Harmonic compensation of APF based on unconstrained CCS-MPC

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Abstract: Active power filter (APF) is a device that can suppress harmonics and compensate reactive power. In order to improve the ability of three-phase active power filter (APF) to track and compensate harmonics in real time, an unconstrained CCS-MPC method based on state space model is proposed. Compared with variable constraint, it has faster response speed and less computation. Firstly, the time domain model of APF is established, and the discrete space state model is changed. The system state and output prediction equations are established iteratively to solve the objective function. The closed-loop solution of APF following harmonic is solved by using the open-loop objective function to achieve the purpose of feedforward and feedback. Finally, the simulation model is established, and the results show that the method has better dynamic response, steady-state characteristics and robustness.

1. Introduction
The large use of power electronic devices and the process of new energy grid connection generate a large number of harmonics, which will lead to the distortion of current and voltage waveforms in the distribution network, bring pollution and consumption of reactive power, as well as unbalanced power quality problems. These power quality problems will bring hidden dangers to the safe and efficient operation of equipment, and even cause industrial accidents. At the same time, due to the use of various advanced equipment, the power quality of the grid has higher requirements, so the governance of power quality has important practical significance. Active power filter (APF) is a widely used harmonic control and harmonic compensation device.

For the control of APF, including AC internal loop control and DC voltage control, the DC side of APF is generally controlled by PI. AC side is the key technology of APF control, which largely determines its compensation effect. Many control methods have been proposed for AC test control. In reference [1], a hierarchical repetitive control method is proposed to improve the dynamic performance of APF. In reference [2], a neural network control method for APF is proposed to improve the compensation accuracy of APF. The APF structure without harmonic detection is proposed in reference [3], which improves the accuracy of APF. An adaptive robust predictive current control method is proposed in reference [4]. Model predictive control (MPC) is a method with rapid development in industry, and it is used in power electronic devices soon. A finite set model predictive control method is proposed in reference [5], which has fast dynamic response, but the switching frequency is not fixed.

In this paper, a negative feedback control method based on discrete state space model is proposed to control AC measurement of APF. According to the discrete state space model of APF, the state prediction and output prediction are carried out, and the real-time feedback coefficient is solved to
obtain the control increment. Unconstrained CCS-MPC does not need to establish the weight matrix and output matrix, which avoids the selection and optimization of its weight coefficient, and does not need to establish constraints on the state quantity and output increment. In the process of calculating the feedback coefficient in real time to solve the control increment, it can quickly get the feedback coefficient and follow the detected three-phase harmonics in time, which ensures the real-time and dynamic performance of APF control. The validity and feasibility of the theory and method are verified by simulation.

2. APF structure and mathematical model
The main circuit structure of three-phase three wire APF is shown in Fig. 1. \(e_a, e_b, e_c\) are grid voltage, \(i_{ca}, i_{cb}, i_{cc}\) are output compensation current of APF, \(i_{La}, i_{Lb}, i_{Lc}\) are load current, \(L \) and \(R \) are filter inductors and equivalent resistance, \(C \) is DC side capacitors.

![Fig.1 Schematic diagram of APF](image)

According to the above figure, assuming the three-phase balance of the system, the dynamic system expression of equation (1) can be established by Kirchhoff current law, where \(u_{ca}, u_{cb}, u_{cc}\) are the output voltage of APF.

\[
\begin{align*}
L \frac{di_a}{dt} &= e_a - R i_a - u_{ca} \\
L \frac{di_b}{dt} &= e_b - R i_b - u_{cb} \\
L \frac{di_c}{dt} &= e_c - R i_c - u_{cc}
\end{align*}
\]

(1)

According to formula (1), the state space model of three-phase two-level APF is established by setting the state variable as \(X=[i_a; i_b; i_c]\) and input as \(U=[e_a-u_{ca}; e_b-u_{cb}; e_c-u_{cc}]\).

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

(2)

By discretizing equation 2, the APF discrete state space model of equation 3 can be obtained

\[
X(k + 1) = \tilde{A}X(k) + \tilde{B}U(k)
\]

(3)

Among them.

\[
\tilde{A} = e^{AT}, \quad \tilde{B} = (e^{AT} - I)A^{-1}B
\]

(4)

3. Calculation of reference harmonics
APF is a kind of power electronic device which works by injecting the reference back into the power grid. One of its key points is to calculate the reference current. At present, the most widely used method is the IP IQ method proposed by H. Akagi. Its basic principle is to detect the three-phase current of the
load and send it to the IP IQ module. The load current is transformed from the three-phase static coordinate system to the d-q coordinate system. Through the low-pass filter, only the fundamental current is left. The load current is subtracted from the fundamental current, and only the harmonic current is left. After inverse transformation, it is taken as the reference current of APF. At the same time, the DC side capacitor voltage is controlled. The reference value of capacitor voltage $U^{*}_{DC}$ subtracts the current measured value. Through PI control, it is used as active current to maintain the stability of DC side capacitor voltage and ensure the AC measurement of APF and bidirectional flow of energy at DC side. Compared with PQ method, it has better dynamic performance. The specific schematic diagram is shown in Figure 2.

![Fig.2 Schematic diagram of ip-iq harmonic detection](image)

The reference value of unconstrained CCS-MPC of APF was established as $X_{ref} = [i_{ah}, i_{bh}, i_{ch}]$.

4. Unconstrained CCS-MPC of APF

4.1. Establishment of prediction model

According to APF's discrete space state mathematical model formula 3, in order to reduce and eliminate static error, incremental model is adopted.

$$\Delta x(k+1) = A\Delta x(k) + B\Delta u(k)$$
$$y(k) = C\Delta x(k) + y(k-1)$$

With

$$\Delta x(k) = x(k) - x(k-1)$$
$$\Delta u(k) = u(k) - u(k-1)$$
$$\Delta d(k) = d(k) - d(k-1)$$

If the prediction domain is $p$ and the control domain is $m$, equation 7 can be obtained by recursive iteration

$$\Delta x(k+p|t) = \hat{A}_t^{p}\Delta x(k+p-1|t) + \hat{B}_t\Delta u(k+p-1|t)$$
$$\Delta x(k+p-1|t) = \hat{A}_t^{p-1}\Delta x(k+p-2|t) + \hat{B}_t\Delta u(k+p-2|t)$$
$$...$$

$$\Delta x(k+1|t) = \hat{A}_t\Delta x(k|t) + \hat{B}_t\Delta u(k|t)$$
$$\Delta x(k|t) = \hat{A}_t\Delta x(k-1|t) + \hat{B}_t\Delta u(k-1|t)$$

Similarly, the predicted output is as follows:

$$y(k+p|t) = \hat{C}_t\hat{A}_t^{p}\Delta x(k|t) + \hat{C}_t\hat{B}_t\Delta u(k|t) + \ldots + \hat{C}_t\hat{A}_t^{p-m}\Delta u(k+m|t)$$
According to equations 7 and 8, the future prediction equation of APF can be obtained as follows:

\[ Y(k+1) = \Psi \Delta x(k) + \Theta \Delta U(k) + I \Delta y \]  

(9)

With

\[ Y(k+1) = \begin{bmatrix} y(k+1|k) \\ \vdots \\ y(k+p|k) \end{bmatrix}, \quad \Psi_t = \begin{bmatrix} \tilde{C}_r \tilde{A}_t \\ \vdots \\ \tilde{C}_r \tilde{A}_t^p \end{bmatrix}, \quad \Delta U(k) = \begin{bmatrix} \Delta u(1|k) \\ \vdots \\ \Delta u(k+m|k) \end{bmatrix} \]

(10)

4.2. Unconstrained CCS-MPC

The principle of model predictive control is to solve the optimization problem, and the first element of the solution of the optimization problem is applied to the system. Firstly, the weight factor of each state quantity is set as \( Q = \text{diag} [q_1, q_2, \ldots, q_p] \) and \( \Theta = \text{diag} [\Theta_1, \Theta_2, \ldots, \Theta_m] \). The reference is \( R(k+1) = [X_{t^1}(k+1); X_{t^2}(k+2), \ldots, X_{t^n}(k+p)] \). At the same time, in order to make the control action not too large, the objective function of equation 11 is adopted.

\[ J = \sum_{i=1}^{m} \left\| \tilde{h}_i (X_{t^1}(k+1) - Y(k+1)) \right\|^2 + \sum_{i=1}^{m} \left\| h_i \Delta u(k + i - 1) \right\|^2 \]  

(11)

Hi is the weight factor of the constraints on the NC control increments at the i-th moment. The larger the hi is, the smaller the expected change of control action is. The open-loop optimization problem of equation 12 is established.

\[ \min_{\Delta U(k)} J(x(k), \Delta U(k), m, p) \]  

(12)

4.3. Optimization problem solving

It can be obtained that the optimal control sequence at time k is equation 14

\[ E_p(k+1) = X_{t^1}(k+1) - \Psi^T \Delta x(k) - I \Delta y(k) \]

(13)

\[ \Delta U^*(k) = (\Theta^T Q^T Q \Theta + H^T H)^{-1} \Theta^T Q^T Q E_p(k+1) \]

The first group of control sequence is applied to APF, so the control gain can be defined as.

\[ g_{mpc} = \begin{bmatrix} 1_{m=nc} & 0 & \ldots & 0 \end{bmatrix} (\Theta^T Q^T Q \Theta + H^T H)^{-1} \Theta^T Q^T Q E_p(k+1) \]

(14)

So, the control input increment is:

\[ \Delta u(k) = g_{mpc} E_p(k+1) \]  

(15)

5. Simulation Analysis

In order to verify the effectiveness of LQR and synovial control strategy, a simulation model is build and the parameters are shown in Table 1. The harmonic source is an uncontrollable diode rectifier bridge. When it is set at 0.3s, the load fluctuates. The reference current is the harmonics detected by \( i_{pr}, i_q \) method.
Table.1 Simulation model parameters

| Parameters       | Value     |
|------------------|-----------|
| Grid Voltage     | 380V      |
| DC Voltage       | 800V      |
| Capacitor C      | 3000μF    |
| Inductor         | 4mH       |
| Resistor         | 0.01Ω     |
| Load Resistor    | 10Ω       |

By setting the parameters above the simulation model and running the simulation in Simulink, we can get the simulation diagram of Fig. 3, which can reflect the dynamic performance and stability performance of the algorithm.
Fig.3, (a) is the three-phase load current; (b) is the three-phase current after compensation; (c) is the DC side voltage control; (d) the total harmonic distortion rate of the current; (e) THD change chart

It can be seen from (a) that the harmonics of the power grid are 5, 7, 11, 13. (b) for the result of using unconstrained CCS-MPC algorithm to control APF for compensation, the current waveform is close to sine wave, and has fast dynamic performance. When the load changes, it can track and compensate the harmonic well. The THD of (f) is 1.87%, which meets the harmonic requirements of power grid. The control method has good tracking performance and can keep a small tracking error.

6. Conclusion
In this paper, based on the discrete state space mathematical model of APF, a MPC control method is proposed to reduce the computational load. It has real-time dynamic feedback coefficient and improves the compensation accuracy of APF. This method weakens the influence of circuit parameters and system disturbance on steady-state and dynamic performance. Simulation and experimental results show that the proposed control strategy can track and compensate harmonics generated by nonlinear load accurately and timely.

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