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# Multistep finite-control-set model predictive control of active power filter

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Abstract. The traditional finite-control-set model predictive control (FCS-MPC) of three-phase active power filter (APF) has the problems of low compensation precision and long control delay. In order to address this problem, this paper proposes a multistep prediction compensation control method for the FCS-MPC of APF, it does not require modulation of PWM link. By utilizing the discrete mathematic model of three-phase parallel APF and keeping the advantages of traditional FCS-MPC, the prediction model is established based on the structural model of traditional FCS-MPC, the predictive controller is designed for predictive control of DC-side voltage. AC-side current and fixed switching frequency, and simulation study is also conducted. The simulation results show that the multi-step predictive control method can effectively track and compensate harmonic, reduce the harmonic component of power grid, and increase the compensation precision of parallel APF.

#### 1. Introduction

In this paper, APF is used to verify the feasibility of multistep FCS-MPC algorithm [1]. In APF, its discrete mathematic model is used to predict the output of APF according to different combination switching state, so that APF can build the objective function in accordance with the harmonic detected by the system by combining the switching changes and different requirement. In the objective function, an optimal group of switching state is chosen, and the switching signal directly works on the APF to ensure that its output can compensate the power harmonics, which does not require the pulse width modulation (PWM) and modulation technique [2]. FCS-MPC has become a main control method in the field of converter control [1-4]. In the FCS-MPC method, the generated switching signal directly works on the converter, which has addressed the problem of system delay and signal loss caused by PWM and improved the response speed and compensation performance of using APF to compensate harmonics.

The basic principle FCS-MPC is introduced in Literature [2], and it is also compared with the classic PI control method, which proves that this control method has fast response and high steady-state precision [2]. In Literature [3], they proposed the application of FCS-MPC in the field of converter for the first time, which was used for current prediction and control of three-phase filter. Literature [4] introduces an objective function for optimization of delay and switching frequency. FCS-MP has also been applied to converter, and become an effective control method for APF [5]. Even though FCS-MPC has improved the response speed and stability of harmonic compensation, there is still an inevitable problem of conservative property during the control process. During the process of obtaining optimal switching state, only the optimal solution at moment k+1 can be obtained, while the optimality at moment k+2 and later cannot be verified.

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In order to address the shortages of delay and low precision of single-step FCS-MPC, in this paper, we analyze the topologic structure of three-phase APF first, and build the current loop and DC-side discrete mathematic model of APF; then, the power harmonics detection method is analyzed. Based on the mathematic model, the principle of multistep FCS-MPC is analyzed, the comprehensive assessment objective function is established, and control signal is generated by the controller and then works on APF, which has accelerated the dynamic characteristics of APF compensation and DC-side stability performance. By building the simulation model of system and comparing the performance of proposed method with that of single-step FCS-MPC, the superiority of multistep FCS-MPC algorithm under power feedforward is verified.

# 2. Mathematical Model of Three-phase Two-level Parallel APF

#### 2.1. APF model

The topological structure of three-phase two-level APF is as shown in Fig.1, in which, the DC side is the capacitor voltage, the AC-side output of filter is connected to the power grid through filter inductance L, and R is its equivalent resistance. iLa, iLb and iLc are the load current of power grid, the grid current is represented as ea, eb and ec, Udc is the DC-side capacitor voltage, and the compensation output of APF is expressed by ica, icb and icc. In the switching motion of APF, three groups of bridge arms Sa, Sb and Sc are defined as only having two switching states. In order to prevent short circuit of APF when they are simultaneously closed or turned off.



Fig.1 Structure diagram of APF

Under different switching state combinations of switching signals Sa, Sb and Sc, 8 voltage vectors can be obtained in total, including two groups of zero vectors: "Sa=0, Sb=0, Sc=0" and "Sa=1, Sb=1, Sc=1", which means there is no output. The switching states and voltage vectors are listed in Table 1.

Table.1 Switching states and voltage vectors				
$S_a$	$S_b$	$S_c$	Voltage vector V	
0	0	0	$\mathbf{V}_0=0$	
1	0	0	$V_1 = 2V_{dc}/3$	
1	1	0	$V_2 = V_{dc} / 3 + j \sqrt{3} V_{dc} / 3$	
0	1	0	$V_{3} = -V_{dc} / 3 + j \sqrt{3} V_{dc} / 3$	
0	1	1	$V_4 = -2V_{dc}/3$	
0	0	1	$V_{5} = -V_{dc} / 3 - j \sqrt{3} V_{dc} / 3$	
1	0	1	$V_6 = V_{dc} / 3 - j \sqrt{3} V_{dc} / 3$	
1	1	1	V <sub>7</sub> =0	

Table.1 Switching states and voltage vectors

#### 2.2. Mathematic(al) model of APF

According to the dynamic load current, based on the topological structure of three-phase two-level parallel APF as shown in Fig.1, the voltage vector equation for each phase can be established, as shown in (1) below.

IOP Conf. Series: Earth and Environmental Science 617 (2020) 012039 doi:10.1088/1755-1315/617/1/012039

$$\begin{cases} v_{aN} = L \frac{di_a}{dt} + Ri_a + e_a + v_{nN} \\ v_{bN} = L \frac{di_b}{dt} + Ri_b + e_b + v_{nN} \\ v_{cN} = L \frac{di_c}{dt} + Ri_c + e_c + v_{nN} \end{cases}$$
(1)

According to (1), the dynamic load current for each phase can be represented as the equation in (2), the vector differential in equation of dynamic load current can be obtained, as shown in (3). V is the output voltage vector of converter; i is the load current vector; e is the load voltage vector, and in the simulation and experiment, e is the sine grid voltage with fixed amplitude and frequency.

$$\mathbf{v} = R\mathbf{i} + L\frac{d\mathbf{i}}{dt} + e \tag{2}$$

$$\mathbf{v} = L \frac{d}{dt} \left( \frac{2}{3} (i_a + ai_b + a^2 i_c) \right) + R \left( \frac{2}{3} (i_a + ai_b + a^2 i_c) \right) + \frac{2}{3} (e_a + ae_b + a^2 e_c) + \frac{2}{3} (v_{aN} + av_{bN} + a^2 v_{cN})$$
(3)

#### $2.3.i_p$ - $i_q$ harmonic detection method

The harmonic detection method of APF is the ip-iq method based on the instantaneous reactive power theory [6]. The current harmonics after distortion are extracted from the three-phase load current, and see Fig.2 below for the specific schematic diagram.



Fig.2 Block diagram of the three-phase harmonic current reference generator

Where

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}, C_{dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix}.$$

#### 3. Predictive Control of APF

#### 3.1. FCS-MPC principle of current

The FCS-MPC of current may have error during tracking under sine signal, and the higher the frequency is, the bigger the error. Therefore, after the collected reference signal is output by the prediction model, make APF track the reference prediction signal in the  $\alpha$ - $\beta$  coordinate system, to provide convenient and intuitive results.

The schematic diagram of the current and voltage predictive control for APF is as shown in Fig.3, in which,  $\Delta$ ip is the predicted active current component of APF, ip is the predicted current, and i\*(k) is the reference current of harmonic at current moment. In general, measures should be taken to obtain the difference between the DC side and the reference value, conduct voltage stability control using the PI regulator, and conduct compensation along with harmonics. The objective function should be used to obtain the optimal switch combination, which should directly work on APF. The output compensation current of APF should be controlled to track the harmonic at current moment though the reference signal at predicted moment.

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Fig.3 Diagram of APF predictive control principle

## 4. Single-step FCS-MPC of APF

#### 4.1. Single-step FCS-MPC

Discretize (2) of last section, and set the sampling time as Ts. This discrete time model predicts the output current of APF of next moment according to the sampling voltage and measured current at moment k. By discretizing the differential element in the above differential equation, (2) can be substituted into (4) to obtain the current prediction model equation (5).

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T_{c}} \tag{4}$$

$$i^{p}(k+1) = \left(1 - \frac{RTs}{L}\right) \cdot i(k) + \frac{Ts}{L} \left(v(k+1) - e(k+1)\right)$$
(5)

In a small sampling period, the RTs term can be ignored. The grid voltage e(k+1) and reference current  $i^*(k+1)$  need to be estimated. Based on the Lagrange's interpolation equation (6), which can obtain the grid voltage and reference current at next moment. The second order or third order is generally used, the second-order interpolation is used in this paper, as shown in (7).

$$i^{*}(k+1) = \sum_{i=0}^{n} (-1)^{n-i} \frac{(n+1)!}{i!(n+1-i)!} \cdot i^{*}(k+i-n)$$
(6)

$$i^{*}(k+1) = 3i^{*}(k) - 3i^{*}(k-1) + i^{*}(k-2)$$
(7)

## 4.2. Establishment of objective function

The selection of objective function is critical to the control of APF output. The load harmonic reference current and the predicted value of APF output are transformed to the  $\alpha$ - $\beta$  coordinate system to compare the difference and obtain the square of difference. Then, the objective function as shown in (8) is established according to the DC-side voltage balance and switching frequency requirement, to choose the optimal switching state.

$$J = \|\hat{i}_{\alpha}^{*}(k+1) - i_{\alpha}^{p}(k+1)\|_{\lambda} + \|\hat{i}_{\beta}^{*}(k+1) - i_{\beta}^{p}(k+1)\|_{\lambda} + \gamma \cdot n_{sw}$$
(8)

where,  $\gamma = 1 - 2^* \lambda$ , in which,  $\lambda$  and  $\gamma$  are corresponding weight coefficients,  $n_{sw}$  is the switching frequency, and its definition is as shown in (9) below.

$$n_{sw} = \|S_{opt}(k+1) - S_{optx}(k)\|_{I}$$
(9)

# 5. Multistep FCS-MPC

#### 5.1. Multistep FCS-MPC

Because the single-step FCS-MPC has the conservative issue, this paper presents the three optimal control states generated by the objective function, the optimal state of next moment will be calculated.

By using the FCS-MPC, the predicted output of APF at next moment is ip(k+1). The three optimal switching states of Sopt1(k+1), Sopt2(k+1), Sopt3(k+1) can be obtained according to the objective function; then, apply these three switching states to (5) and (9), respectively, and obtain the solutions of

IOP Conf. Series: Earth and Environmental Science 617 (2020) 012039 doi:10.1088/1755-1315/617/1/012039

ip(k+1) and v(k+1); (5) can be obtained through backward differentiation of (5). In (5), continue to predict the output based on the three optimal states of ip 1(k+1), ip 2(k+1), ip 3(k+1) generated by single-step FCS-MPC.

$$i^{p}(k+2) = \left(1 - \frac{RTs}{L}\right) \cdot i^{p}_{x}(k+1) + \frac{Ts}{L}\left(v(k+2) - \hat{e}(k+2)\right) \qquad x = 1, 2, 3$$
(10)

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#### 5.2. Establishment of objective function

Based on the prediction in step 2, build the new objective function (11) and switching constraint (12). Transform the predicted output and harmonic current to the  $\alpha$ - $\beta$  coordinate system for tracking compensation.

$$J = \left\| i_{\alpha}^{*}(k+2) - i_{\alpha}^{p}(k+2) \right\|_{\lambda} + \left\| i_{\beta}^{*}(k+2) - i_{\beta}^{p}(k+2) \right\|_{\lambda} + \gamma \cdot n_{swp}$$
(11)

 $n_{swp} = \left\| S_{opt}(k+2) - S_{optx}(k+1) \right\|_{I} x = 1, 2, 3$ (12)

where,  $\gamma = 1-2^{*\lambda}$ ,  $\gamma = 1-2^{*\lambda}$  is the optimal switching state predicted in step 2, and the switch change can be obtained by subtracting the value obtained at moment k+1.

#### 6. Simulation Study

In order to verify the effectiveness and feasibility of the FCS-MPC method, the three-phase two-level parallel APF is used in the study. The model based on Fig.4 was built for analysis and verification of the algorithm. The specific parameters are listed in Table 2.

Table.2 Parameters of simulation model		
Parameter	Value	
Power grid voltage	380V, 50Hz	
DC-side capacitor	800V	
Inductance	4mH	
Equivalent resistance	0.1Ω	
Load resistance	8Ω	

With phase a as example. The load has sudden change at 0.15s, Fig.9 presents the single-phase harmonics and the oscillogram after compensation. Fig.4 (a) shows the tracking compensation effects of single-step FCS-MPC; Fig.4 (b) shows the tracking compensation effects of multistep FCS-MPC, which presents strong dynamic performance and better compensation effects.





The DC-side voltage adopts PI control of power. After the load change at 0.1s, it shows the characteristics of fast response and small ripple, which enables the DC-side voltage to be maintained at the reference value, as shown in Fig.5 (a).

By adding constraint on the switching frequency into the objective function, it can not only reduce the tracking compensation of APF, but also lower the switching frequency at the same time. The Number of groups changed by switch, as shown in Fig. 5 (b). The change is within 2 in each period, and partial compensation time is selected in this graph.



Fig.6 shows the graphs of power grid current before and after compensation. It is close to sine after compensation, and the FCS-MPC method can provide great compensation effects. (a) shows the compensation effects of single-step FCS-MPC; (b) shows the compensation effects of multistep, which are better than the effects of single-step FCS-MPC.



The FFT analysis is presented in Fig.7. After compensation, the THD satisfies the standard of grid total harmonic distortion of THD<5%. (a) shows the total harmonic distortion of the compensation results obtained with single-step FCS-MPC; (b) shows the total harmonic distortion of the compensation results obtained with multistep FCS-MPC, which presents great compensation performance.



#### 7. Conclusion

This paper presents the advantages of using multistep FCS-MPC for feedforward control of voltage in comparison with the single-step FCS-MPC, based on this method, a simulation model was built. The multistep FCS-MPC shows great dynamic performance with better control and compensation effects, and the harmonic component of power grid system is also lower. The DC-side voltage stability control of power feedforward has improved the compensation speed and steady-state performance and reduced the DC-side ripples, and the constraint on switching frequency has also reduced the loss caused by switch change. The results verify the effectiveness and feasibility of the proposed method, which can improve the compensation performance of APF. Similarly, multi-step FCS-MPC can also be applied to

control objects such as motors to reduce control errors caused by delays, which can be achieved in the future through mathematical models.

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