Research on Direct Power Control of DC Side for the Active Power Filter

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Abstract: This paper addresses the principle and control topology of active power filter (APF). The control strategy of direct power control based on DC side is introduced, and the control output is implemented by using the principle of hysteresis control. The active power filter can effectively control the power system harmonics, improve the quality of electricity and purify power grid. The experimental results are provided to illustrate that the direct power control based on DC side has the advantages of simple structure, stable DC output voltage and fast dynamic response.

Keywords: DC Side; Power Control; Active Power Filter; Hysteresis Control

1 Introduction

With the rapid development of electrification and high precision equipment, the nonlinear load in power system has been widely used in extensive applications. Many kinds of nonlinear devices, especially power electronic devices, may yield a large numberof harmonics in the power grid, which have a serious impact on the power quality, and cause great security risks to the normal operation of the power grid. In view of the serious decline of power quality in power grid, Active Power Filter (APF) is a focal topic of research that has attracted much attention in recent years.

APF is mainly composed of two parts in the structure control topology: the part of harmonic current detection and the part of compensation current generation. The main function of the harmonic current detection section is to detect the harmonic component in the load current, The main function of the harmonic current detection circuit is the detection of the harmonic component in the load current. The compensation current output circuit controls the output compensation current of the converter under the action of the instruction current to send out the compensation current command signal, so as to be used to remove the harmonic current from the load current. Thus, harmonic currents in the load current can be removed.

The main theories used in harmonic detection include instantaneous reactive power theory, fast Fourier transform (FFT) theory, FBD power theory and so on. For the part of compensation current generation, hysteresis control algorithm, PI control, feedforward control, repetitive control, PI control under DQ coordinates and generalized integral control are the main parts of the compensation current. In various algorithms, hysteresis control has higher accuracy and faster response. It is a universal current tracking control method, but the switching frequency of hysteresis control algorithm is not fixed. Therefore, the harmonic generated by the switching frequency cannot be effectively suppressed[1].

Based on the hysteresis control, this paper proposes a control strategy that is the direct power control based on DC (DPC: Direct Power Control), which has good robustness, fast tracking speed, and rapid response to mutations in the state, and improves the harmonics of switching frequency on the basis of hysteresis control. So it improves the performance of the equipment.

2 Hysteresis control algorithm

2.1 The working principle of APF

The process of APF is: The voltage and current signals of the nonlinear load are detected by the system voltage transformer and the load current transformer, after the conditioning circuit processing, the instruction signal i_C* of the compensation current is calculated by the central control unit, and then the compensation control circuit is passed through the isolation drive circuit to control the inverter to produce the corresponding compensation current i_C, the inverter is controlled to generate a corresponding compensation current i_C.

As shown in Figure.1, the system current is i_S, consisting of the load current i_L and the APF output current i_C.

$$i_S = i_L + i_C \tag{1}$$

According to the analysis of the current synthesis theory, the load current i_L is composed of the fundamental current component i_{Lf} and the harmonic current component i_{Lh}. The fundamental current component is also composed of the active component i_{Lfp} and the reactive component i_{Lfq}. Therefore, the load current is the sum of the fundamental active component i_{Lfp}, the fundamental reactive component i_{Lfq} and the harmonic component i_{Lh}. Formula is as follows:

$$i_L = i_{Lf} + i_{Lh} ;$$

$$i_{Lf} = i_{Lfp} + i_{Lfq} ;$$

$$i_L = i_{Lfp} + i_{Lfq} + i_{Lh} \tag{2}$$

The output current of the active filter is:

$$i_C = - i_{Lh} \tag{3}$$

Only the fundamental current is present in the supply current, so:

$$i_S = i_L + i_C = i_{Lf} \tag{4}$$

This will suppress harmonics.

2.2 hysteresis control algorithm

Hysteresis control is a method of comparing the actual output current to the target current. Its working principle is: Calculating the compensation current target value as the reference to design a hysteresis band, when the actual output current exceeds the upper limit value of the hysteresis band, the trigger output controls the switch action to make the output current fluctuating in the hysteresis band, around its target value fluctuation[2]. In this algorithm, the switching frequency of the power device, the response speed of the system and the tracking precision of the output current are all affected by the bandwidth. The size of the band width directly affects the speed and the accuracy of the system response.

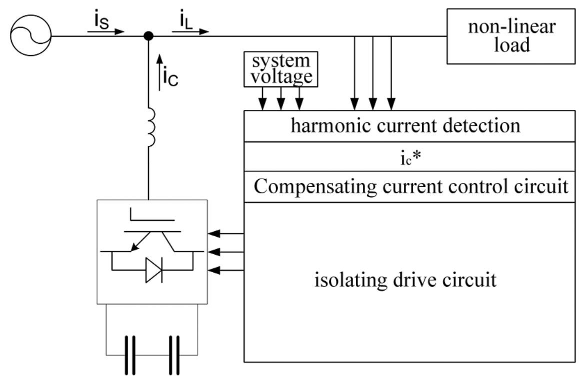

Fig. 1 structure of active power filter

The control principle using hysteresis comparison is shown in Figure.2 In the algorithm, Δi_c is a deviation between the target current signal and the actual output current signal. This signal is used as the input of the hysteresis comparator, and the PWM signal of the IGBT switch in the main circuit is controlled by a hysteresis comparator, so as to control the output current following the change of the compensating current.

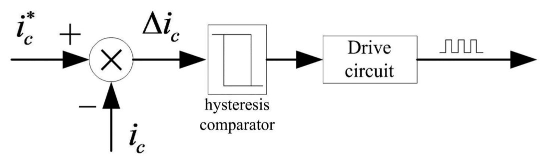

Fig. 2 principle diagram of hysteresis comparison method

Hysteresis control algorithm has the advantages of simple hardware circuit, fast current response, no carrier, anti-interference ability, high reliability and so on. After simplifying the system model, the resistance effect of the filter reactor is neglected, so a dynamic equation in the switching period can be obtained:

$$\frac{di_C}{dt}L_m = \begin{cases} (Vdc - Vac)\cdots\cdots kT < t < kT + td \\ -(Vdc + Vac)\cdots kT + td < t < (k+1)T \end{cases} \quad (5)$$

Among them, the i_c is the APF compensation current, and the Vdc is the DC side voltage, Vac is the AC power supply voltage, Lm is the output reactor of APF, TD is the opening time of a switch cycle, T is the sampling cycle time and K is the switching cycle counting. Since the switching frequency of the APF can reach tens of kHz, it can be considered that the DC side voltage and the AC supply voltage are constant during a switching period.

Thus, the peak equation and the mean equation of the system can be calculated according to the following formula:

$$i_C(k+1)L_m = Vdc(k)\,[2td(k) - T] - Vac(k)T + i_C(k)Lm \quad (6)$$

$$\bar{i}_C(k) = i_C(k) + \frac{-2Vdc(k)\ [T - td(k)]^2 + [Vdc(k) - Vac(k)]\,T^2}{2LmT} \quad (7)$$

2.3 direct power control

Direct power control (DPC: direct Power Control) is a double-closed loop system with DC side voltage as outer loop and instantaneous power control as inner loop through the principle of power conservation.The DPC can control the instantaneous input current by controlling the instantaneous active power and reactive power of the converter, thus obtaining the preset power factor and the direction of power flow.

The control methods of direct power control are as follows:

Voltage based direct power control (V-DPC) has the advantages of simple control algorithm, simple train of thought, fast dynamic response speed, low harmonic generation and low hardware cost. There are some disadvantages, such as no fixed switching frequency, control accuracy depends on sensor conversion accuracy and system sampling frequency.

Direct power control based on virtual flux chain (VF-DPC) not only has the advantages of V-DPC, but also has the advantages of lower sampling frequency and less effect of voltage distortion on the current distortion rate. However, VF-DPC is not suitable for the control system with fixed switching frequency.

Compared with V-DPC and VF-DPC, direct power control based on instantaneous power theory uses additional voltage sensors, but the calculation of instantaneous power does not depend on the switching state of the system, which greatly simplifies the algorithm and provides more accurate instantaneous value of active and reactive power. This control strategy also has the advantages of fast dynamic response and low current distortion rate on the input side, but its disadvantages are obvious, the switching frequency is not fixed, and the sampling frequency is high.

Direct Power Control based on Space Vector (SVM-DPC) because no nonlinear controller is used, the switching frequency is fixed. It has the advantages of convenient selection of inductance parameters, low sampling frequency, obtaining voltage vector in any direction , having no reactive power loss region and lower distortion rate of input current. There are some disadvantages, such as the complexity of the control algorithm, the estimation of instantaneous power depends on the current switching state of the system, and the complexity of debugging is increased by multiple PI links.

In addition, there are others control methods of direct power control: direct power control based on power prediction (P-DPC), direct power control based on power decoupling, direct power control based on double switch table and direct power control based on output regulator space.

Direct power control based on DC side voltage is a combination of the advantages of the above direct power control. It is an improved control algorithm, which realizes the system power conservation by controlling the DC side voltage of the converter.

This algorithm inherits the advantages of V-DPC and VF-DPC control algorithm, reduces the computation link, improves the response speed, and optimizes the control precision and stability.

2.4 direct power control of DC side voltage

In the literature research of APF, the control methods are mostly instantaneous reactive power theory or adaptive algorithm and other calculation methods. Firstly, calculating the load harmonic current components in the current, then the load current and fundamental current are subtracted to get the output target current. Finally, according to the target current, the PWM control method or space vector method is adopted to control the output compensation current and increase the DC side voltage control. This is a mathematical computation of the response speed of the device.

The direct power control principle of the DC side of the APF system is shown in Figure 2.3.

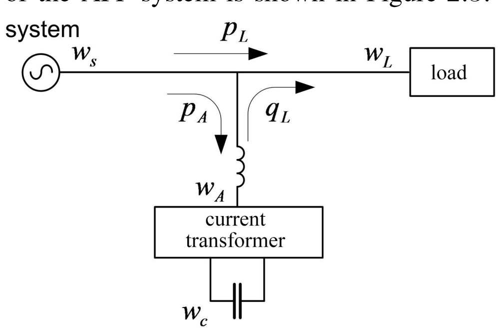

Fig. 3 voltage mode APF power transfer diagram

As shown in Figure. 3, the harmonic current generated by the load and the fundamental reactive current are compensated. The system power outputs the active power and the loss power of the APF to the load. The system power outputs the active power p_L to the load and the loss power p_A of APF. The reactive power q_L required for load is output by APF. It is assumed that the supply voltage is sinusoidal. Assuming $u_s(t) = U_s \sin(\omega t)$, the load instantaneous current is:

$$i_L(t) = I_{pL}\sin(\omega t) + I_q\cos(\omega t) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \theta_n) \quad (8)$$

Instantaneous load power is:

$$\begin{aligned} w_L(t) &= u_s(t) i_L(t) = p_L + q_L \\ &= I_{pL} U_s \sin^2(\omega t) + I_q U_s \sin(\omega t)\cos(\omega t) \\ &+ \sum_{n=2}^{\infty} U_s \sin(\omega t) I_n \sin(n\omega t + \theta_n) \end{aligned} \quad (9)$$

The output power of the power supply is:

$$\begin{aligned} w_S(t) &= p_L + p_A = I_{pL} U_s \sin^2(\omega t) + I_{pA} U_s \sin^2(\omega t) \\ &= (I_{pL} + I_{pA}) \sin(\omega t) u_s(t) \end{aligned} \quad (10)$$

The output power of the active filter is:

$$\begin{aligned} w_A(t) &= q_L - p_A \\ &= I_q U_s \sin(\omega t)\cos(\omega t) \\ &+ \sum_{n=2}^{\infty} U_s \sin(\omega t) I_n \sin(n\omega t + \theta_n) - I_{pA} U_s \sin^2(\omega t) \end{aligned} \quad (11)$$

$$\begin{aligned} q_L &= I_q U_s \sin(\omega t)\cos(\omega t) \\ &+ \sum_{n=2}^{\infty} U_s \sin(\omega t) I_n \sin(n\omega t + \theta_n) \end{aligned} \quad (12)$$

The integral in one cycle of reactive power q_L is:

$$\int_0^T q_L dt = \int_0^T \Big(I_q U_s \sin(\omega t)\cos(\omega t) + \sum_{n=2}^{\infty} U_s \sin(\omega t) I_n \sin(n\omega t + \theta_n) \Big) dt = 0 \quad (13)$$

The integral in one cycle of loss power p_A is:

$$\begin{aligned} \int_0^T p_A dt &= \int_0^T (I_{pA} U_s \sin^2(\omega t)) dt = \frac{T}{2} I_{pA} U_S \\ &= \frac{1}{2} C [U_{dc} + \Delta U_{dc}]^2 - \frac{1}{2} C U_{dc}^2 \end{aligned} \quad (14)$$

Equation (13) and (14) show: Although reactive power(q_L) generates energy exchange between systems, the integral of energy is zero in one cycle. Therefore, under the influence of reactive power (q_L), the DC side capacitance voltage should be kept as a fixed value in a period. In fact, there is a loss power(p_A) in the actual period, and the integral is not zero, which causes the change of the periodic value of the capacitor voltage. For the APF system, the transmission of active power is the fundamental cause to the change of the periodic value of the reactive capacitance voltage[3][4]. For the stability control of DC voltage, it is also the control of the active power transmission in the system.

If in each T cycle, the sampling frequency is 10kHz. According to integral principle:

$$\int_0^T (I_{pA} U_s \sin^2(\omega t))dt = \int_0^T (I_{pA} \sin(\omega t) \times U_s \sin(\omega t))dt$$

$$= \frac{1}{2} C\, [U_{dc} + \Delta U_{dc}]^2 - \frac{1}{2} C\, U_{dc}^2$$

$$= \sum_{n=1}^{200} I_{pA} \sin(\omega Tn) \times U_s \sin(\omega Tn) \times \frac{0.02}{10000} \quad (15)$$

IpA is the DC side loss current, n indicates that in 20ms, the sampling frequency of 10kHz has 200 sampling points, and ω is the angular frequency.

According to the formula (14), the DC side of delta Udc is Udcref and actual DC voltage Udc by PI control target value. Where Udcref is a fixed value, and Udc is a real value. According to formulas (14) and (15), the reference value IpA of IpAref can be obtained. By combining the above reasoning, we can get:

$$I_{pAref} = \left[\frac{1}{2} C\, (U_{dc} + \Delta U_{dc})^2 - \frac{1}{2} C U_{dc}^2\right]$$

$$\div \sum_{1}^{200} \sin(\omega Tn) \times U_s \sin(\omega Tn) \times \frac{0.02}{10000} \quad (16)$$

According to hysteresis control principle, make $i_C^* = I_{pAref}$, comparing with i_{-c} to be able to get Δi_C. The required compensation current is generated by opening and closing the hysteresis control IGBT.

3 prototype experiment and theoretical verification

Based on the DC direct power control strategy, a prototype is developed. The three-phase three wire circuit topology is adopted. The filter inductance of the rectifier is 0.5mH, the resistance is ignored, and the hysteresis frequency is highest 10kHz. Ring width is set 2A. The DC bus filter capacitor is consisted of 8 capacitors with a capacity of 450V/6800μF and is connected in series with 2.

In the Figure.4, Udc is the waveform of the actual DC voltage, I_Load is the actual load waveform, I_Cmp is the actual output current waveform, and I_Src is the actual waveform of the compensation system current[5]. As it can be seen from the diagram, It can be seen from the diagram that the result of direct power control through direct current side can meet the desired purpose. The result is good, the output is stable and the waveform is normal.

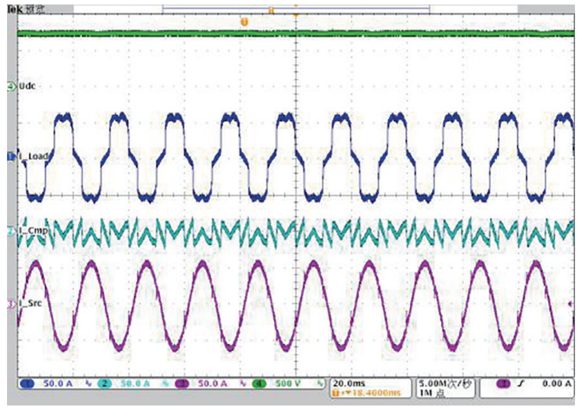

Fig. 4 practical results of direct power control based on DC side

4 Conclusion

Through direct side power control, the APF system directly controls the power consumption of the system. It avoids the complicated process of traditional control calculation and the transformation process of coordinate transformation, it directly controls the output power of DC side and simplifies the control path of the system. By using the fast tracking characteristics of hysteresis control, the stability of the system and the stability of the DC side voltage are improved, the periodic load and sudden load are also well compensated. On the basis of this theory, an experimental prototype is developed, then the compensation effect and data of the prototype are analyzed. The experimental results show that the high efficiency of the control algorithm is achieved.

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