

The Role of Passive Filter in Harmonic Suppression

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Abstract

In modern power systems, harmonic problems are exacerbated by the widespread use of nonlinear loads and pulse width modulation (PWM) inverters, which have an adverse impact on power quality and system stability. Passive filters (PF) have become a key technology for harmonic suppression due to their simple structure, low cost, easy maintenance, and operational reliability. This paper systematically reviews the working principle, classification, and design considerations of passive filters, specially focusing on LC and LCL filters in harmonic suppression and power quality improvement. This article analyzes the latest developments in filtering technology and control methods and elaborates on the application of passive filters in various fields.

Keywords

Passive Filter; LC Filter; LCL Filter; Resonance Peak; Harmonic Suppression.

1. Introduction

In modern power systems and power electronic devices, the increasing use of Pulse Width Modulation (PWM) inverters and nonlinear loads has exacerbated harmonic issues. Harmonic currents and voltages not only do increase system power losses, but they can also lead to overheating of equipment, electromagnetic interference, and other operational instabilities. Furthermore, harmonics can introduce electromagnetic interference (EMI), disrupting communication systems and sensitive electronic devices.[1] To solve these problems, harmonic suppression techniques have become a critical aspect of power system design. Filters are one of the key methods for harmonic suppression. There are two main categories of filters: active filters (APF) and passive filters (PF). Among them, passive filters are widely applied in harmonic suppression due to the simple structure, low cost, easy maintenance, and operational reliability. [2].

This paper aims to provide a comprehensive review of the design principles and application of simple passive filters in harmonic suppression. It will analyze the effectiveness of passive filters in various practical applications, comparing their performance, advantages, and limitations. Furthermore, the paper will explore current challenges in passive filter design, such as their limited adaptability to varying harmonic conditions and potential resonance issues. Through this review, aiming to contribute to the advancement of harmonic suppression techniques and promote more stable and efficient power system operations in the face of increasing harmonic distortion.

2. The Working Principle and Classification of Passive Filters

2.1 The Working Principle of Passive Filters

Passive filters mainly use resonant circuits to achieve filtering. These filters typically consist of inductors, capacitors, and resistors, forming resonant circuits. A resonant circuit is made up of inductors(L) and capacitors (C).

In a series resonant circuit, the inductor, capacitor, and resistor are connected in series. At resonance, the inductive reactance and capacitive reactance of the inductor and capacitor in the circuit cancel each other out, as shown in Equation (1). At this point, the total impedance of the circuit is the smallest, equal to the only resistance value, and the current reaches the maximum value. This phenomenon is called series resonance. The series resonant passive filter can effectively suppress specific harmonics and eliminate harmonic currents through the series resonant circuit.[3] Series resonance can be used for resonant notch filters, as shown in Figure 1. The traditional harmonic suppression and reactive power compensation method is to connect a passive filter in parallel with the nonlinear load to be compensated. The filter forms a low-impedance path for certain harmonics, allowing the corresponding harmonic current to flow into the passive branch instead of into the power grid, thereby filtering out harmonics while also appropriately compensating for reactive power.[4].

$$X_L = X_c \text{ or } \omega L = \frac{1}{\omega C} \quad (1)$$

In a parallel resonant circuit, the inductor and capacitor are connected in parallel. At resonance, the current through the inductor and the current through the capacitor are equal in magnitude but opposite in direction, cancelling each other out, resulting in the minimum total current and the maximum circuit impedance. This phenomenon is known as parallel resonance. Parallel resonance can be applied in resonant filters, as shown in Figure 2.

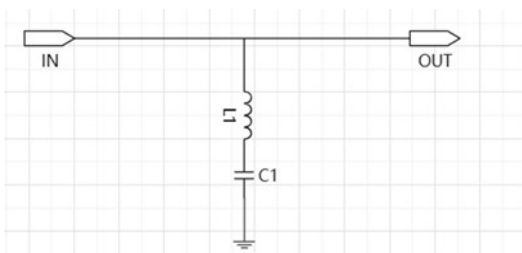


Figure 1. resonant notch filters

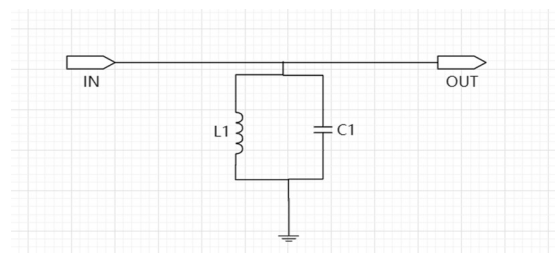


Figure 2. resonant filters

Compared to traditional passive filters, new types of passive filters, such as based on the fundamental wave resonance principle, can enhance filtering effectiveness. This method establishes an equivalent circuit to analyze the filtering principles and compares them with traditional approaches.[5].

2.2 The Classification of Passive Filters

The filter design process is focused on the amplitude-frequency characteristics, and it can be made into many types of filters, with the most commonly known being low-pass filters, high-pass filters, band-pass filters, and band-stop filters. These filters serve different purposes in harmonic reduction and are adjusted easily, depending on the requirements of the electrical network.

Low-pass filters are essential in electrical and signal processing systems. Low-pass filters transmit low-frequency signals. And it can eliminate high-frequency harmonics as appear in the phase of the system and the load, while preserving the quality of the fundamental signal. Conversely, high-pass filters are designed to perform the opposite function. High-pass filters are designed to allow high-frequency signals to pass while suppressing low-frequency harmonics. In certain cases, such as when low-frequency harmonic interference is significant, high-pass filters can improve system stability and efficiency.

Band-pass filters transmit harmonics in a given frequency range and prevent harmonics in other frequencies. They are especially useful in harmonic suppression cases when the treatment of a different frequency band is provided for, such as decrease of the 3rd, 5th, or even the 7th harmonics.

Generally, the advantage of band-pass filters is focusing on the problems of harmonics in the special frequency range and to remove them in a more effective way. Band-stop filter, also known as notch filter, allows signals outside a specific frequency band to pass through while suppressing signals within that frequency band. Its working principle is to construct a high impedance region within a frequency range, so that signals within that frequency range are attenuated while signals at other frequencies are not affected.

Moreover, passive filters can also be grouped into T-type filters, π -type filters, C-type filters, ladder filters, and other high order filters based on their circuit topological structure. The T-type filter being comprised of two inductors, one at the input terminal and another one at the output, while a capacitor placed between them. The π -type filter uses two capacitors and one inductor, giving it a triangular shape, similar to the letter " π ". The two capacitors make it a capacitive input-output circuit, with an inductor placed in the center. The C-type filter design is an upgrade from the π -type filter design, which uses a parallel capacitor that has been connected in the inductor branch. This setup provides a higher level of suppression of the high order harmonics, and not affecting the fundamental voltage. The ladder filter is formed by connecting together many L-type or T-type filters with possible alteration applied to the more complex and more in-depth components in this ladder, where each filter stage is made to pass or block a different frequency range.

Passive filters can effectively suppress harmonics of different frequencies by properly selecting filter types and design parameters in harmonic suppression, improving the stability and efficiency of the power system and reducing the impact of power quality issues on equipment. The core of these filter designs is to optimize the performance of the filter according to the harmonic spectrum characteristics of the system to meet specific harmonic suppression.

3. Simple Passive Filter

3.1 LC Filter Design

An LC filter is composed of an inductor (L) and a capacitor (C) and represents a simple passive filter topology. The impedance characteristics of the inductor and capacitor determine the frequency selectivity of the LC filter, making it effective in filtering out harmonic components at specific frequencies. By appropriately designing the parameter values of L and C, the harmonic suppression range and performance of the filter can be adjusted. The resonant frequency of the LC filter is Equation (2). LC filter resonant frequency is typically set to be lower than the inverter switching frequency to provide a broader bandwidth. This approach ensures effective filtering of switching harmonics, resulting in smoother output and improved harmonic suppression.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

When designing an LC filter, choosing the right inductor (L) is a critical step in ensuring filter performance. The choice of inductor is based on multiple factors, including the type of filter, operating frequency, load conditions, and physical limitations in the actual application. The inductor can be calculated based on the resonant frequency, as shown in Equation (3). In some designs, an inductor needs to be matched to a specific impedance, especially in high-frequency applications. The impedance of an inductor varies with frequency, as shown in Equation (4).

$$L = \frac{1}{(2\pi f)^2 c} \quad (3)$$

$$L = \frac{z_L}{2\pi f} \quad (4)$$

The capacitor serves to offer a low impedance route for harmonics. The capacitor size greatly influences the overall filter dimensions. The value of the capacitor can be determined using Equation (5), where ‘r’ represents the reactive power absorption by the filter, V_{load} and P_{out} are the rated voltage and power, respectively, and f_{out} refers to the operating frequency. The value of ‘r’ typically ranges between 0.01 and 0.05.[6].

$$C = \frac{rP_{out}}{2\pi f_{out}v_{load}} \quad (5)$$

3.2 The Resonance Peak of LC Filter

At the resonance frequency, the gain becomes infinite, leading to a resonance peak. In an ideal state, the gain at the resonance frequency would indeed be infinite. However, in practical circuits, the connected load introduces impedance, which reduces the gain at resonance. The gain at resonance varies with different load conditions: the smaller the load resistance, the lower the gain at the resonance point, thereby decreasing the likelihood of noise amplification. To avoid affecting the frequency reduce of the filter after the resonance frequency, Jayaraman and Sreedevi (2017) placed a resistor in series within the circuit to reduce the resonance peak. The inductance is 4 mH. The capacitance of 2 μ F is connected in series with a resistor of 3 ohms, in parallel in the inductor. The Bode plot of the designed LC filter is shown in Figure 3.[7].

The cut off frequency of filter is approximately 2300 Hz, with enhanced harmonic attenuation occurring beyond this point. Harmonic attenuation in the higher frequency range progresses at a rate of 60 dB/decade. It can be seen that, without damping resistance, the attenuation is high, but there is a prominent resonance peak. Adding damping resistance reduces the resonance peak while only slightly affecting the harmonic attenuation rate. While increasing the resistance value would further decrease the resonance peak, it would also lead to higher losses in the resistance. Therefore, it is essential to choose an optimal resistance value that minimizes resonance peaking while keeping resistance losses low. [7].

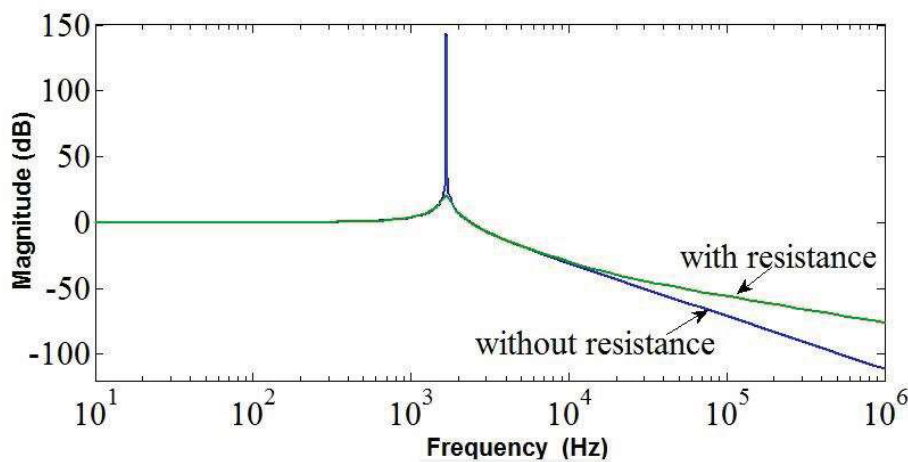


Figure 3. LC Filter Frequency Plot

Li (2009) employs two techniques to reduce the LC resonance peak. One method is the use of Virtual resistor technology. Virtual resistance can be implemented through control, simulating the effect of physical resistor without incurring losses. This virtual resistance can be connected in parallel with the inductor or capacitor, or in series with the inductor, effectively suppressing the LC resonance. [8] Figure 4 illustrates the implementation method of conventional external virtual impedance. The conventional implementation of virtual impedance is achieved by modifying the reference voltage. This method requires the use of a high-pass filter to prevent noise amplification, but it can lead to steady-state phase and amplitude errors. He and Li (2012) propose a generalized closed-loop control

(GCC) scheme that allows the effects of virtual impedance to be directly added to the PWM voltage reference of the voltage source converter (VSC), as shown in Figure 5. This method enables better realization of frequency-variable virtual inductance without the need for complex harmonic extractors. [9] Another technique to reduce LC resonance peak is to use control-signal-shaping technology. The two-step (or half-cycle) Posicast controller is a simple and effective method that divides the input command into two intermediate steps, allowing it to offset the oscillatory response caused by the first step. By combining these two methods, virtual damping resistance can address the shortcomings of the control signal shaping technique, enhancing robustness against changes in system parameters. The synergy of these two approaches can more effectively suppress LC resonance peaks. [8].

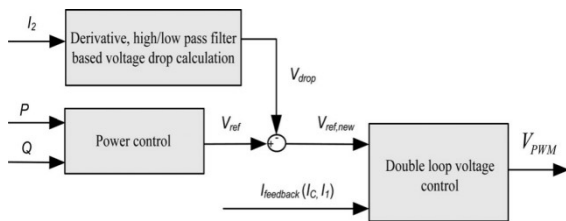


Figure 4. Conventional external virtual impedance

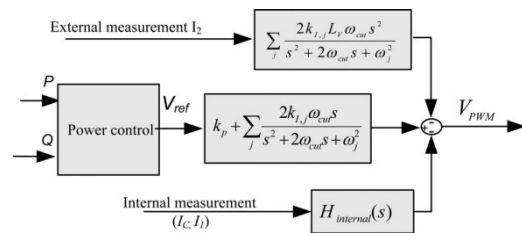


Figure 5. GCC external virtual impedance

3.3 Parallel LC Filter and Series LC Filter

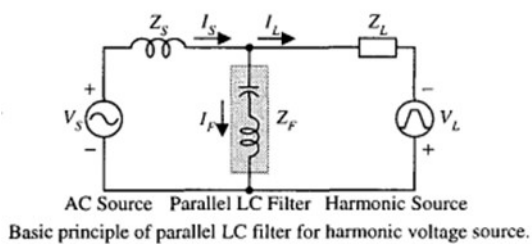
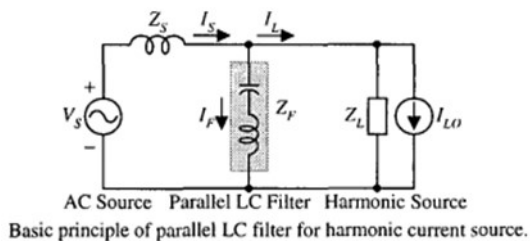


Figure 6. Parallel LC Filter

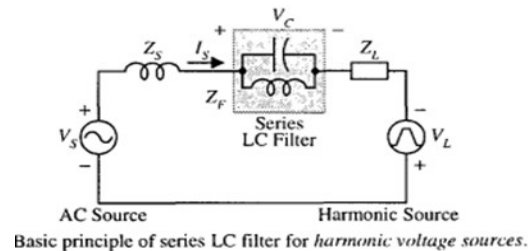
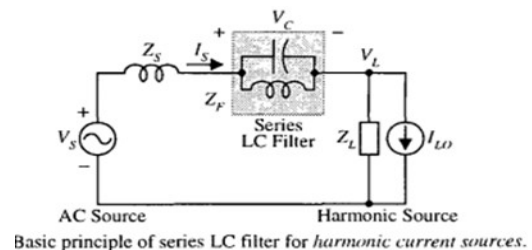


Figure 7. Series LC Filter

A parallel LC filter comprises multiple low-impedance shunt LCR branches, each tuned in series to harmonic frequencies. To keep things general, harmonic current sources are modeled as Norton equivalent circuits and harmonic voltage sources are modeled as Thevenin equivalent circuits, as shown in Figure 6. Traditional parallel LC filters work well for nonlinear loads that behave as harmonic current sources. However, they are ineffective for nonlinear loads that act as harmonic voltage sources, such as adjustable-speed AC drives with diode rectifier front ends. In fact, for voltage-source-type nonlinear loads, parallel LC filters may worsen harmonic currents and increase DC voltage ripples. Authors propose a series LC filter that is highly effective for harmonic compensation in nonlinear loads of the harmonic voltage source type, such as AC drives. The proposed series LC filter consists of multiple high-impedance LCR circuits connected in series, each tuned in parallel at harmonic frequencies. Figure 7 presents the basic principles of a series of LC filters designed specifically for both harmonic current source and harmonic voltage source nonlinear

loads. Parallel LC filters are suitable for current-source-type nonlinear loads, while series LC filters are appropriate for voltage-source-type nonlinear loads.[10].

Harmonics are also classified into harmonic voltage sources and harmonic current sources. For harmonic suppression of current-type harmonic sources, series resonant circuits are typically used to form low-impedance parallel branches, reducing the harmonic pollution caused by the harmonic source to the grid through shunting. In contrast, for harmonic suppression of voltage-type harmonic sources, parallel resonant circuits are used to form high impedance, connected in series in the circuit to reduce the harmonic pollution to the grid by acting as a voltage divider.[11].

3.4 LCL Filter

As power quality standards for the grid become more stringent, LC filters require larger component values to meet these requirements, making them bulkier and more expensive. The LCL filter offers a more attractive alternative by adding an inductor to the LC filter configuration. With smaller component values, the LCL filter is more compact and cost-effective. It also provides better filtering performance and can suppress harmonics more effectively. Compared to LC filters, LCL filters offer higher harmonic attenuation capabilities.[12] By establishing a mathematical model and using MATLAB for comparison, the filtering effects of L-type filters, LC filters, and LCL filters were evaluated. Among them, the LCL filter demonstrated the best filtering performance, with a total harmonic distortion (THD) of 7.59%. The LCL filter can achieve similar filtering performance to the other two filters while using a smaller total inductance, and it offers superior dynamic performance.[13] Although LCL filters provide better filtering performance, they also present resonance issues. Therefore, in the design of LCL filters, passive damping solutions are required to address these resonance problems, such as using resistive damping or SC-RL damping schemes.[12] Yang and Zhang (2015) recommend a cascaded nonlinear controller based on feedback linearization for grid-connected converters with LCL filters. This approach achieves precise decoupled control of active and reactive currents on both the converter and grid sides, effectively eliminating the resonance peaks of the LCL filter and enhancing the overall control performance of the grid-connected converter.[14].

4. Applications of LC and LCL Filter

LC passive filters have widespread applications in harmonic suppression, particularly in power electronics and power quality improvement. In PWM inverter circuits, LC filters can effectively reduce the output harmonic content.[15][16][17] Hyosung and Sul (2011) propose a novel design method for output LC filters in PWM inverters, aimed at minimizing transient current overshoot while maintaining good control dynamics.[18] In Stand-Alone photovoltaic (PV) systems, LC filters are connected between the inverter and nonlinear loads to filter out the harmonic components generated by the DC/DC boost converter, the DC/AC inverter, and the nonlinear loads.[19] LC filters can also be used to reduce the dv/dt of the inverter output, limit the rate of rise of the inverter output voltage, and reduce the common mode noise of the motor.[20] LC filters can also be used in combination with other filters. Calzo et al design a filter architecture that combines a standard second-order passive low-pass LC filter with one or more tuned notch filter sections, suitable for off-grid and grid-connected distributed generation units. By employing appropriately sized damping circuits to achieve suitable damping, the LC characteristic resonance can be selectively damped without compromising high-frequency performance. This design methodology is applied to the output power filter design of a 40 kVA three-phase inverter. [21].

The LCL filter can be applied in small renewable energy conversion systems based on photovoltaic (PV) technology. Compared to the LC filter, the LCL filter achieves a lower total harmonic distortion (THD) of 1.06% in standalone photovoltaic applications, whereas the LC filter's THD is 3.8%. This demonstrates the superior filtering performance of the LCL filter. [7] Additionally, the LCL filter offers optimized size, weight, and volume compared to the LC filter, making it more suitable for use in standalone PV systems. Compared to traditional LC filters, LCL filters can reduce the total

inductance significantly required to achieve the same filtering effect, making them more suitable for high-power grid-connected inverter systems.[22] Liu et al (2018) present a novel LCL filter design using a variable inductor for large-scale microgrid applications. Traditional LCL filters use fixed inductance values, which can lead to poorer harmonic performance under light load conditions due to the intermittent nature of renewable energy sources. The proposed variable inductor has an inductance value three times higher at low current compared to its value at rated current. This helps reduce current harmonics under all operating conditions and stabilizes the microgrid by mitigating the propagation of LCL resonance. [23].

5. Conclusion

Passive filters play an important role in harmonic suppression, offering a cost-effective and reliable solution for enhancing power quality in modern electrical systems. LC and LCL filters demonstrate superior performance in harmonic mitigation, especially when appropriately designed and tuned. Their effectiveness can be further enhanced by employing suitable damping techniques to reduce resonance effects. However, challenges remain in optimizing filter designs to address different harmonic sources and ensuring compatibility with evolving power system requirements. Future research should focus on improving filter designs, exploring the application of advanced materials, and integrating intelligent control systems to meet the dynamic demands of renewable energy systems and grid-connected devices. As harmonic pollution continues to increase, the ongoing development of passive filter technology will be crucial for maintaining system stability and ensuring high power quality.

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