Research on three-phase four-wire active power filter based on LCLCL coupling structure

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Abstract. In this paper, the main circuit topology of the three-phase four-wire active power filter (APF) and its harmonic current detection and control algorithm are studied. An active power filter system combining LCLCL filter and a three-phase H-bridge structure is proposed. This paper has applied harmonic detection algorithm based on an improved synchronous phase-locked loop (SRF-PLL) and recursive discrete Fourier transform (RDFT) while using triangular carrier modulation control based on PI adjustment to realize the harmonic compensation of the power filter to the grid current. The system has a notch effect on the harmonic at the switching frequency. It can detect the fundamental component and each harmonic component of the load current separately with a small amount of calculation, good real-time performance. Finally, a 5KVA single-phase APF prototype was built to test the superiority of the main circuit topology and the algorithm of current detection and control.

1. Introduction

In recent years, with the continuous increase of various types of high-power non-linear electronic equipment for power users, current harmonic pollution in power grid has become increasingly serious. Harmonic affects power quality and seriously threatens the safe and stable operation of power systems. Therefore, the management of harmonics and the compensation of reactive power have become an urgent need for the development of modern industry. Active power filter (APF) can realize dynamic continuous harmonic and reactive power compensation, and has fast response speed, small size and flexible application [1], [2]. The following is a study of several key technical points in the APF.

In order to suppress the high-frequency harmonics generated by the pulse width (PWM) technology, the traditional APF uses an L-type filter. The L-type filter has low cost and simple structure, but the filtering effect is poor. Although increasing the inductance value can improve the filtering Effect, but also affects the dynamic response speed of APF. [6] proposed an LCL filter. The LCL filter has a better high-frequency harmonic attenuation effect, but the LCL filter has no prominent harmonic filtering effect near the switching frequency of the main circuit. [3-5] insert an inductor into the capacitor branch of the LCL filter to form a new type of LLCL filter, which solves the problem that the LCL filter has a poor attenuation effect near the switching frequency, but its high-frequency attenuation rate is only -20dB / ten octave, making it difficult to filter the harmonics of twice the switching frequency and above [3]. With the in-depth study of APF, various harmonic current detection methods have been continuously proposed [9-12]. [9] used the p-q method to detect harmonics, but the p-q method has poor detection accuracy when the grid voltage is distorted, and its applicable range is small. [10] comparatively analyzed five detection methods of instantaneous
reactive power theory. The comparison found that d-q method has better performance and better real-time performance when the grid voltage is distorted, but it can only be applied to a three-phase system, and multiple coordinate transformations are required, which is difficult to implement. In addition, Fourier transform is also a commonly used type of harmonic detection method. The harmonic detection method based on fast Fourier transform (FFT) requires sampling a group of data and then calculating. There is a large delay, so this method is not suitable for APF. In terms of grid voltage phase detection, the synchronous rotating phase-locked loop (SRF-PLL) has good robustness [13], [14], but [13] mentioned that the phase-locking effect of SRF-PLL is not good when the grid voltage is distorted.

Suitable solutions have been proposed in the paper to the defects of related technical points in the current active power filter (APF). For the coupling problem between APF and power grid, this paper proposes an LCLCL filter, which not only has the advantages of bypassing the switching frequency harmonic current, but also has higher attenuation rate for harmonics with twice the switching frequency and above. In this paper, the APF main circuit rectifier studied is based on a three-phase H-bridge structure [7], [8]. Each phase of the three-phase H-bridge has a strong independence. The phase voltage is added to each H bridge arm instead of the line voltage, which reduces the requirement for the DC side capacitor withstand voltage value [8]. For the problem of harmonic detection, [11], [12] proposed an algorithm based on recursive discrete Fourier transform (RDFT). The entire recursive calculation process of RDFT only needs to complete a whole summation operation in the first frequency cycle, and then iterating continuously based on the calculated value at the previous sampling time, this recursive algorithm reduces the operation delay and ensures that the harmonic detection is fast and accurate. This paper uses RDFT algorithm to detect the harmonic current. In order to cooperate with the requirements of RDFT algorithm for the power grid voltage phase detection accuracy, an N-order moving average filter (MAF) is added before the phase detector of the SRF-PLL. MAF has a very strong attenuation ability for the harmonics of integer multiples fundamental frequency. It can accurately extract the fundamental wave component, and then output to the SRF-PLL to extract a more accurate grid voltage phase value.

2. System Design
The basic principle block diagram of the three-phase four-wire active power filter based on the LCLCL filter structure proposed in this paper is shown in Figure 1. The main circuit of the APF is simplified here. The entire structure of the main circuit is included in Figure 2. The APF system mainly includes two parts: the main circuit and the control algorithm. The control algorithm is mainly divided into four parts: harmonic detection, phase-locked loop, the control of compensating current and DC-side voltage.

In Figure 1, \( V_a \) is the phase voltage and \( I_o \) is the load current. The phase-locked loop obtains the phase of the grid voltage by collecting the \( V_a \) voltage signal. The harmonic detection unit analyzes the harmonic components in \( I_o \) by collecting the \( I_o \) current signal and obtains the command current \( I^* \). The current control algorithm collects the actual compensation current \( I_c \) to form a closed-loop control, which achieves the purpose of \( I_c \) continuously tracking \( I^* \). In order to achieve a stable and fast compensation effect, closed-loop control of the voltage of DC-side capacitor is also required. The following section mainly discusses the principle of the system from the APF main circuit and four control algorithms.

2.1. APF main circuit topology
The topology of the APF main circuit determines the compensation current control method, which directly affects the accuracy of harmonic compensation. The main circuit topology includes a rectifier bridge and a rectifier filter. The rectifier bridge uses a three-phase H-bridge structure in this paper. Aiming at the shortcomings of LCL and LLCL [3-5], a new type of LCLCL structure is used in this paper. The rectifier bridge and filter combine to form the APF main circuit. Figure 2 shows the topology of the APF main circuit.
2.1.1. Rectifier bridge structure
The three-phase H-bridge rectifier structure is composed by three single-phase full-bridge rectifier bridges. The main advantage of this structure is that it reduces the required withstand voltage of power devices. The phase voltage is added to each H bridge arm instead of the line voltage, and makes the system in a more secure environment, ensuring the controllability and independence of the system. A three-phase H-bridge circuit is shown in Figure 2.

2.1.2. LCLCL filter structure
This paper applies an LCLCL filter, which retains the advantages of LCL and LLCL filters, solves the shortcomings of these two filters and improves the overall performance of the filter. The two filters, LCL and LLCL, have different characteristics:

- The amplitude frequency characteristics of the two filters are the same in the low frequency band
- The LCL filter has stronger attenuation capability in the high frequency band, but the attenuation effect is worse near the switching frequency.
- The notch effect of the LLCL filter at the switching frequency is relatively obvious, but at 2 times the switching frequency and above, the LLCL filter attenuates at -20dB/ten octave, and the attenuation rate is too slow.

Therefore, combining the excellent characteristics of the two filters in different frequency bands, this paper proposes an LCLCL type filter.

The LCLCL type filter is shown in Figure 3. Based on the LCL type filter, the additional LC resonance branch bypasses harmonics near switching frequency, and does not change the original high-frequency attenuation speed. The transfer function of the LCLCL filter is as follows:

\[
G_{LCLCL}(s) = \frac{i_s(s)}{u_{inv}(s)} = \frac{L_1 L_f C_f C_s s^4 + L_f C_f C_s R_d s^3 + (L_f + L_2) C_f s^2 + R_d C_f s + 1}{\alpha_5 s^5 + \alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s} \tag{1}
\]

\[
\begin{align*}
\alpha_5 &= L_1 L_f L_2 L_f C_s \\
\alpha_4 &= L_2 L_f C_f C_s + (L_2 + L_3) L_f C_f C_d \\
\alpha_3 &= L_2 (C_f + C_h) + (L_3 + L_2) L_f C_n \\
\alpha_2 &= (L_3 + L_2) C_f R_d \\
\alpha_1 &= L_1 + L_2
\end{align*} \tag{2}
\]

The LCLCL filter achieves series resonance at the switching frequency, and achieves the same
attenuation speed as the LCL filter in the high frequency band above the switching frequency. Although the LCLCL filter has a new resonance peak in the high frequency band, the resonance peak is less than 0dB. Therefore, it will not have a large impact on the filtering effect.

![Figure 3. LCLCL filter circuit.](image1)

![Figure 4. MAF amplitude-frequency response.](image2)

2.2. phase-locked loop of Grid voltage

Paper[13], [14] analyzed the principle of SRF-PLL in detail. To cope with the problems of poor phase lock performance of SRF-PLL when the grid voltage is distorted, a moving average filter is added before the phase detector of SRF-PLL. The frequency response of an N-order moving average filter is:

$$H(e^{j\omega}) = \frac{1}{N} \sum_{n=-\infty}^{\infty} e^{-jn\omega} = \frac{\sin(N\omega/2)}{N\sin(\omega/2)}$$

In this formula: \(\omega=2\pi f_T\), \(T_s\) is the sampling period. Set \(f_s=10\text{KHz}\), \(N=200\), find the MAF cutoff frequency \(f=22.60\text{Hz}\). The amplitude-frequency characteristics of MAF are shown in Figure 4. It can be known from Figure 4 that MAF has a very strong attenuation ability to the harmonics that are integer multiples of the fundamental wave. It can extract the fundamental wave component when the grid voltage is distorted, and then output it to the SRF-PLL to extract a more accurate grid voltage phase value. The improved SRF-PLL principle is shown in Figure 5. Compared with the traditional SRF-PLL, a MAF filter is added to eliminate the harmonic components in the grid voltage.

![Figure 5. Advanced SRF-PLL Block Diagram.](image3)

2.3. Harmonic current detection

As shown in Figure 6, this paper combines a harmonic detection algorithm based on RDFT and a wavelet denoising algorithm. The sampled current signal is first denoised by wavelet transform, and then the RDFT algorithm is used to perform harmonic analysis on the load current.

Wavelet denoising firstly performs wavelet decomposition on the sampled signal to obtain a set of wavelet coefficients, then processes the high-frequency coefficients, finally it uses this set of coefficients to perform wavelet reconstruction. The reconstructed signal is the denoised signal [15]. After adding wavelet denoising, the minimum detection signal-to-noise ratio of the algorithm is
reduced from the previous SNR = 25.81dB to SNR = 18.49dB, indicating that lower SNR environment will not affect the calculation of the algorithm and enhance the anti-noise ability of the algorithm.

![Wavelet denoising diagram](image)

Figure 6. Harmonic denoising detection algorithm.

The RDFT algorithm is derived from the discrete Fourier transform (DFT) using a sliding window iterative method [11]. In Figure 6, \( i_L \) is the load current, \( \omega \) is the fundamental angular frequency, \( n \) is the harmonic order, \( A_n \) and \( B_n \) are the real and imaginary parts of the \( n \)th harmonic component, \( i_{Ln} \) is harmonic current. The principle of RDFT is analyzed below.

The periodic signal can be obtained by superposing sinusoidal signals of different frequencies. A periodic signal can be expressed by the following formula:

\[
x(k\tau) = \sum_{n=1}^{N} A_n \cos(n\omega k\tau) + \sum_{n=1}^{N} B_n \sin(n\omega k\tau)
\]  

(4)

Where:

\[
A_n = \frac{2}{N} \sum_{k=0}^{N-1} x(\tau) \cos(n\omega k\tau)
\]  

(5)

\[
B_n = \frac{2}{N} \sum_{k=0}^{N-1} x(\tau) \sin(n\omega k\tau)
\]

\( A_n \) and \( B_n \) are the cosine and sine amplitudes of \( n \)th frequency component; \( N \) is the number of sampling points; \( k = 0, 1, ..., N-1 \); The sampling period \( \tau = T/N \). Taking the calculation of the fundamental current component as an example, the improvement of formula (5) can be obtained as follows:

\[
\begin{aligned}
A_i &= A'_i + \frac{2}{N} \left[ x(N_{cu}\tau) - x((N_{cu} - N)\tau) \right] \cos(\omega N_{cu}\tau) \\
B_i &= B'_i + \frac{2}{N} \left[ x(N_{cu}\tau) - x((N_{cu} - N)\tau) \right] \sin(\omega N_{cu}\tau)
\end{aligned}
\]  

(6)

Observe formula (6) and find that there is a recursive relationship between \( A_i, B_i \) and \( A'_i, B'_i \). The entire recursive calculation process of RDFT only needs to complete a whole summation operation in the first frequency cycle. For applications with very high real-time requirements such as APF, the recursive algorithm reduces the operation delay, which ensure the fast and accurate detection of harmonics.

2.4. Current tracking control

The DC side capacitor is a voltage source for compensating current. The stability of the DC side capacitor voltage affects the effect of harmonic compensation. Therefore, before controlling the switching device of the main circuit, it is necessary to perform closed-loop control on the DC-side capacitor voltage. The left side of the dotted line in Figure 7 is the DC-side capacitor voltage control principle. In this figure, \( U_{ref} \) is the set value of the capacitor voltage, and \( U_{dc} \) is the actual value of the capacitor voltage. After sine wave modulation, the active current \( i_p \) is obtained. Finally, \( i_p \) is added to the harmonic current \( i_L \) detected earlier to obtain the command current \( i_c^* \).
In Figure 7, the differential equation of the PI regulator is as follows:

$$y = k_p (E + \frac{1}{T} \int_0^t edt) + y_0$$

(7)

Write this differential equation as the corresponding difference equation:

$$y_n = K_p (e_n + \frac{1}{T_i} \sum_{k=0}^{n} e_k * T) + y_0$$

(8)

In the formula, $e_n$, $e_{n-1}$ are respectively the deviation signals obtained from the $n$th and $n$-1th samples. $T_i$ is the integration time constant. $y_n$ is the $n$th output of the PI regulator. From equation (8), $y_{n-1}$ can be obtained, and $y_n - y_{n-1}$ can be obtained as an incremental PI calculation:

$$\Delta y_n = K_p (e_n - e_{n-1}) + \frac{T_i}{k_p} e_n$$

(9)

In the equation (9), $K_p$, $K_i$ are the proportional coefficient and the integral coefficient, respectively. It can be known from equation (9) that the deviation $\Delta y_n$ of the control variable $y$ can be calculated from the $e_n$, $e_{n-1}$ in the previous two sampling periods, and then superimposed with $y_{n-1}$ to get the current output $y_n$, $y_n$ is the output value of the PI regulator.

The right side of the dotted line in Figure 7 is the principle of triangular carrier current control. This method performs PI control on the actual compensation current $i_c$ and command current $i_{c*}$ produced by APF, and then modulates it with high-frequency triangular carrier to obtain a PWM signal. Compared with the traditional hysteresis comparison control method, the triangular carrier current control method has a fixed switching frequency. In combination with the LCLCL filter designed in this paper, a higher quality compensation current can be obtained.

3. Experiment & Results

A single-phase APF experimental platform with the capacity of 5KVA was built to verify the three-phase four-wire active power filter based on the LCLCL filter described above. The following three sets of experiments were set to analyze its ability of current compensation. 1) Steady-state response to load current harmonics. 2) Dynamic response when load changes.

3.1. Steady-state response

A load (30Ω // 10mH) was produced to test the platform. Connecting the test load. The experimental waveform and current spectrum are measured by oscilloscope RIGOL DS2202A and Single Phase Power Quality Analyzer Fluke 43B.
The experimental waveforms of grid voltage $U_{sa}$, grid current $i_{sa}$, non-linear load current $i_{Lsa}$, harmonic reference current $i_{sha}$, and compensation current $i_{sha}$ are given in Figure 8. As can be seen from the Figure 8, the non-linear load current $i_{Lsa}$ waveform is seriously distorted and there are large harmonics. After PI control, the compensation current generated by the experimental platform is basically the same as the detected command current waveform. The grid current approaches a sine wave by the compensation of the platform. The total harmonic distortion (THD) of the grid current is reduced from 61.95% to 3.15% after the system works stably. The comparison of grid current and load current spectrum is shown in Figure 9.
Then, LCLCL, LCL and LLCL-type APF were used to compare the harmonics of the power grid. As shown in Figure 10, the current THD of the LCLCL filter is 1.37% less than that of the LCL filter, which is much less than the LLCL filter by 1.62%, and the switching harmonic is significantly lower than that of the traditional filter. This shows that the LCLCL filter in the paper has better harmonic compensation performance.

3.2. Dynamic response Test

Loading experiment and load shedding experiment were designed to verify the dynamic performance of the control current strategy of the system, so that the system can meet the application requirements under different loads.

3.2.1. Load adding experiment

For the purpose of observing the dynamic characteristics of the system under non-linear load changes, the following is the waveform diagram of the grid voltage, grid current, and load current for a period of time after the system is instantaneously added to the load. The platform dynamic time is about one fundamental frequency period as shown in Figure 11.

Figure 11. Load the experimental waveform.

Figure 12. Load reduction experiment waveform.

3.2.2. Load reducing experiment

The waveform when switching from full load to half load is shown in Figure 12 above. After switching the load, the system response process is faster than the loading experiment, and the grid current $i_L$ is instantly compensated, and the DC side voltage fluctuation is small, which proves that the system can respond to the quickly harmonic changes.

4. Conclusion

This paper is aimed at the problems of the impact of harmonic filtering and APF response speed on the L filter and LCL filter in the traditional three-phase four-wire APF. Through detailed analysis, this paper proposes to add a resonance branch to the LCL filter. A LCLCL filter is presented in this paper, which not only accelerates the attenuation of the switching harmonics of the inverter, but also minimizes the size and saves the cost of the filter. At the same time, combined with the RDFT harmonic detection algorithm and the improved SPF-PLL, it ensures that the system has fast dynamic response capability and good current phase tracking accuracy in the compensation current control strategy. The THD in the grid current is reduced from 61.95% to 3.15% by the hardware platform, indicating that the system has good current compensation performance and fast dynamic response capabilities. However, when the grid frequency changes significantly, the system cannot track the changing frequency, resulting in a decrease in the accuracy of the compensation current. Therefore, in the future research, it is significant to study how to implement fast frequency tracking in grid-side frequency measurement to improve the stability of the system.
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