Study of Three-Phase Shunt Active Power Filter based on Deadbeat Control Method

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Abstract. As electrical power converting circuits are widely used in power grid, the harmonic waves are produced in electrical power system, and harmonic waves also causes the decrease of electrical power quality and have adverse effect to the electrical equipment. In order to ease these disadvantageous influences, on the basis of analysing existing series and shunt active electric power filter, a direct current control method based on deadbeat control strategy is proposed in the paper. The principle of deadbeat control method was illustrated first, then a simulation model was built to prove the effectiveness of the method. The simulation result indicated the shunt active filter based on deadbeat control method can obviously improve power quality.

1 Introduction
A large number of non-linear loads were used in the power grid, resulting in a large number of harmonics, reactive power loss and negative Sequence current leads to the degradation of the power quality of the power grid, which brings great security risks. Active power filter is one of the most effective harmonic suppression and reactive power compensation tools, which is suitable for various harmonic sources and can realize dynamic compensation.

2. Deadbeat control technology of shunt active power filter

2.1 Control system of shunt active power filter
The control system of shunt active power filter can be divided into two layers. The inner layer directly faces the main circuit of power electronics to tracking instruction current. Usually, two methods are used, sinusoidal pulse width modulation (SPWM) and hysteresis control. The outer layer includes harmonic detection, command voltage generation and DC capacitor voltage control. The detection circuit is basically the same as the series active power filter. As it is connected in shunt in the power grid, it can be controlled to directly absorb fundamental current from the power grid, so DC capacitor voltage is easy to control compared with series type, and the operation circuit of instruction current is shown in Figure 1:
2.2 Principle of deadbeat control
Deadbeat control is a unique control method of digital system. Its outstanding advantage is its fast response, which can greatly improve the dynamic response performance of PWM converter, and has a strong ability to suppress the distortion of output voltage waveform caused by nonlinear load.

Deadbeat, also known as "no overshoot", the output of the system at each sampling point is completely consistent with its instructions, without any phase lag and amplitude deviation. It is similar to the minimum beat control in that both of them have the characteristics of "limited regulation time."

\[
\begin{align*}
x(k+1) &= Ax(k) + Bu(k) \\
y(k) &= Cx(k)
\end{align*}
\]

Then the output of next beat can be expressed as:

\[
y(k + 1) = Cx(k + 1) = CAx(k) + CBu(k)
\]

If the left end of (1-2) is replaced by the command of the next beat, it is obtained:

\[
r(k + 1) = Cx(k + 1) = CAx(k) + CBu(k)
\]

\[
y(k) = r(k), \forall k
\]

The above shows that the output of the system is equal to the command in every beat, which is the deadbeat control effect.

3 Analysis of tracking control algorithm for shunt active power filter
At present, most of the active power filters in the power system are shunt. The reference instruction of the shunt active power filter is the current value, not the voltage value. So how to use SVPWM to track the compensation current reference value is the focus of the research. The calculation of compensation reference value needs a lot of matrix calculation, which not only takes up a lot of DSP system resources, but also causes the calculation delay, so the harmonic is injected into the power grid again. How to compensate the calculation delay is a big problem to be solved in this research.

In consideration of digitization and the real-time control of APF, the deadbeat control harmonic
current tracking algorithm is used, and the reference value of compensation current is tracked by SVPWM modulation algorithm [9-10].

The compensation structure is shown in Figure 2:

![Fig.2](image)

**Fig.2 Structure of Shunt APF compensation**

Reference current is calculated in the synchronous rotation dq coordinate system as shown in Figure 3.

![Fig.3](image)

**Fig.3 Current control diagram**

Firstly, the sampled three-phase load current $i_a, i_b, i_c$ are transformed into $i_d, i_q$ through dq transformation, where $i_d$ is in phase with the supply voltage, which is the active current, $i_q$ is perpendicular to the supply voltage, which is the reactive current. The purpose of compensation is to make the supply current is free of harmonic component and reactive component. Therefore, the reference compensation current shall be:

$$\begin{align*}
    i_{cd}^* &= -\tilde{i}_d + i_{dc} \\
    i_{cq}^* &= -i_q
\end{align*}$$

(5)

$i_{cd}^*$: The d-axis reference compensation current, which is the sum of capacitance voltage compensation component and harmonic component.

$i_{cq}^*$: The q-axis reference compensation current, the reactive current value.

$i_d$: The AC component of d-axis load current, representing the harmonic part.

$i_q$: The reactive part.

$i_{dc}$: The d-axis DC component, which represents the active fundamental part.

The control equations of APF can be derived as following,

$$\begin{bmatrix}
    \frac{di_a}{dt} \\
    \frac{di_b}{dt} \\
    \frac{di_c}{dt}
\end{bmatrix} = -\frac{R}{L_c} \begin{bmatrix}
    0 & 0 & 0 \\
    0 & 0 & 0 \\
    0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} + \frac{1}{L_c} \begin{bmatrix}
    u_a - e_a \\
    u_b - e_b \\
    u_c - e_c
\end{bmatrix}$$

(6)

If transformed to the d-q coordinate, the above formula becomes:
Then written in the form of state space as follows:

$$\dot{X} = AX + BU$$

(8)

where:

$$X = \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix}, \quad U = \begin{bmatrix} u_{sq} - e_q \\ u_{sd} - e_d \end{bmatrix},$$

$$A = \begin{bmatrix} \frac{R}{L_c} & \omega \\ \omega & \frac{R}{L_c} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L_c} & 0 \\ 0 & -\frac{1}{L_c} \end{bmatrix}$$

By discretizing equation (8) as

$$\begin{bmatrix} i_{cd}(k+1) \\ i_{cq}(k+1) \end{bmatrix} = G \begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H \begin{bmatrix} u_{sd}(k) - e_x(k) \\ u_{sq}(k) - e_y(k) \end{bmatrix}$$

(9)

Further:

$$\begin{bmatrix} e_x(k) \\ e_y(k) \end{bmatrix} = H^{-1} G \begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H^{-1} \begin{bmatrix} u_{sd}(k+1) \\ u_{sq}(k+1) \end{bmatrix} \begin{bmatrix} u_{sd}(k) \\ u_{sq}(k) \end{bmatrix}$$

(10)

From formula (1-10), it can be seen that the load current of this period can be predicted by some methods such as adaptive and neuron, but it is difficult to guarantee the real-time performance of the system by using these methods. Considering the periodic characteristics of harmonic current and reactive current in power system, in order to simplify the control method, the load current recorded in the previous cycle can be used to realize the prediction of load current, which is expressed as follows:

$$\begin{bmatrix} i_{cd}^*(n,k) \\ i_{cq}^*(n,k) \end{bmatrix} = -\tilde{i}_{cd}(n-1,k+1)$$

$$\begin{bmatrix} e_x^*(n,k) \\ e_y^*(n,k) \end{bmatrix} = -\tilde{i}_{cq}(n-1,k+1)$$

(11)

In this way, the compensation voltage reference value $[e_x(k), e_y(k)]^T$ can be obtained, and the SVPWM can be used for tracking.

4. Simulation and analysis of shunt APF

4.1. Simulation model of shunt APF
Matlab 2019a Simulink is used to build the model in a visualized way, and the Simscape Electrical toolbox in Simulink is utilized to build the circuit simulation model. The waveforms of series APF and parallel APF before and after current and voltage compensation are compared, which further verifies the complementarity and effectiveness of hybrid APF. Parallel active power filter is similar to series active power filter in simulation structure and harmonic detection method. Here, only the realization model of deadbeat algorithm is simulated in Figure 5:

4.2 Analysis of simulation results
The current simulation waveforms before and after compensation are shown in Figure 4
Figure 4 shows the spectrum of A-phase current before and after adding APF. Figure 5(a) shows the waveforms of phase a load current, harmonic current and fundamental current. The waveforms of voltage, current and compensation current of phase A after adding APF are shown in Figure 5(b). Obviously, it can be seen that the compensation current can track the change of its command signal in real time, and the tracking performance is good, so it can play a good role in current compensation, and achieve the purpose of improving the power quality.

It can be seen from the spectrum analysis chart that almost all the harmonics are reduced to below
In the original wave, the 5th harmonic is reduced to 0.56%, the 7th harmonic is reduced to 0.39%, the 13th harmonic is reduced to 0.19%, and the total harmonic distortion rate is only 1.96%. The harmonic is well suppressed. And because of the deadbeat control, the calculated delay is compensated to a certain extent, and the harmonic injected into the power grid is greatly reduced.

5 Conclusion
The theoretical analysis and simulation results show that SVPWM and deadbeat control technology can not only improve the dynamic performance of compensation, but also reduce the size of the device. The SVPWM and deadbeat control methods are better than the traditional methods. This compensation method has good harmonic suppression ability in three-phase rectifier circuit and power system with nonlinear load, and has a broad application prospect.

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