Sliding Mode Variable Structure Control for Three-Phase Three-Wire Active Power Filter

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Abstract. Based on the established three-phase three-wire active power filter model, a sliding mode variable structure control method is designed. Since the active power filter (APF) is switched by the switching function continuously, a suitable sliding surface is an effective method for improving the current tracking performance. Although the ordinary hysteresis comparison method has the characteristics of fast dynamic response, good robustness and strong adaptability to loads, the chattering phenomenon is serious. In this paper, a new sliding mode variable structure control is constructed by the design of sliding surface. The simulation proved that the designed sliding mode variable structure control method has less chattering and current tracking error than hysteresis comparison, the current contains fewer harmonics after processing. The effect of overall harmonic compensation is better than the ordinary hysteresis comparison method.

1. Introduction
In contemporary society, the large-scale application of various nonlinear brings power quality problems in power systems. The APF is to make the compensation circuit generate the compensation current with the same amplitude and opposite phase to the harmonic current. Achieve the purpose of eliminating harmonics. The active power filter includes three parts: a current tracking module, a harmonic current detection control module and a compensation current generation module. The harmonic detection control usually adopts the Instantaneous Reactive Power Theory, also known as the p-q method [1]. The compensation current generating circuit usually adopts a three-bridge arm structure. Some current tracking methods, such as hysteresis current control, sliding mode control, artificial Neural network control, etc. also be used[2].

This paper mainly studies SMVS-sliding mode variable structure control. SMVS is very fast, has complete robustness to internal parameter changes and external disturbances, and is especially suitable for harmonic current tracking control of APF[3][4]. The principle of the device and the SMVS control method are introduced. The existence, accessibility and stability of the sliding mode were analyzed also. Paper [5] proposed a variable-synchronous sliding mode variable structure control method, which can make the maximum deviation be corrected in a short time, and avoid the large amplitude chattering phenomenon. It provides a way of thinking for the design of variable-straining sliding mode variable structure control. Based on the linearization APF model, a model reference adaptive PI controller is designed and the adaptive control law is introduced by Lyapunov stability theory. Experiments show that the designed model reference adaptive control PI controller is much better than the traditional PI controller, which improves the robustness of the system to parameter changes[6].
In this paper, by constructing a new sliding surface, a sliding mode variable structure control is designed, which has good tracking performance, small chattering, simple calculation and easy implementation. It has good theoretical and practical significance. The simulation results show that the SMVS control can be applied to the APF and obtain good results.

2. The three-phase three-wire active power filter model

The structure of the parallel APF is as shown in Fig. 1. In order to eliminate harmonic components in the power current, the compensation current generating circuit generates a compensation current having the same magnitude and opposite direction as the harmonic current.

As shown in Figure 1, the current \(i_s\), \(i_{sb}\), \(i_{sc}\) is a sine wave with the same phase as the voltage; \(i_{sa}\), \(i_{sb}\), \(i_{sc}\) is the load current, which contains a certain harmonic; \(i_{ca}\), \(i_{cb}\), \(i_{cc}\) is the actual compensated current. According to Kirchhoff’s current law:

\[
\begin{align*}
\begin{cases}
i_s + i_{ca} &= i_{la} \\
i_{sb} + i_{cb} &= i_{lb} \\
i_{sc} + i_{cc} &= i_{lc}
\end{cases}
\end{align*}
\]  

(1)

The state equation of three-phase three-wire active filter is as follows:

\[
\begin{align*}
\begin{cases}
L \frac{di_{ca}}{dt} &= u_{sa} - u_{ca} \\
L \frac{di_{cb}}{dt} &= u_{sb} - u_{cb} \\
L \frac{di_{cc}}{dt} &= u_{sc} - u_{cc}
\end{cases}
\end{align*}
\]  

(2)

\[
\begin{align*}
u_{ca} &= u_{de} (2j_a - j_b - j_c) / 3 \\
u_{cb} &= u_{de} (-j_a + 2j_b - j_c) / 3 \\
u_{cc} &= u_{de} (-j_a - j_b + 2j_c) / 3
\end{align*}
\]  

(3)

Switching Function \(j_i = \begin{cases} 1 & \text{the upper bridge arm turned on} \\ 0 & \text{the lower bridge arm turned off} \end{cases} \quad i = a, b, c \)

3. The design of sliding mode variable structure controller

\(i_{ca*}, i_{cb*}, i_{cc*}\) is the detected harmonic current, \(i_{ca}, i_{cb}, i_{cc}\) is the actual compensated current, and the purpose of the control is to make each phase current tracking error \(e_i = i_{ci} - i_{ci}^* = 0 \quad i = a, b, c \)

Defining a sliding surface
\[ S_i = e_i + \lambda_i \cdot e_i^* \quad \lambda_i > 0 \quad i = a, b, c \] (4)

The voltage across the capacitor can only be processed constant and is not controllable. The positive and negative of the switching function are connected with the control signal: when \( S_i \) is positive, the upper arm of the \( i \) phase bridge is turned on; when \( S_i \) is negative, the lower arm of the \( i \) phase bridge is turned on, therefore, the constant value switching control can be obtained:

\[ u_i = K_i u_{dc} \cdot \text{sgn}(S_i) \quad K_i = \frac{1}{3} \text{ or } \frac{2}{3} \quad i = a, b, c \] (5)

The overall control rules are shown in Table 1:

| situation | Sa | Sb | Sc | ji Switch mode |
|-----------|----|----|----|----------------|
| I         | +  | +  | -  | (1,1,0)        |
| II        | -  | +  | -  | (0,1,0)        |
| III       | -  | +  | +  | (0,1,1)        |
| IV        | -  | -  | +  | (0,0,1)        |
| V         | +  | -  | +  | (1,0,1)        |
| VI        | +  | -  | -  | (1,0,0)        |

4. Simulation and analysis
Simulation experiments were performed using the Sim Power System in SIMULINK and compared with the hysteresis comparison method. The power supply selects a three-phase AC power supply of 220V 50HZ; the inductance of the compensation circuit is 1.4mH; and the capacitance of the DC side is 0.1F; \( U_{dc} \) selects 400V and uses PI control method for constant control; the compensation circuit is connected to the circuit after 0.04s through the access switch; For studying the influence of external interference on the compensation effect of active power filter, after 0.08s a non-linear load is connected through the switch.

The load current contains the harmonic current, as shown in Figure 6, THD=24.72%, far exceeding the electromagnetic compatibility standard IEC-61000, low-voltage power grid (<1kV), THD <5% standard.
The hysteresis comparison method can compensate harmonic current which is shown in Figure 5, the compensated power phase A current THD=3.55%.

The phase A current waveform is divided into three phases: 0-0.04 seconds, the compensation circuit is not connected, the current waveform is distorted; 0.04-0.08 seconds, the compensation circuit is connected, the current is compensated; 0.08-0.15 seconds, nonlinear Load 2 is connected to the circuit and the current amplitude is increased by 1.8 times.

The simulation results of sliding mode variable structure control are as follows:

After the harmonic compensation is implemented by the SMVS control method, the phase A current THD is reduced by 1% compared with the hysteresis comparison method. At the same time, the current tracking error is reduced, and the jitter of the power phase A current is also weakened after compensation.
5. Conclusion
The APF is equivalent to a reactive power source. The command current is the detected harmonic current and has certain uncertainty. Sliding mode variable structure control is fast, robust, stable and insensitive to external interference. It is very suitable for the control of APF. Based on the hysteresis comparison way, a sliding mode surface is defined and a sliding mode variable structure control is constructed. The three-phase three-wire active power filter model is simulated. The results show that sliding variable structure control method can effectively reduce the harmonic content of the power current and significantly reduce the tracking error of the current, and weaken the chattering of the power current. Therefore, the application to active power filters has great advantages.

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