A Novel Control Strategy for Shunt Active Power Filter Based on Gray Prediction and Optimal Voltage Vector

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Abstract. To enhance furtherly the current of compensation performance, a novel strategy of gray prediction and voltage vector controlling APF is proposed. This method produce leading current instruction based on gray predicting of nonlinear load current, moreover, this instruction implementated the optimal voltage vector controlling of double hysteresis-current control for APF. As far as voltage vector controlling is concerned, including the concept of target region, weak controlling region and strong controlling region, clearly and compactly describing voltage vector controlling basing on current error; As for gray prediction of load current and formation of APF leading current instruction, determining gray forecast parameters for APF experimental system. The contrast and analysis of simulation of pure dynamic resistance and unbalanced load show that gray forecast and voltage vector controlling can improve furtherly compensation precision and decrease THD of current in power source side, besides the advantage of maintaining conventional voltage vector controlling APF.

1. Introduction

As a power quality compensation device, the control method of active power filter - APF compensation current is very important to its performance and efficiency. Compared with other control strategies, the double current loop optimal voltage vector control has the advantages of high DC side voltage utilization rate, fast dynamic response, low switching frequency and less high harmonic content. The related research is in the ascendant. However, in this control method, the compensation current command value of APF is formed based on the current load current [1-5]. Due to the hysteresis of APF filter inductance, current conversion circuit, low-pass filter in command signal forming channel and control program, the compensation current of APF under this control mode always lags behind the change of load current, which will inevitably affect the compensation effect of APF. Grey prediction is an effective method to realize signal prediction and improve control system performance. It has been used in the research of synchronous generator excitation control and APF control [6-7]. This paper combines grey prediction with voltage vector control strategy to form a predicted value ahead of the current load current and an advanced APF compensation current
command value through grey prediction so as to realize advanced voltage vector control in order to further improve the performance of voltage vector control APF.

2. Grey prediction - basic principle of voltage vector control APF

This paper studies a new control strategy of APF that combines current grey prediction with voltage vector control. Grey prediction - voltage vector control APF consists of IGBT inverter based on voltage source, output filter inductor, current detection, grey prediction, command current generation, voltage vector current hysteresis control and drive circuit, etc., as shown in Figure 1. The gray prediction link uses the load current vector at time \( k \) \( \hat{i}(k) = [i_{ab}(k) \ i_{bc}(k) \ i_{ca}(k)]^T \) to predict a load current vector ahead of the current time \( p \) beat \( \hat{i}(k+p) \). Based on park transform, The command current generating section generates an APF output current vector reference value \( \hat{i}^* \), and the difference between the reference value and the APF actual output current vector \( i_c \) forms a bias current vector \( \Delta i_c \). Based on the magnitude and phase of \( \Delta i_c \) and the voltage vector control strategy, the control section determines the switching function \( S \) to carry out on-off control on the IGBT elements of the inverter bridge, so as to realize the desired three-phase compensation current and the power supply side current.

![Figure 1. Schematic of gray prediction and voltage vector controlling APF](image)

3. Optimal voltage vector control of double hysteresis current

The paper [1~5] makes a deep research on APF with double hysteresis current voltage vector control. Through transformation relation

\[
f = f_a + jf_b = \frac{2}{3}(f_a e^{j2\pi/3} + f_c e^{-j2\pi/3})
\]

We can transform the three-phase vectors \( f_a, f_b, f_c \) in Figure 1 into a stationary orthogonal \( ab \) coordinate system. Let the DC side voltage \( E \) of APF shown in Figure 1 remain constant, Then the differential equation of APF bias current vector \( \Delta i = i_e - i_c \) in the \( ab \) coordinate system is

\[
\frac{d}{dt} \Delta i = \text{diag}[L \ L \ L]^{-1}[u^* - u(n)]
\]
\[ u^* = \frac{d}{dt} i^* + e \] is the reference value of APF output voltage vector, in which \( e \) is the power supply voltage vector.

\[ u(n) = \begin{cases} 
\frac{2}{3} E e^{(n-i)c} & (n = 1, 2, 6) \\
0 & (n = 0, 7) 
\end{cases} \]

is the actual output voltage vector for APF. As shown in Figure 2, in the \( \alpha \beta \) coordinate system, the region surrounded by the vertex connection lines of \( u(n) \) \( (n = 1, 2, 6) \) is divided into 6 regions of I – VI, and the \( u(0) \) and \( u(7) \) are located at the origin of the coordinates. The values of switching vector function of Inverter Bridge \( S = [s_1 \, s_0 \, s_j] \) are also shown. For example, \( s_a = 1 \) indicates that the upper bridge arm of phase A is on and the lower bridge arm is off. By seeking an appropriate output voltage vector \( u(n) \), the voltage vector control method can control the mode of the deviation current \( |\Delta i| \) within the allowable error range.

**Figure 2.** The output voltage vector of APF

The double hysteresis loop of bias current is shown in Figure 3. The radii of the inner ring and the outer ring are \( \varepsilon_1 \) and \( \varepsilon_2 \), respectively. \( |\Delta i| < \varepsilon_1 \) is target area, \( \varepsilon_1 < |\Delta i| < \varepsilon_2 \) is a flexible control area, and \( |\Delta i| > \varepsilon_2 \) is compulsory control area. In order to seeking the optimal \( u(n) \), the flexible control area...
are divided into zone 1~7, and the compulsory control area are divided into zone 7~12. Zone 1 and zone 7 take \( u(1) \) as the bisection line, and the bisection lines of other zones are the same. It is considered that the reference value of APF output voltage vector \( u' \) will not change within one switching period, and it can be proved that when the value of DC side voltage \( E \) is large enough, \( u' \) will always fall within the 6-sided region shown in Figure 3, so that the bias current can be controlled.

When APF starts up or the system suffers from large disturbance, the deviation current value is relatively large. The end point of the deviation current \( \Delta i \) is usually located in the compulsory control area. If the number of the compulsory control area is set as, then the deviation current value is selected as the output voltage vector of APF, which can maximize the projection in the opposite direction so that the end point will move to the soft control area as fast as possible. If the end point is located in the soft control area, then according to the position of the and, the projection in the reverse direction will be minimized, and the end point will move to the target area as slowly as possible, which is beneficial to prevent the occurrence of rapid reverse overshoot, reduce the number of switches and the content of higher harmonics. After entering the target area, the controller keeps the previous beat unchanged until it leaves the target area again and the controller chooses to implement control again.

4. Grey prediction of load current and generation of lead command signal

Article [7] applies the gray prediction method to the prediction of nonlinear load current and APF output current, and realizes the deadbeat control of APF. This paper combines the grey prediction of load current with the optimal voltage vector control strategy to further improve the compensation effect of the optimal voltage vector control APF.

The basic method of signal gray prediction is to take into consideration the prediction accuracy and calculation amount, and generally take 4 data to be predicted to form the original data column according to the sampling sequence.

\[
[x(k-3), x(k-2), x(k-1), x(k)]
\]

From which accumulated data columns are constructed

\[
x_{\Sigma}(i) = \sum_{j=1}^{i} x(j), \ i = k-3, k-2, k-1, k
\]

Calculate coefficients a and b according to the following formula:

\[
[a \ b]^T = (M^T M)^{-1} M x^*
\]

In which,

\[
M = \begin{bmatrix}
x_{\Sigma}(k-2) - x_{\Sigma}(k-3) & 1 \\
x_{\Sigma}(k-1) - x_{\Sigma}(k-2) & 1 \\
x_{\Sigma}(k) - x_{\Sigma}(k-1) & 1
\end{bmatrix},
\]

\[
x^* = \begin{bmatrix}
x(k-2) \\
x(k-1) \\
x(k)
\end{bmatrix}
\]

Solving differential equation

\[
x_{\Sigma}(t) + ax_{\Sigma}(t) = b
\]

It can be obtained

\[
x_{\Sigma}(k + p) = \frac{b}{a} + [x(k-3) - \frac{b}{a} e^{-a(k+p-1)}]
\]

In which, \( p \) is called prediction step size.

The predicted value of the original data ahead of the current time \( p \) beat is

\[
x(k + p) = x_{\Sigma}(k + p) - x_{\Sigma}(k + p - 1)
\]
For the original values of the three-phase load current at the four consecutive sampling times of rolling refresh, the gray prediction algorithm is used to obtain the predicted values of the three-phase load current \( i_{k+p} \) ahead of the current time \( p \) beat, then the fundamental active current component of the load current is obtained through park transformation, low-pass filtering and park inverse transformation, and finally the APF compensation current command value \( i^*_c \) is formed. The calculation flow of is shown in Figure 4. The grey prediction module in the Figure is written by s function of MATLAB, and

\[
C = \sqrt{2} \frac{1}{3} [\cos \theta \cos(\theta - \frac{2\pi}{3}) \cos(\theta + \frac{2\pi}{3})]
\]

Is the row of orthogonal park matrix corresponding to the active current \( \hat{i}_d \) in dq coordinate system.

In which, the phase signal \( \theta = \omega t \) is provided by a phase locked loop PLL. The dq coordinate system rotates with fundamental frequency of power supply voltage \( \omega \) and ABC positive phase sequence direction, and d axis leads q axis \( \pi / 2 \). \( \hat{i}_{ds} \) is the DC component of \( \hat{i}_d \). \( \hat{i}_{ls} \) is the fundamental active current component in ABC coordinate system. While the command current \( i^*_c \) is equal to the harmonic of the load current \( p \) beat ahead of the current moment and the inverse value of the fundamental reactive current.

The control based on this advanced command current can effectively reduce the hysteresis effect of APF output compensation current caused by APF output filter inductance, signal conditioning circuit and operation, and obtain better compensation effect.

Figure 4. The calculation flow of leading current instruction

5. Simulation and analysis
Matlab / Simulink is used to simulate and compare the compensation effects of the three-phase APF shown in Figure 1 under the conventional voltage vector control and the gray prediction-voltage vector control proposed in this paper. The parameters of APF are: DC side voltage = 350 V; Filter inductance \( l = 7mH \); The inner and outer ring widths of the bias current are about 2% and 5% of the system current peak, respectively. Grey prediction step \( p = 2 \). The supply line voltage is 190 V. The load types are respectively three-phase rectifier variable resistance load, three-phase fully controlled rectifier variable resistance load and three-phase asymmetrical rectifier resistance load. The three load circuits, the load side current and the power supply side current compensated by APF are shown in Figure 5 (a), (b) and (c) respectively. Because there is little difference between the simulation curves under the conventional voltage vector control and the gray prediction-voltage vector control, the simulation curves under the gray prediction-voltage vector control are only shown in the figure. As can be seen from Figure 5, regardless of whether conventional voltage vector control or gray prediction-voltage vector control is used, APF has good compensation and tracking capability regardless of whether the load is symmetrical or time-varying, but the steady state THD under the two control modes is different, and the latter effect is better, as shown in Table 1. The resistance load is specially used in the load circuit. Compared with resistive-inductive load, the change of load current is more drastic at this time, and the effect of grey prediction is the worst. This is to evaluate the compensation effect of the gray prediction-voltage vector control APF under relatively harsh conditions. From Figure 4, it can
also be seen that the compensated power supply side current has burrs at the positions corresponding to the abrupt change points of the load current rate, and the same is true of the observation results of the experimental device. In voltage vector control, dynamically adjusting the hysteresis width of bias current can reduce glitches and reduce the operating frequency of switching devices and APF losses. An improved grey prediction algorithm is expected to achieve good results in reducing burrs by combining it with the dynamic adjustment of current hysteresis width. Relevant research authors are currently in progress.

6. Conclusion
The new control strategy of grey prediction - voltage vector control APF is studied. In terms of voltage vector control, the concepts of target area, soft control area and strong control area are condensed, and the current deviation double hysteresis voltage vector control strategy is clearly and concisely expounded. In the aspects of load current grey prediction and APF lead command current generation, the grey prediction parameters suitable for APF experimental system are determined. The simulation and comparative analysis under the pure resistance dynamic and unsymmetrical load conditions show that the grey prediction - current double loop voltage vector control APF can further improve the compensation accuracy and reduce the harmonic distortion rate of the current on the power supply side on the basis of maintaining the advantages of the conventional voltage vector control APF.

![Figure 5. Load circuit and simulation curves](image)

Table 1. APF in steady state under two kinds of control methods compensation comparison

| Three-phase load type                  | THD/ % | Power source current |                  |
|---------------------------------------|--------|----------------------|------------------|
|                                       | Load current | Conventional voltage vector control | Grey prediction - voltage vector control |
| Rectifying variable load              | 31.1   | 8.7                  | 7.7              |
| Controllable rectification variable load | 35.4   | 12.1                 | 11.3             |
| Asymmetrical rectification load       | 21.3*  | 8.7                  | 7.6              |

Note: the standard * is the three-phase average.
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