Research on Finite Control Set Model Predictive Control Strategy of Three-level APF

Hang shi¹, XueJiao Gong¹*, GongSangPuChi¹ and JuanJuan Zhang¹

¹ Electric Engineering College, Tibet Agriculture & Animal Husbandry University
860000, China

* sushe11203@126.com

Abstract. Active power filters (APF) can compensate for harmonics and reactive power. The traditional APF PI control has difficulty in parameter setting, and has the characteristics of control lag, and the control accuracy of current is low. The control of three-level APF needs to consider multiple objectives. Finite Control Set Model Predictive Control (FCS-MPC) is a newly proposed method that can increase constraints and multi-objective control. According to the limited switching state, it tracks the reference current and has dynamic Fast response and good compensation results. In this paper, the finite set model predictive control algorithm of three-level APF is studied, and the results show that the harmonic content of the power grid is low, which meets the relevant requirements.

1. Introduction
Nowadays, many power electronic devices are used in people's daily life. Because of their nonlinear characteristics, the harmonic pollution caused by them has become more and more serious. Since their discovery, they have attracted people's attention in related fields. For the problem of harmonic suppression, people have also proposed a lot of treatment methods, including starting from the harmonic source, improving the topological structure, and reducing the occurrence of harmonics, including the use of three-level structure or high-frequency pulse width modulation technology. The most widely used type of passive management is to add harmonic compensation devices to the power grid. The most used is APF, which injects the detected harmonic currents into the power grid in the opposite direction and can also compensate for reactive power.

The harmonic frequencies that APF can manage are widely distributed, so they are used in various occasions. Many algorithms are also proposed for APF control, and the stability and reliability of its application have been further improved. The three-level APF, because of its special structure, can output more vector combinations, and because it is also a harmonic source, its special structure makes its impact on the power grid lower [1, 2]. Literature [2] proposed a three-level APF sliding model control, which is a traditional nonlinear control method that can stably control the harmonic content of the power grid, but the calculation is large, and the control has the problem of delay. MPC opinions are applied to many areas of power electronics, such as two-level converters, multi-level converters, and SVG.

The FCS-MPC of the three-level APF studied in this paper has a clear physical meaning and is easy to understand. It is improved from the traditional MPC to the field of converter control. The basic principle is to establish a discrete mathematical model of the control object, calculate the predicted current value according to different switch vector outputs, establish a value function, find the optimal
switch combination under the minimum value function, and apply it to the APF. The APF DC side capacitor voltage adopts PI control, and the weight coefficient control is added to the three-level two capacitor voltage balance.

2. The structure and mathematical model of three-level APF

2.1. Topology

The main circuit structure diagram of the three-phase three-wire APF is shown in Fig.1. \(e_a, e_b, e_c\) are the grid voltages, \(i_{ca}, i_{cb}, i_{cc}\) are the output compensation currents of the APF, \(i_{La}, i_{Lb}, i_{Lc}\) are the load currents, and \(L\) and \(R\) are filter inductance and equivalent resistance, \(C_1\) and \(C_2\) are DC side balancing capacitors, and their capacitance values are equal.

![Fig.1 Structure diagram of three-level APF](image)

For the three-level APF, each bridge arm has 4 points of IGBT, and there are 27 different switching states in total. From this, it can be defined that the formula of the switching function is equation (1).

\[
S_x = \begin{cases} 
P & S_{x1} = S_{x2} = 1, S_{x3} = S_{x4} = 0; \\
0 & S_{x1} = S_{x4} = 0, S_{x2} = S_{x3} = 1; \\
N & S_{x1} = S_{x2} = 0, S_{x3} = S_{x4} = 1; 
\end{cases} 
\]  

(1)

The 27 switching states of the three-level APF can generate 19 different voltage vectors, including three sets of zero vectors and 12 sets of redundant vectors. These 27 switching states and vectors can be expressed as Fig. 2.

![Fig.2 27 sets of switches vector](image)
2.2. Mathematische(al) model of three-level APF
According to the structure diagram of Fig. 1, the mathematical model of a, b and c three-phase can be obtained as equation (2), where $u_{ca}$ is the output voltage value of APF.

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

(2)

Since in the three-phase coordinate system, the current output tracking reference value will have cumulative errors, the mathematical model is established in the $\alpha$-$\beta$ coordinate system.

$$
\begin{align*}
L \frac{di}{d\alpha} &= u_{\alpha} - e_{\alpha} - R i_{\alpha} \\
L \frac{di}{d\beta} &= u_{\beta} - e_{\beta} - R i_{\beta}
\end{align*}
$$

(3)

The dynamic equation of DC side capacitor $C_1, C_2$ is equation (4)

$$
\begin{align*}
\frac{du_{i1}}{dt} &= \frac{1}{C} i_{i1} \\
\frac{du_{i2}}{dt} &= \frac{1}{C} i_{i2}
\end{align*}
$$

(4)

3. finite control set model predictive control of three-level APF

3.1. FCS-MPC principle of current
In the $\alpha$-$\beta$ coordinate system, there are 27 voltage vectors in total. The principle diagram of predictive control is shown in Fig. 3. At each sampling moment, all switching states are cycled in turn, and the detected harmonic current value is used as the reference value. Find the variance with the predicted value. At the same time, add the item to balance the capacitor voltage, carry out the weight factor distribution, integrate all the reference tracking values, select the switch state that minimizes the value function, and output to the APF. This method can be cycled later to track the harmonic current in real time. And wireless pulse width modulation (PWM).

3.2. FCS-MPC of three-level APF
After discretizing the difference of equations (3) and (4), equations (5) and (6) are obtained
\[
\begin{align*}
\begin{cases}
i_{c}(k+1) = \frac{T}{L} u_{c}(k) - \frac{T}{L} e_{c}(k) + (1 - \frac{RT}{L}) i_{c}(k) \\
i_{p}(k+1) = \frac{T}{L} u_{p}(k) - \frac{T}{L} e_{p}(k) + (1 - \frac{RT}{L}) i_{p}(k)
\end{cases}
\end{align*}
\]

(5)

\[
\begin{align*}
u_{c}(k+1) &= \frac{1}{C} i_{c}(k) T + u_{c}(k) \\
u_{p}(k+1) &= \frac{1}{C} i_{p}(k) T + u_{p}(k)
\end{align*}
\]

(6)

The \(i_{c1}(k)\) and \(i_{c2}(k)\) in equation (6) are the current values determined by the switch and the output current together, which are defined by equation (7).

\[
\begin{align*}
i_{c1}(k) &= i_{c}(k) - G_{1x} i_{c}(k) - G_{2x} i_{c}(k) \\
i_{c2}(k) &= i_{c}(k) + G_{1x} i_{c}(k) + G_{2x} i_{c}(k)
\end{align*}
\]

(7)

\(G_{1x}, G_{2x}\) are determined by the current switch state, and their value is represented by equation (8), \(i_{c}(k)\) is the current on the DC side at the current moment.

\[
G_{1x} = \begin{cases} 1, & S_{x} = P \\ 0, & \text{others} \end{cases}
\]

(8)

\[
G_{2x} = \begin{cases} 1, & S_{x} = N \\ 0, & \text{others} \end{cases}
\]

Since the reference harmonic current is at the current moment, the second-order LaGrange interpolation prediction is performed on it

\[
i^\ast(k+1) = 4i^\ast(k) - 6i^\ast(k-1) + 4i^\ast(k-2) - i^\ast(k-3)
\]

(9)

According to the above prediction equation, the cost function of equation (10) can be established

\[
J = \lambda_{1} \|i_{c1}(k+1) - i_{c1}(k+1)\|^2 + \lambda_{2} \|i_{c2}(k+1) - i_{c2}(k+1)\|^2 + \lambda_{3} \|u_{c1}(k+1) - u_{c2}(k+1)\|^2
\]

(10)

### 4. Simulation Analysis

In order to verify the effectiveness of the FCS-MPC control strategy for the three-level APF, a simulation model was built in MATLAB/Simulink, and the parameters are shown in Table 1. The harmonic source is an uncontrollable diode rectifier bridge, and the load fluctuates at 0.3 seconds. The reference current is the harmonics detected by the \(ip-iq\) method. Take \(\lambda_{1} = \lambda_{2} = 0.45\) and \(\lambda_{3} = 0.1\).

| Parameters | Value  |
|------------|--------|
| Grid Voltage | 380V   |
| DC Voltage  | 800V   |
| Capacitor \(C_{1}\), \(C_{2}\) | 3000μF |
| Inductor    | 4mH   |
| Resistor    | 0.01Ω  |
| Load Resistor | 10Ω   |

Set the above parameters of the simulation model, and run the simulation in Simulink, you can get the simulation diagrams in Fig. 4, which can reflect the dynamic performance and stability of the algorithm.
Fig. 4 (a) is the three-phase load current; (b) is the detected three-phase harmonic; (c) is the grid current after compensation; (d) is the APF output tracking A phase harmonic effect diagram, (e) Is the voltage value of capacitors $C_1$ and $C_2$; (f) is the total harmonic distortion rate at 2.35 seconds.

It can be seen from (a) that the harmonics of the power grid are mainly 3, 5, and 7 order harmonics, and the harmonic content is relatively high. It is detected by the $ip-iq$ method, and (b) is the detected three-phase harmonic current. (c) As the result of applying FCS-MPC algorithm to control the APF for compensation, the current waveform is close to a sine wave and has fast dynamic performance. When the load changes, it can track and compensate the harmonics well and perform FFT analysis on them. (d) In (f), the THD is 2.07%, which meets the harmonic requirements of the power grid. It can be seen from (d) that this control method has good following performance and can maintain a small tracking error. The key point of the three-level is the balance of the DC side capacitor voltage. The corresponding weighting factor is added to the value function. It can be seen from (e) that the capacitor voltage balance performance is good, and the expected value can be quickly reached after the load changes.
5. Conclusion
Because of its structure, the three-level APF has a richer output voltage vector, a better compensation effect, and a lower harmonic content. The three-level capacitor voltage balance is also the key to its control. In establishing a dynamic mathematical model for it, adding weight factors to control it reduces the complexity of its control. It also has a better performance through simulation verification. The current maintains a low harmonic content, which proves the effectiveness and feasibility of this method. Because the selection of multiple weighting factors is a complicated and difficult to optimize problem, reducing the distribution of weighting factors is a direction that needs to be considered.

Acknowledgement
Natural Science Foundation of Tibet Autonomous Region (XZ2019ZRG-52(Z))

References
[1] Vodyakho and C. C. Mi, "Three-Level Inverter-Based Shunt Active Power Filter in Three-Phase Three-Wire and Four-Wire Systems," in IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1350-1363, May 2009, doi: 10.1109/TPEL.2009.2016663.
[2] S. Sezen, A. Aktas, M. Ucar and E. Ozdemir, "A three-phase three-level NPC inverter based grid-connected photovoltaic system with active power filtering," 2014 16th International Power Electronics and Motion Control Conference and Exposition, Antalya, 2014, pp. 1331-1335, doi: 10.1109/EPEPEMC.2014.6980697.
[3] B. Singh, K. Al-Haddad, and A. Chandra, "Active power filter with sliding mode control," in IEE Proceedings - Generation, Transmission and Distribution, vol. 144, no. 6, pp. 564-568, Nov. 1997, doi: 10.1049/ip-gtd:19971431.
[4] A. Fahmy, M. S. Hamad, A. K. Abdelsalam and A. Lotfy, "Power quality improvement in three-phase four-wire system using a shunt APF with predictive current control," IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, 2012, pp. 668-673, doi: 10.1109/IECON.2012.6388748.
[5] B. Peng and G. Zhang, "A Single-Objective FCS-MPC Method for Three-Level APF," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 2916-2921, doi: 10.1109/ECCE.2019.8912274.