Research on Active Power Filter Based on Linear Active Disturbance Rejection Control

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Abstract. In view of the key technology of active power filter (compensating current tracking control) to solve the harmonic problem of power system, the traditional PID control has defects and is divorced from the engineering practice. However, ADRC inherits the advantages of PID control and modern control theory. Without knowing the specific mathematical model of the object and the specific form of the external disturbance, it can compensate the internal disturbance while suppressing the external disturbance. It has strong robustness and adaptability. However, the traditional nonlinear auto-disturbance rejection technology has too many parameters, which hinders its wide application. Therefore, we introduce linear auto-disturbance rejection technology and design a current tracking control system of active power filter based on linear auto-disturbance rejection, which makes the control performance of active power filter more ideal and more widely used. Simulation experiments verify the feasibility of the study.

1. Introduction
With the continuous development of power electronic technology and the wide application of power electronic devices, the harmonic problem of power system is more and more serious. Active power filter (APF), as a substitute of traditional passive filter, can dynamically compensate harmonics, and its research and application have attracted extensive attention. In recent years, the key technologies of active power filter control have emerged one after another, such as the research based on active disturbance rejection control, the control strategy of single hysteresis SVPWM, the control strategy based on the reduced order vector proportional integrator and other new research controls. In Literature [6], active disturbance rejection technology was introduced into the active power filter, but the introduced active disturbance rejection technology is nonlinear, the parameters are still too many, and the application is also not widespread. The PID control proposed in literature [9] in the study of active power filter, although it has verified the steady state performance and dynamic characteristics of PID control, but compared with the new active disturbance rejection technology, its control still has defects and poor control effect. Therefore, in view of the defects of traditional PID control and traditional nonlinear active disturbance rejection control, as well as the problem of the new control method with many parameters. Linear Active Disturbance Rejection (LADRC) technique is proposed for active power filters. Based on the mathematical model of APF and ADRC, an active power filter based on linear ADRC is reconstructed. The control performance of APF is better.
2. APF modelling

In order to facilitate the establishment of APF mathematical model, APF is idealized: (1) The switching loss and switching time of the switching device are not considered; (2) The three-phase circuit is symmetric and contains only positive sequence fundamental wave component, that is, \(u_a = u_b = u_c\). Based on the above two conditions, APF switch equivalent circuit is made, as shown in Fig. 2. Where, \(u_i (i = a, b, c)\) is the three-phase voltage of the grid, \(R\) is the equivalent resistance, \(L\) is the connection inductance, \(S_i (i=A,B,C)\) is the ideal switching device, \(u_i (i=A,B,C)\) is the voltage at both ends of the switching device, and \(U_d\) is the voltage at the DC side.

![Figure 1. APF equivalent switching circuit](image)

According to Kirchhoff's law, let's define a switching function \(k_j\).

\[
k_j = s_j - \frac{1}{3} \sum_{j=A,B,C} s_j
\]  

(1)

Where \(s_j\) represents the switching state of the switching device. The value is 1 only when the upper bridge arm is on, and 0 only when the lower bridge arm is on. The AC voltage can be related to the DC side voltage by means of a switching function.

\[
u_j = k_j U_d
\]  

(2)

According to Kirchhoff's law, the DC-side current equation is

\[
C \frac{dU_d}{dt} = s_A i_A + s_B i_B + s_C i_C
\]  

(3)

Combine PI (1)- PI (3) and write it as a state space

\[
\begin{bmatrix}
\frac{d}{dt} i_A \\
\frac{d}{dt} i_B \\
\frac{d}{dt} i_C \\
\frac{d}{dt} u_A \\
\frac{d}{dt} u_B \\
\frac{d}{dt} u_C \\
\end{bmatrix} = \begin{bmatrix}
\frac{1}{L} & 0 & 0 & -\frac{1}{L} & i_A \\
0 & \frac{1}{L} & 0 & -\frac{1}{L} & i_B \\
0 & 0 & \frac{1}{L} & 0 & i_C \\
\frac{1}{T} & 0 & 0 & 0 & u_A \\
0 & \frac{1}{T} & 0 & 0 & u_B \\
0 & 0 & \frac{1}{T} & 0 & u_C \\
\end{bmatrix}
\]  

(4)

Can be correspondingly expressed as

\[
\dot{X} = AX + BU
\]  

(5)

In other words, (5) is the state space model of three-phase three-wire APF under low frequency conditions.

3. Control of LADRC

3.1. Fundamentals of ADRC

The active disturbance rejection controller is mainly composed of a tracking differentiator (TD), an extended state observer (ESO) and a nonlinear error feedback control rate (NLSEF).

The function of the tracking differentiator (TD) is to obtain a smooth input signal according to the input signal, and give each order derivative of the input signal at the same time. The expression of the first-order TD is as follows:
\[
\begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= -r \text{sign}(x_1 - v_0(t) + x_2|x_2|) \\
\end{align*}
\]

(6)

Where \(v_0(t)\) represents the input signal, \(x_1\) represents the tracking signal of \(v_0(t)\), \(x_2\) is the derivative of \(x_1\), \(R\) is the time constant of the tracking differentiator, \text{sign()}\ is the sign function, and its expression is

\[
\text{sign}(x) = \begin{cases} 
1, & x > 0 \\
0, & x = 0 \\
-1, & x < 0 
\end{cases}
\]

(7)

The extended state observer (ESO) is the core part of the active disturbance rejection controller, which estimates the information of the internal state variables of the system through the input and output of the system, and expands a state variable to estimate all the disturbances of the system in real time and make compensation in the feedback. The second-order ESO is expressed as follows:

\[
\begin{align*}
ed &= z_1 - y \\
\dot{z}_1 &= z_2 - \beta_1 e + b_0 u \\
\dot{z}_2 &= -\beta_2 \text{fal}(e, \alpha, \varepsilon) \\
\end{align*}
\]

(8)

Where \(u\) and \(y\) respectively represent the input and output of the system, \(z_1\) represents the state variable tracking output, \(z_2\) represents the disturbance estimated by the system, \(b_0\) represents the input control gain, and \(\text{Fal()}\) is the link that automatically adjusts the gain along with the input error, which can prevent the system instability caused by excessive gain, and its expression is

\[
\text{fal}(e, \alpha, \varepsilon) = \begin{cases} 
e^{-\alpha}, & |e| \leq \varepsilon \\
\text{sign}(e), & |e| > \varepsilon 
\end{cases}
\]

(9)

The error signals and derivatives of the system can be obtained by the output difference between TD and ESO. After the difference between the initial control quantity of the output of NLSEF and the estimated disturbance quantity, the control signal is generated to compensate the disturbance. The expression of first-order NLSEF is as follows:

\[
\begin{align*}
ed_1 &= x_1 - z_1 \\
u_0 &= K\text{fal}(\ed_1, \alpha, \varepsilon) \\
\end{align*}
\]

(10)

3.2. APF current tracking control system design of LADRC

Based on the mathematical model of ADRC, combined with the idea of introducing linear active disturbance rejection technology, the expression of a first-order system is set as follows:

\[
\begin{align*}
x_1 &= x_2 + bu \\
\dot{x}_2 &= h(x, w) \\
y &= x_1 \\
\end{align*}
\]

(11)

Where, the input and output of the system are \(u\) and \(y\) respectively, \(b\) is the input control gain, \(w\) is the unknown external disturbance, and \(h\) is the generalized disturbance, including all the uncertainties of the system.
According to the APF state space model in (5), any phase is a first-order system, so three first-order LADRC (LESO is the second-order) are adopted to adjust three phases A, B and C respectively. In order to obtain the mathematical model of the control system, A phase is taken as an example.

For further parameterization, the observer bandwidth $w_0$ and the controller bandwidth $w_c$ are introduced. A-LC characteristic equation of LESO of order 2 is:

$$s^2 + \beta_1 s + \beta_2 = (s + \omega_0)^2$$  \hspace{1cm} (12)

Where I is the identity matrix. By allocating the poles of the characteristic equation at $-w_0$, we can get

$$s^2 + \beta_1 s + \beta_2 = (s + \omega_0)^2$$  \hspace{1cm} (13)

That is:

$$\begin{cases}
\beta_1 = 2w_0 \\
\beta_2 = \omega_0^2 \\
k_p = \omega_c
\end{cases}$$  \hspace{1cm} (14)

A good control effect can be achieved by selecting appropriate $w_0$ and $w_c$.

4. The simulation results

In order to verify the feasibility of this study, a simulation was built in Matlab/Simulink environment. The harmonic detection method based on instantaneous reactive power is adopted, and the LADRC control is used as the harmonic current tracking strategy. The simulation parameters are as follows: the three-phase power supply is symmetrical and ideal, the effective value of each phase line voltage is 380V, and the frequency is 50Hz; Nonlinear load for three-phase diode rectifier bridge with $R = 15 \Omega$, $L = 3$ mH resistance load; DC side capacitance voltage $U_d = 750V$; Connecting inductance $L_0 = 5$mH. It can be known that

$$b_0 = \frac{U_d}{2L_0 V_{tri}}$$

by substituting system parameters, $b_0 = 139.6$; After repeated adjustment, the most appropriate parameters of LADRC controller $w_0 = 40$ and $w_c = 150$ were selected. When Fig. 2 (a), (b) and (c) are steady-state, APF simulation waveform is adopted in the linear active disturbance rejection control. After compensation, the waveform of A-phase current on the network side is a standard sine wave, and THD is 1.90%.

(a) A phase reference current $i_{ca}^*$ and tracking current $i_{ca}$ waveform

(b) Compensated grid side A phase current waveform

(c) The compensated A-phase current spectrum on the network side

Figure 2. Simulation waveform of linear ADRC
When Fig. 3(a), (b) and (c) are steady state, APF simulation waveform is adopted when PID control is adopted, where 3(a) is the tracking current tracking reference current effect diagram. 3(b) and 3(c) are the waveform and spectrum of the compensated A-phase current at the network side respectively. After compensation, the waveform of A-phase current on the network side is a standard sine wave, and THD is 2.71%.

![Waveform Diagram](image)

(a) A phase reference current $i_{ca}^*$ and tracking current $i_{ca}$ waveform

![Waveform Diagram](image)

(b) A-phase current waveform at the network side after compensation

![Spectrum Diagram](image)

(c) The spectrum of compensated A-phase current on the network side

Figure 3. PID control simulation waveform

In order to simulate a disturbance, increasing load when $t = 0.2$ s, $R = 30$ Ω at this time, $L = 6$ mH. PID control simulation waveform and LADRC simulation waveform are shown in Fig. 4 (a), (b), (c) and Fig. 5 (a), (b), (c) respectively. It can be seen that when the load changes, the PID control system needs 1.5 cycles to reach the steady state. The LADRC system can reach steady state within 0.5 cycles. The THD after compensation of the latter is 2.06%, which is 1.53% lower than that after compensation of the former is 3.59%.

![Waveform Diagram](image)

(a) A phase reference current $i_{ca}^*$ and tracking current $i_{ca}$ waveform

![Waveform Diagram](image)

(b) Compensated grid side A phase current waveform

![Spectrum Diagram](image)

(c) The compensated A-phase current spectrum on the network side

Figure 4. Simulation waveform of PID control under disturbance
6

(a) A phase reference current $i_{ca}^*$ and tracking current $i_{ca}$ waveform

(b) Compensated grid side A-phase current waveform

(c) Compensated grid side A-phase current spectrum

Figure 5 Simulation waveform of linear ADRC under disturbance

5. Conclusion
The linear active disturbance rejection technology is introduced into the active power filter to solve the harmonic problem more effectively, and the application level is also extensive. In the LADRC control study, there are 5 less control parameters than the ADRC control, which solves the problem that the ADRC control parameters are too many and difficult to set. Compared with the PID control in the simulation experiment, the LADRC control has better performance no matter in the steady state or under the disturbance. At the same time, the introduction of linear active disturbance rejection technology is a good solution to the traditional PID and nonlinear ADRC drawbacks, has a good application value.

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