Application of Active Disturbance Rejection Controller in Three-Phase PWM Rectifier

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Abstract. For the three-phase voltage type PWM rectifier which is a strong nonlinear, a strong coupling and time-varying system, a double-loop control structure of DC voltage outer loop and current inner loop is designed to control it. In practice, the traditional PID controller is commonly used. However, it is relatively sensitive to changes in system parameters and the control effect is not ideal. This paper proposes to use the auto disturbance rejection control instead of the traditional PID control. The auto disturbance rejection controller is based on the improvement of the PID controller. It inherits the core concept of PID error feedback control. And it solves the problem of contradiction between response fastness and overshoot by using a processing method that arranges a transition process. I compare the results of the two controllers by simulation, which proves that the scheme of auto disturbance rejection control is more suitable for the PWM rectifier system than the traditional PID control. The auto disturbance rejection controller has better dynamics, stability, and faster response times.

1. Introduction

The three-phase voltage type PWM rectifier has the advantages of sinusoidal current on the grid side, bidirectional flow of energy, unity power factor operation, fast dynamic response, etc., and plays an important role in the wind power generation system[1] and the elevator energy feed system. In engineering practice, the double-loop control of the traditional PID controller is often used, including the voltage outer loop and the current inner loop. As a result, the current sinusoidal degree is low and the THD is less than ideal. Therefore, the PWM rectifier control strategy is still constantly searching, such as H_control[2], IDA-PB control[3], state feedback accurate pre-decoupling control[4] and repeat observer PWM rectifier deadbeat control[5]. This paper proposes the use of auto disturbance rejection control for three-phase voltage-type PWM rectifiers.

Since the introduction of active disturbance rejection control (ADRC) in the 1990s[6], due to its simple implementation and excellent control performance, it has been successfully applied to motor control, flight control and many other fields, and have received extensive attention to their control ideas. The ADRC consists of three modules, first is the tracking differentiator (TD), second is the extended state observer (ESO), and third is the nonlinear state error feedback control law (NLSEF)[7]. The real-time estimation of disturbance and compensation is the two most essential functions of the auto disturbance rejection controller[8][9], so any module that has these two functions can be called an auto disturbance rejection controller. Its control block diagram is shown in Figure 1:
2. Three-phase voltage type PWM rectifier

The main circuit of the three-phase PWM rectifier is shown in Figure 2. It consists of AC power $u$, equivalent resistance $R$, filtering and boosting reactor $L$, switching tube $S$, DC filter capacitor $C$ and load $RL$.

It can be seen that the transfer function of the PWM rectifier is: $G_p(s) = \frac{1}{T_p s + 1}$.

Where $T_p$ is the time constant of the rectifier.

3. Self-disturbance controller

3.1. Tracking differentiator

In general, the inertial link is used to track the dynamics of a given signal, while the approximate differential signal is acquired by integration. This structure is the tracking differentiator. In short, it is to give the same differential signal while tracking the input signal. In the ADRC controller, the tracking differentiator is mainly used to arrange the transition process.

The response speed and overshoot of the classic PID control will be contradictory, and in the auto disturbance rejection control, the transition process is used to solve this problem. The next step is how to achieve rapid and no overshoot by scheduling the transition process. The system order is closely related to the transition process characteristics of the system to the step response. Therefore, two factors should be considered when arranging the transition process. One is the various constraints of the system, and the other is the order of the system. How to arrange the transition process for the various levels of the system will not be repeated here.
3.2. Extended state observer
In a sense, the Extended State Observer (ESO) is a disturbance observer. It is to expand a variety of disturbance variables into new state variables, and then construct a viewable expansion through its unique feedback mechanism status.

The extended state observer only uses the input and output information of the object, and does not use any information about the transfer function. The ESO structure diagram is shown in Figure 3.

![Figure 3. Structure diagram of the extended state observer.](image)

The extended state observer uses the input and output information of the object, and does not use any information about the transfer function. The ESO structure diagram is shown in Figure 3.

The error integral feedback applied in the classical PID control proves that the effect of suppressing the constant value disturbance is significant, but the cost is that the delay of the closed loop system becomes longer, the oscillation increases, and the control amount saturates. In order to solve these problems, we choose to replace the error integral feedback function by other means, that is, use ESO to estimate the sum of the disturbances received by the system and to estimate compensation it. This disturbance estimation compensation method is very good for reducing the constant value disturbance. The effect can also reduce the effects of other forms of disturbance.

In terms of disturbance suppression, if a disturbance acts on the system, it does not affect the output of the system. For the output signal, this type of disturbance does not need to be suppressed. If a disturbance can affect the controlled output that can be detected visually, then information about the disturbance must be included in it, so the disturbance acting on the system must be inversely derived from the obtained controlled output. This is how ESO works to estimate system disturbances.

3.3. Nonlinear state error feedback control law
The nonlinear combination component takes the error based on two signal estimates, one is to track the differentiator output signal, and the other is the state variable given by the extended state observer, thereby forming a state variable error. The control quantity is composed of the nonlinear feedback of the state variable error and the disturbance estimation compensation amount.

The state error of the system refers to \( e_1 = v_1 - z_1 \), \( e_2 = v_2 - z_2 \), and the control law \( u_0 \), which is the error feedback law, for controlling the pure integrator series object determined according to the errors \( e_1, e_2 \). The final control amount is determined by the compensation of the error feedback control amount \( u_0 \) with the disturbance estimation value \( z_3 \).

\[
 u = u_0 - \frac{z_3}{b_0} \text{ or } u = \frac{u_0 - z_3}{b_0}
\]  

(1)

Among them, \( b_0 \) is a "compensation factor" used to control the strength of the final control amount compensation, and is used as an adjustable parameter.

4. Auto disturbance rejection controller
The complete algorithm of the implementation process of the ADRC with real-time estimation of disturbance and compensation is divided into 4 steps:

1) Arrange the transition process with the set value \( v_0 \) as input.

\[
 e = v_1 - v_0 
\]  

(2)

\[
 f h = fhan(e, v_2, r_0, h)
\]  

(3)

\[
 v_1 = v_1 + hv_2 
\]  

(4)
\[ v_2 = v_2 + hf \]

2) Track system state and disturbance with system output \( y \) and input \( u \).

\[ e = z_1 - y \]
\[ f e = fal(e, 0.5, \delta) \]
\[ fe_1 = fal(e, 0.25, \delta) \]
\[ z_1 = z_1 + h(z_2 - z\beta_{01}e) \]
\[ z_2 = z_2 + h(z_3 - \beta_{02}fe + b_0u) \]
\[ z_3 = z_3 + h(-\beta_{03}fe_1) \]

Where \( \beta_{01}, \beta_{02}, \beta_{03} \) are a set of parameters.

3) State error feedback law

\[ e_1 = v_1 - z_1, e_2 = v_2 - z_2 \]
\[ u_0 = k(e_1, e_2, p) \]

Where \( p \) is a set of parameters.

4) Disturbance compensation process

\[ u = u_0 - \frac{z_3(t)}{b_0} \]

5. Simulation analysis

Based on the above design of the auto disturbance rejection controller and the PID controller, the simulation model is built using Matlab/Simulink. The AC side line voltage is 380V, the frequency is 50Hz, the DC voltage is 40V, the reactor is 4mH, the equivalent resistance is 0.001W, the DC filter capacitor is 4100uF, and the load resistance is 77.25W.

The response under the input step signal.

The response under the sawtooth signal is input.
The response of the sine wave signal with a frequency of 50Hz is input.

Input step signal, adding 10 power white noise interference response.

$T_T$ is the time to reach steady state, $V_T$ is the steady state voltage, $T_p$ is the time to reach the peak, $V_{p}$ is the peak voltage, and the data comparison between the PID controller and the auto disturbance rejection controller is as Table 1:
Table 1. PID controller and auto disturbance rejection controller data comparison.

| Controller response | Input signal | PID controller | ADRC controller |
|---------------------|--------------|----------------|-----------------|
| Step signal         | Tr=1.9s, V=40v | Tr=1.4s, V=40v |                 |
| Sawtooth signal     | Tr=1.8s, V=40v | Tr=1.1s, V=40v |                 |
| Sine wave signal    | Tr=1.8s, V=40v, Tp=0.4s, Vp=87v | Tr=1.1s, V=40v |                 |

Step signal and interference

Unstable

Tr=1.4s, V=40v, Tp=0.4s, Vp=67v

It can be seen from the table that when the input signal is a step signal and a sawtooth signal at different inputs, the PID controller and the auto-disturbance are not over-tuned to be stable, and the self-interference is stable for a shorter period of time; When the input signal is a sine wave signal, the PID controller overshoots and oscillates before the steady state, and the auto disturbance rejection controller is still overshoot to achieve stability. When the step signal is input and white noise interference is added, the PID controller system has been oscillating and cannot achieve stability. However, although the auto disturbance rejection controller has overshoot and has a large error, the system is still stable. In summary, the anti-interference controller has stronger anti-interference ability and shorter response time on the three-phase PWM rectifier. There are too many adjustment parameters for nonlinear auto-disturbance, so the linear auto-disturbance is introduced, and the adjustment parameters are reduced to three, but the nonlinear auto-interference ratio has more freedom, possibility and Better adaptability than linear anti-interference. These are not available in the PID controller.

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