Study of the Modeling and Control Strategy for Active Power Filter

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Abstract. Improvement of active power filter’s performance through the reasonable control strategy is becoming a hot research for various counties’ scholars. In this paper, active power filter model is regarded as a starting point and the modeling process has been introduced in detail. For the following characteristics, such as harmonic current detection must be real-time and accurate, active power filter’s uncertainty and nonlinear, the harmonic current detection method which is based on instantaneous reactive power is used. In this way, harmonic current, reactive and negative sequence current in grid can be accurately tested out. The active power filter which is developed according to this current real-time detection algorithm can balance asymmetrical three-phase load. The simulation model is built in MATLAB/simulink. The simulation results show that this active power filter can be more rapid, accurate compensate harmonic current than the conventional active power filter.

1. Introduction

With the development of productivity, a large number of power electronic converter devices have been applied in modern industry. Most of these loads are nonlinear (such as frequency control devices, electric arc furnaces, rectifiers in distribution networks, etc.). This kind of load has the characteristics of impact and unbalance and produces a lot of harmonics. Harmonics do great harm to the safe operation of power grid and electrical equipment, mainly in the following aspects: result in higher additional loss, reduce the efficiency of power transmission and transformation, causes the pulsating torque of the motor, cause local overheating of transformer, vibration noise, affect the operation of relay protection device and electric meter, the high frequency harmonic will interfere with the communication system. At the same time, due to the complex composition of harmonics, certain frequencies of harmonics may cause local series or parallel resonance of the power grid, amplifying the above hazards[1]. In some special occasions for power quality request is higher, the inferior quality of power supply may cause inestimable, catastrophic[2]. According to relevant data show that in Europe each year because of the economic loss caused by power quality as high as $150 billion, but our country is still in the less developed state, so the power quality can be imagined, and the loss caused is even more impossible to estimate[3]. Power supply quality has a direct impact on the overall benefit of the national economy, how to improve power supply quality has become an urgent problem to be solved.
Harmonic pollution has caused great harm to modern industry. In order to deal with harmonics, many experts and scholars have done research, and have done a lot of research on harmonic detection technology, which is one of the key technologies of harmonic control. At present, harmonic current detection methods mainly include: P-Q method based on instantaneous reactive power theory, adaptive detection method and FBD method, etc [4].

According to the above problem, this article embarks from the mathematical model of the active filter, is proposed based on improved instantaneous reactive power compensation of harmonic current detection method, compared with traditional detection method, three-phase asymmetry in power grid or single phase short circuit occurs, this method still can make author introduction: accurately detect the harmonic current quickly, so that the active filter has better performance.

2. Principle and mathematical model of active power filter

The active power filter (APF) uses instantaneous filter formation technology to "correct" sine waves containing harmonic and reactive components. The core part mainly consists of two parts, one is the operation of instruction current, the other is the generation of compensation current. The main principles are briefly described as follows: First, harmonic current component $i_{Lh}$ and fundamental reactive current $i_{Lr}$ are separated from load current $i_L$ by the command current operation circuit. Then, the harmonic current component $i_{Lh}$ and the fundamental reactive current $i_{Lr}$ are acted against the polarity to issue the command signal $i_c = (i_{Lh} + i_{Lr})$ of compensation current. Finally, the compensation generator circuit $i_{co}$ tracks $i_c$ to calculate the trigger pulse of each switch device of the main circuit. After the pulse passes through the driving circuit, it acts on the main circuit to generate compensation current $i_{cc}$. As $i_c = i_{co}$, so:

$$i_s = (i_t + i_c) = (i_L + i_{co}) = i_L - (i_{Lh} + i_{Lr}) = i_{lp}$$

(1)

That is, the current contains only the active component of the fundamental wave, so as to achieve the purpose of eliminating harmonics and making reactive compensation.

Figure 1. The APF main circuit topology structure diagram.

The topology of the main circuit of the active power filter is shown in Figure 1. Where $e_a$, $e_b$, $e_c$, is the grid voltage, $i_{sa}$, $i_{sb}$, $i_{sc}$, is the grid current, $i_{ca}$, $i_{cb}$, $i_{cc}$, is the output current of the active power filter, $i_{la}$, $i_{lb}$, $i_{lc}$ is the load current, $U_{dc}$ is the voltage of the DC energy storage capacitor, $L$ is the output reactor, $L_s$ is the equivalent inductance of the transmission line, $L_1$ is the equivalent inductance of the load, C is the DC energy storage capacitor, $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, $S_6$ is the IGBT. Figure 2 shows the equivalent circuit of the active power filter.
Now make the following assumption, ignore the IGBT itself loss, and replace it with the ideal switch. As shown in Figure 1, Figure 2, $U_{dc}$ is constant, $e_a$, $e_b$, $e_c$ is the grid voltage, the resistance of the transmission line is equivalent to resistance $R$, and the inductance is represented by $L$. And the upper bridge arm through, the lower bridge arm broken for 1, the upper bridge arm broken, the lower bridge arm through for 0. The neutral point of grid voltage is selected as the voltage reference point. According to Kirchhoff’s voltage law, the reference equation of instantaneous value of three-phase circuit can be obtained as follows:

$$
\begin{align*}
\begin{cases}
    u_A &= Ri_A + L \frac{di_A}{dt} + e_A \\
    u_B &= Ri_B + L \frac{di_B}{dt} + e_B \\
    u_C &= Ri_C + L \frac{di_C}{dt} + e_C \\
\end{cases}
\end{align*}
$$

(2)

Switching functions $S_A$, $S_B$, $S_C$, so the phase voltage equation of the output of the active power filter is:

$$
\begin{align*}
\begin{cases}
    u_A &= u_{NO} + u_{AN} = u_{NO} + s_A U_{dc} \\
    u_B &= u_{NO} + u_{BN} = u_{NO} + s_B U_{dc} \\
    u_C &= u_{NO} + u_{CN} = u_{NO} + s_C U_{dc} \\
\end{cases}
\end{align*}
$$

(3)

And because of the three-phase symmetry, We can get:

$$
\begin{align*}
\begin{cases}
    i_A + i_B + i_C = 0 \\
    u_A + u_B + u_C = 0 \\
\end{cases}
\end{align*}
$$

(4)

From Equations (1), (3) and (4), it can be known that:

$$
u_{NO} = -\frac{1}{3} (S_A + S_B + S_C)
$$

(5)

According to Equations (4) and (5), we can get:

$$
\begin{align*}
\begin{cases}
    u_A &= (2S_A - S_B - S_C)U_{dc} \\
    u_B &= (-S_A + 2S_B - S_C)U_{dc} \\
    u_C &= (-S_A - S_B + 2S_C)U_{dc} \\
\end{cases}
\end{align*}
$$

(6)

$$
\begin{align*}
\begin{cases}
    L \frac{di_A}{dt} &= \left( \frac{2}{3} S_A - \frac{1}{3} S_B - \frac{1}{3} S_C \right) U_{dc} - Ri_A - e_A \\
    L \frac{di_B}{dt} &= \left( -\frac{1}{3} S_B + \frac{2}{3} S_B - \frac{1}{3} S_C \right) U_{dc} - Ri_B - e_B \\
    L \frac{di_C}{dt} &= \left( -\frac{1}{3} S_A - \frac{1}{3} S_B + \frac{2}{3} S_C \right) U_{dc} - Ri_C - e_C \\
\end{cases}
\end{align*}
$$

(7)

Equation (7) is the mathematical model of the active power filter. It can be seen from Equation (7) that the mathematical model takes the inductance as a parameter and has generality. It laid a foundation for the follow-up work.
3. Improved detection for harmonic current of instantaneous reactive power

For the detection of harmonic current of active power filter, it needs high accuracy and good real-time performance, and it needs good adaptive tracking and detection ability when the load changes. On this basis, this paper proposes a harmonic current detection method, which can quickly detect the harmonic content in the power grid. When the voltage of the power network is distorted, it can still work normally. Figure 3 shows the schematic diagram of harmonic current detection based on instantaneous reactive power. The voltage $U_{dc*}$ at both ends of the capacitor is compared with the detected voltage $U_{dc}$ at both ends of the capacitor, and the results obtained through the PI regulator are compared with the Positive sequence fundamental wave components which comes from the result of the positive sequence component of grid current after Clark transformation. Passing Chebyshev low pass filter, and the target positive sequence fundamental wave components are obtained through PI mediation. Through Clark inverse transformation, the three-phase current value containing only positive sequence fundamental wave is obtained. The three-phase current value $I_{abc}$ detected by the power grid is compared with the three-phase current value containing only positive sequence fundamental wave to obtain the switching signal required by the inverter. The mathematical model is deduced as follows:

\[
\begin{align*}
\frac{U_{abc}}{\sin\cos} & = c_{32} \frac{U_{ab}}{\sin\cos} \\
\frac{I_{abc}}{\sin\cos} & = c_{32} \frac{I_{ab}}{\sin\cos}
\end{align*}
\]

Figure 3. Schematic diagram of harmonic current detection.

Set the instantaneous values of three-phase voltage in the power network as $u_a$, $u_b$, $u_c$, and the instantaneous values of current as $i_a$, $i_b$, $i_c$, and transform them to the two-phase static $\alpha-\beta$ coordinate system:

\[
\begin{bmatrix}
U_{a} \\
U_{b} \\
U_{c}
\end{bmatrix} = c_{32} \begin{bmatrix}
U_{a} \\
U_{b} \\
U_{c}
\end{bmatrix}
= c_{32} \begin{bmatrix}
i_{a} \\
i_{b} \\
i_{c}
\end{bmatrix}
\]

Among them

\[
c_{32} = \frac{1}{\sqrt{3}} \begin{bmatrix}
0 & -\frac{1}{2} & -\frac{1}{2} \\
\sqrt{2}/2 & -\sqrt{2}/2 & 0
\end{bmatrix}
\]

Let the amount of stationary $\alpha-\beta$ two-phase coordinate system be converted to the $i_p-i_q$ orthogonal coordinate system rotating at the angular velocity $\omega$, where $i_p$ is in phase with the resultant voltage vector $e$, and $i_q$ is orthogonal to it, thus obtaining:
\[ i_p = \begin{bmatrix} \sin \omega t \\ -\cos \omega t \\ -\sin \omega t \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \]  \hspace{1cm} (10)

Combination (8) – (10) can get \( i_a, i_b, i_c - i_p, i_q \) coordinate transformation:

\[ \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C_{3/2} \begin{bmatrix} \sin \omega t \\ -\cos \omega t \\ -\sin \omega t \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \]  \hspace{1cm} (11)

Let \( i_p \) in (11) =0, after \( i_p \) passes through the low pass filter, the positive sequence active component \( i'_p \) of the fundamental wave in the ideal state is obtained. After the transformation from the orthogonal rotating coordinate system to the two-phase stationary coordinate system, and then from the two-phase to the three-phase coordinate system, the following is obtained:

\[ \begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} = C_{3/2}^{-1} \begin{bmatrix} \sin \omega t \\ -\cos \omega t \\ -\sin \omega t \end{bmatrix}^{-1} \begin{bmatrix} i'_p \\ 0 \end{bmatrix} \]  \hspace{1cm} (12)

After the inverse transformation, subtraction is done with the current signals \( i_a, i_b \) and \( i_c \) detected from the power grid, then the harmonic value of the three-phase current to be compensated can be obtained:

\[ \begin{align*}
   i_{ah} &= i_a - i_{a1} \\
   i_{bh} &= i_b - i_{b1} \\
   i_{ch} &= i_c - i_{c1}
\end{align*} \hspace{1cm} (13)

### 3.1. The design of Chebyshev digital low pass filter

Based on instantaneous reactive power theory, the harmonic current detection method in the design of low pass filter is the important factors influencing the precision of harmonic detection, this paper uses the chebyshev digital low-pass filter to filter, and the chebyshev digital low-pass filter introduced after PI controller, composed of the modified method of instantaneous reactive power detecting harmonic.

- The amplitude-frequency characteristics of Chebyshev digital low pass filter

Chebyshev filter is pushed out by the orthogonal function of Chebyshev polynomials, and the principle of constant fluctuation in the passband and monotonically increasing decay outside the passband is adopted to approximate the characteristics of the ideal filter\([5]\). Equation (14) is the amplitude-frequency characteristic equation.

\[ |H(\omega)| = \frac{1}{\sqrt{1+\varepsilon^2 T_n^2(\frac{\omega}{\omega_c})}} \]  \hspace{1cm} (14)

In the type, \( \varepsilon \) is decided to the size of the ups and downs within passband fluctuation coefficient, as a positive number less than 1; \( \omega_c \) for passband cutoff frequency; \( T_n(\omega) \) is n order chebyshev polynomial. At \( 0 \leq \omega \leq \omega_c \), \( |H(\omega)| \) fluctuates equally between 1 and \( 1/\sqrt{1+\varepsilon^2} \), the \( \varepsilon \) is smaller, the smaller the volatility. All curves pass through \( 1/\sqrt{1+\varepsilon^2} \) point at \( \omega = \omega_c \).When \( \omega=0 \), if n is odd, \( |H(\omega)| = 1 \); If n is an even number, then \( |H(\omega)| = 1/\sqrt{1+\varepsilon^2} \); The error distribution in the passband is uniform.

- The order of Chebyshev low pass filter

The attenuation function of Chebyshev filter is defined as

\[ \alpha = -20 \log |H(\omega)| = 10 \log \left( 1 + \varepsilon^2 T_n^2(\frac{\omega}{\omega_c}) \right) \]  \hspace{1cm} (15)

Passband ripple \( \alpha_{max} \) is defined as

\[ \alpha = -20 \log |H(\omega)| = 10 \log \left( 1 + \varepsilon^2 T_n^2(\frac{\omega}{\omega_c}) \right) \]  \hspace{1cm} (16)
Fluctuation coefficient $\varepsilon$ is

$$\varepsilon = \sqrt{10^{\frac{\alpha_{\text{max}}}{10}}}.$$  

Accordingly, the order required by the filter can be determined from the filter's passband cutoff frequency $\omega_c$, the maximum attenuation allowed in the passband $\alpha'_{\text{max}}$, the stopband lower cutoff frequency $\omega_c$ and the minimum attenuation allowed in the stopband $\alpha_{\text{min}}$. Among them, the minimum allowable attenuation in the stopband is

$$\alpha = -20 \log[H(\omega)] = 10 \log \left(1 + \varepsilon^2 T_n^2 \left(\frac{\omega}{\omega_c}\right)\right)$$

According to (15) - (17), the order of the filter is

$$n = \frac{\sqrt{\left(\frac{10^{\alpha_{\text{max}}}}{10^{\alpha_{\text{min}}}} - 1\right)}}{\sqrt{\left(\frac{10^{\alpha_{\text{max}}}}{10^{\alpha_{\text{min}}}} - 1\right)}}$$

The pole Distribution of Chebyshev Filter

Substitute $j\omega = s$ into the amplitude-frequency characteristic function of Chebyshev low-pass filter

$$H(s)H(-s) = \sqrt{\frac{1}{1+\varepsilon^2 T_n^2 \left(\frac{s}{\omega_c}\right)}}$$

Normalize, write $s/\omega_c$ as $\tilde{s}$, so

$$H(\tilde{s})H(-\tilde{s}) = \sqrt{\frac{1}{1+\varepsilon^2 T_n^2 \left(\frac{\tilde{s}}{\omega_c}\right)}}$$

If the pole $s_k = \sigma_k + j\omega_k$,

$$\begin{align*}
\sigma_k &= \sin \left(\frac{2k-1}{n} \pi\right) \text{sh} \left(\frac{1}{n} \text{sh}^{-1} \left(\frac{1}{\varepsilon}\right)\right)
\omega_k &= \cos \left(\frac{2k-1}{n} \pi\right) \text{ch} \left(\frac{1}{n} \text{ch}^{-1} \left(\frac{1}{\varepsilon}\right)\right)
\end{align*}$$

The pole Distribution of Chebyshev Filter

After obtaining the pole of the amplitude square function, the pole of the left half plane of $S$ can be obtained to obtain the transfer function of the filter system.

$$H(s) = \frac{k}{(s-s_{p1})(s-s_{p2})...(s-s_{pm})}$$

Through Equations (15) to (22), the specific parameters of Chebyshev low-pass filter can be determined, and the corresponding program can be compiled according to the characteristics of the system.

To sum up, in order to verify the correctness of the control strategy, the simulation model of the active power filter system was built and simulated in the Matlab /Simulink environment [6-7]. System simulation parameters are as follows: power supply voltage $U=220V$, power supply frequency $f=50Hz$; Nonlinear load. Figure 4 shows the comparison between the command current and the compensation current. It can be seen from the figure that the actual compensation current has a good fitting relationship with the DC current. Due to the nonlinear characteristics of the switching device, the actual compensation current has a slight ripple, but within the allowable error range.

4. Simulation model and simulation results

The use of sections to divide the text of the paper is optional and left as a decision for the author. To sum up, in order to verify the correctness of the control strategy, the simulation model of the active power filter system was built and simulated in the Matlab /Simulink environment [6-7]. System simulation parameters are as follows: power supply voltage $U=220V$, power supply frequency $f=50Hz$; Nonlinear
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Figure 4. APF simulation model diagram.

(a) APF simulation model diagram.  
(b) After compensation.

Figure 5. APF command current and trace current diagram.
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Figure 6. A phase current diagram before and after APF compensation.

(a) Harmonic current histogram before filtering
(b) Harmonic current histogram after filtering

Figure 7. Spectrum analysis diagram of A-phase current of power grid.

5. Conclusion
The key of active power filter based on instantaneous reactive power is harmonic current detection and low pass filter design. Based on the detailed analysis of the structure and principle of the active power filter, this paper deduces the mathematical model of the active power filter, and analyzes the principle of harmonic current detection and the design process of the low pass filter in detail. And the mathematical simulation model is established in Matlab/Simulink platform. The simulation results show that the harmonic of the power grid is greatly reduced after adopting APF, and the accuracy of harmonic detection by using the improved instantaneous reactive power theory can meet the compensation requirements, and the fitting between the compensation current and the command current after inverting is very close. The effect of harmonic suppression is achieved. It has important research significance and broad application prospect for harmonic control of power system and reliable operation of power grid.

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