADRC control is used for the voltage outer loop, it can be obtained by formula (2):
\[ C_{dc} \frac{du_{dc}}{dt} + \frac{u_{dc}}{R_L} = i_{dc} \]  

(3)

Through the conservation principle of the active power on the DC side and AC side of the inverter, the following calculation formula can be obtained:

\[ u_{dc}i_{dc} = \frac{3}{2}e_i i_d \]  

(4)

Perform modification on formula (4), and the following calculation formula can be obtained:

\[ i_{dc} = \frac{3}{2u_{dc}}e_i i_d \]  

(5)

Substitute formula (3) into formula (5), then:

\[ C_{dc} \frac{du_{dc}}{dt} + \frac{u_{dc}}{R_L} = \frac{3}{2u_{dc}}e_i i_d \]  

(6)

Dividing the left and right sides of formula (6) by \( C_{dc} \), the following formula can be obtained:

\[ \frac{du_{dc}}{dt} + \frac{u_{dc}}{R_L C_{dc}} = \frac{3e_i}{2C_{dc}} i_d \times \frac{1}{u_{dc}} \]  

(7)

Knowing from the above formula, there must be a variable \( \omega(t, u, x_i) \), which makes \( \frac{3e_i}{2C_{dc}} i_d + \omega(t, u, x_i) \). In addition, \( u \) represents the control variable, and \( x_i \) is the state variable, namely the output variable. Then the formula (7) can be equivalent to the following form:

\[ \frac{du_{dc}}{dt} = \frac{u_{dc}}{R_L C_{dc}} + \frac{3e_i}{2C_{dc}} i_d + \omega(t, u, x_i) \]  

(8)

If the control output is \( y = x_i = u_{dc} \), \( b = \frac{3e_i}{2C_{dc}} \), and \( \frac{u_{dc}}{R_L C_{dc}} \) is included in \( \omega(t, u, x_i) \), the above formula can be converted into the following form:

\[ \dot{y} = \omega(t, u, x_i) + bi_d \]  

(9)

Through the above analysis, it can be seen that the voltage outer loop output is used as the given value \( i_d^* \) of the inner loop current, which is the output control chain of LADRC. Therefore, \( i_d \) in equation (9) can be set as the given value of the inner loop current, namely

\[ i_d \text{ represents the external disturbance received during the operation of the photovoltaic system, and } i_d^* \text{ refers to the control quantity } u \text{. Converting formula (10) into the "anti-disturbance paradigm" model of the photovoltaic power generation system, there will be:} \]

\[ \begin{cases} \dot{y} = f(t, u, x_i) + bu \\ y = x_i \end{cases} \]  

(11)

3.2 Obtain Optimal Parameters

Although the nonlinear active disturbance rejection controller can eliminate the volatility of photovoltaic power generation, the internal structure of the controller is too complicated, which leads to a substantial increase in the overall workload of the system, making it seldom used in actual projects.
Considering the shortcomings mentioned above, the frequency scale transformation is introduced according to the establishment of the "disturbance-resistance paradigm" model of the photovoltaic power generation system, and a set of LADRC parameters are correlated with the controller frequency as well [9-10]. Meanwhile, the parameter tuning is achieved through LADRC technology, so that a very satisfactory control effect is obtained. In addition, the simplified active disturbance rejection controller mainly consists of three parts, namely:

(1) Linear extended state observer;
(2) Linear PD combination;
(3) Disturbance compensation link.

The controlled object of the photovoltaic system is expressed as:

$$\dot{y} = f(y, \dot{y}, \ddot{y}, \omega, t) + bu(t) = -a_2\ddot{y} - a_1\dot{y} - a_0y + \omega + bu$$  \hspace{1cm} (12)

In the above formula, $f(y, \dot{y}, \ddot{y})$ represents the unknown function; $b$ refers to the control gain; $u(t)$ indicates the control input; $\omega(t)$ is the unknown disturbance. Rewrite the items mentioned above, then:

$$\ddot{y} = -a_2\ddot{y} - a_1\dot{y} - a_0y + b + (b - b_0)u + b_0u = f + b_0u$$  \hspace{1cm} (13)

The parameters in the linear active disturbance rejection controller are parameters to be tuned, and the changes in the control parameters of different parts in the controller will affect the control effect of the system to varying degrees. The specific steps are summarized as follows:

(1) Calculate $b_0$ through system nominal parameters.

(2) Determine the multiple relationship between ESO bandwidth $\omega_b$ and $\omega_c$;

(3) Choose one $\omega_b$ and $\omega_c$ for each group, and set the parameters according to the previous principle;

(4) Increase $\omega_b$ and $\omega_c$ according to the corresponding ratio. Reduce the value of $\omega_b$ and $\omega_c$ until the noise cannot withstand the system output fluctuation or vibration. Meanwhile, the dynamic performance and stability of the system should be considered.

(5) Appropriately reduce the values of different parameters, but increase $\beta_4$ until the closed-loop dynamic performance of the system reaches the desired state of the system without overshooting. Meanwhile, record the parameters set by the current $b_0$ value;

(6) Appropriately adjust the values of $k_p$, $k_d1$, and $k_d2$.

(7) Continuously adjust $b_0$ to obtain the corresponding value, and then follow the above operation process until a set of better parameters is obtained, so that the volatility of photovoltaic power generation can be eliminated.

4 Experimental Results and Analysis

4.1 Test Device and Parameter Setting

In order to verify the anti-disturbance and feasibility of the proposed method when eliminating photovoltaic power generation volatility based on linear active disturbance rejection control, simulation experiments are carried out through Matlab/Simulink simulation software. The experimental environment are Anaconda3.7, Python3.7 and Tensor Flow (2.0). In addition, some settings are as follows. The output power of the photovoltaic array under standard illumination is
approximately 40kW, the open circuit voltage of the photovoltaic cell is 650V, and the short-circuit current is 63.3A. Besides, the MPPT voltage is 530V, the MPPT current is 65A, and the DC bus capacitance is 2000μF. The PCC line voltage is 380V/ 50Hz, and DC unloading resistance is 21Ω. Additionally, due to the volatility of the controller frequency, it is difficult to achieve synchronous sampling. Therefore, a quasi-synchronous test system is adopted to select an appropriate sampling frequency according to the fast measured frequency, so that the data sampling can achieve quasi-synchronization.

4.2 Phase A Voltage

The phase A voltage on the grid side when LADRC control is not added is compared with the phase A voltage on the grid side when LADRC control is added in the paper. The comparison result is shown in Figure 1.

![Figure 1. Comparison result of A phase voltage](image)

According to the phase A voltage on the grid side when LADRC control is not added and the phase A voltage frequency on the grid side when LADRC control is added in the paper in Figure 1, it can be seen that the phase A voltage on the grid side fluctuates in the range of 780V~832V when LADRC control is not added. The impact is relatively large, and the A-phase voltage has an instantaneous spike due to the change of active power. However, when LADRC control is added in the paper, the voltage fluctuation of phase A on the grid side is small, which is within the controllable range of 790V~810V. The anti-disturbance performance is better.

4.3 Execution Efficiency

In order to further verify the effectiveness of the method proposed in the paper, it is necessary to compare the execution efficiency when LADRC control is not added with the execution efficiency when LADRC control is added in the method proposed in the paper. The specific experimental comparison results are shown in the following table:

| DC side voltage/(V) | Execution efficiency without LADRC control(%) | Execution efficiency when adding LADRC control(%) |
|---------------------|-----------------------------------------------|-----------------------------------------------|
| 25                  | 94.58                                         | 98.69                                         |
| 25                  | 92.85                                         | 98.69                                         |
| 50                  | 91.74                                         | 99.63                                         |
| 75                  | 90.25                                         | 99.77                                         |
| 100                 | 89.63                                         | 99.52                                         |
| 125                 | 88.52                                         | 99.14                                         |
| 150                 | 85.33                                         | 99.85                                         |
| 175                 | 94.58                                         | 99.10                                         |
According to the data in Table 1, the execution efficiency when LADRC control is added is up to 99.85%, while the execution efficiency when LADRC control is not added is only 94.58%. The execution efficiency when LADRC control is added is higher than that when LADRC control is not added. The high efficiency indicates that the photovoltaic power generation variability elimination effect of the method proposed in this paper is better.

4.4 Execution Efficiency under 60kW Output Power

When the output power of the photovoltaic array is approximately 60kW under standard illumination, the execution efficiency when the LADRC control is not added or when the LADRC control is added in the method proposed in this paper is respectively tested. The specific experimental comparison results are shown in Figure 2.

![Figure 2. Comparison results of execution efficiency at 60kW output power](image)

According to Figure 2, when the output power is 60kW, the execution efficiency without LADRC control is between 24% and 69%, and the curve fluctuates greatly. However, when LADRC control is added in the method proposed in this paper, the execution efficiency is relatively stable, which is between 87% and 90%. Therefore, a comprehensive analysis of the experimental data in the above table and the data in the figure shows that no matter the output power is 40kW or 60kW, the execution efficiency of the method proposed in this paper is higher when LADRC control is added, which improves the effect of eliminating the volatility of photovoltaic power generation, and the above experimental data is fully verified the superiority of the method proposed in the paper.

5. Conclusion

In order to improve the effect of eliminating the volatility of photovoltaic power generation, a method is proposed in the paper to eliminate the volatility of photovoltaic power generation based on linear active disturbance rejection control, which correlates the linear active disturbance rejection control parameters with the controller frequency, so that the linear active disturbance rejection control technology can be promoted to realize parameter tuning, thereby eliminating the fluctuation of photovoltaic power generation. What is more, the specific simulation experiment data shows that the method proposed in this paper has strong stability and practicability. However, due to time constraints, the method proposed in the paper still has certain drawbacks, which will be further improved in the future.

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