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Harmonic Effects on the Operation of Power Electronic Devices

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Abstract:

This study examines the effects of harmonics on power systems and their equipment, focusing on and exploring the application of different types of filters in harmonic suppression. Harmonics, a significant concern in modern power systems, leads to waveform distortion, increased losses, and reduced system efficiency. These include passive filters (PPFs), active filters (APFs) and optimisation strategies for hybrid filters. By analysing current harmonic optimisation techniques, further improvements in control algorithms and measures to optimise energy consumption and reduce costs are proposed to increase the adaptability and efficiency of filters in complex power environments. In addition, this research helps to advance the development of filtering techniques. It gives ideas that can be applied to developing renewable energy systems and smart grids, as harmonic suppression is vital in improving overall power quality and system reliability. The results of this study could guide future developments in power system optimisation to ensure smoother operation in an increasingly complex and interconnected grid.

Keywords: Harmonics; power filters; optimization; power quality; active power filters.

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1. Introduction

In modern power systems, harmonic distortion has become an important issue affecting the efficiency and reliability of equipment. Harmonics cause distortions in current and voltage waveforms, leading to energy losses, reduced equipment life, and decreased power quality. This is particularly serious for systems using rotating machinery and power electronics, as harmonics can increase the additional losses in the equipment and lead to instability in the system's operation. Several filtering techniques have been developed to address harmonic problems, including passive filters (PPF), active filters (APF), and hybrid filters. Each has its advantages in different scenarios. PPFs are suitable for systems with more stable harmonic frequencies due to their simple structure and low cost. At the same time, APFs can dynamically compensate for changing harmonics and are more adaptable. Hybrid filters combine the advantages of PPFs and APFs for flexibility and cost-effectiveness. This study aims to assess the impact of harmonics on power systems and explore ways to optimize filtering techniques, particularly by improving control algorithms, optimizing materials, and reducing costs to enhance the reliability and efficiency of filters in complex power environments.

2. The Impact of Harmonics on Power Electronic Devices

A harmonic is a wave or signal whose frequency is an integer multiple of a reference signal or wave. In electrical environments, harmonics describe distortions in the average current waveform, usually caused by nonlinear load transmission. For some equipment, such as generators and motors, harmonic currents or voltages generate additional losses in the stator windings, rotor circuits, and cores, reducing power generation and transmission efficiency. Hysteresis, losses, and electrical stresses in the insulating materials in electrical equipment can increase due to harmonic voltages. In addition, harmonic currents increase the copper consumption of the transformer, causing local overheating of the equipment and thus accelerating the aging of the insulation, significantly reducing the life of the equipment and negatively affecting the stability of the power supply [1]. Harmonics also produce oscillations or resonances by interacting with system impedances and control loops in power electronic systems[1]. Especially in the high-frequency range, these oscillations can lead to system instability. Frequency coupling effects may trigger sub-synchronous or synchronous oscillations, weakening the system's stability [2]. Adverse damping effects, on the other hand, increase the likelihood of system oscillations and also affect the device's overall performance. Figure 1 illustrates the effect of different harmonic amplitudes on waveform distortion. The red curve represents the fundamental waveform unaffected by harmonics, and as the amplitude of the harmonics decreases, the waveform distortion decreases in turn. Finally, the waveform (blue curve) is smooth again, indicating that the harmonics have been successfully compensated or filtered out. This visually demonstrates the effectiveness of harmonic filters in reducing harmonic distortion.

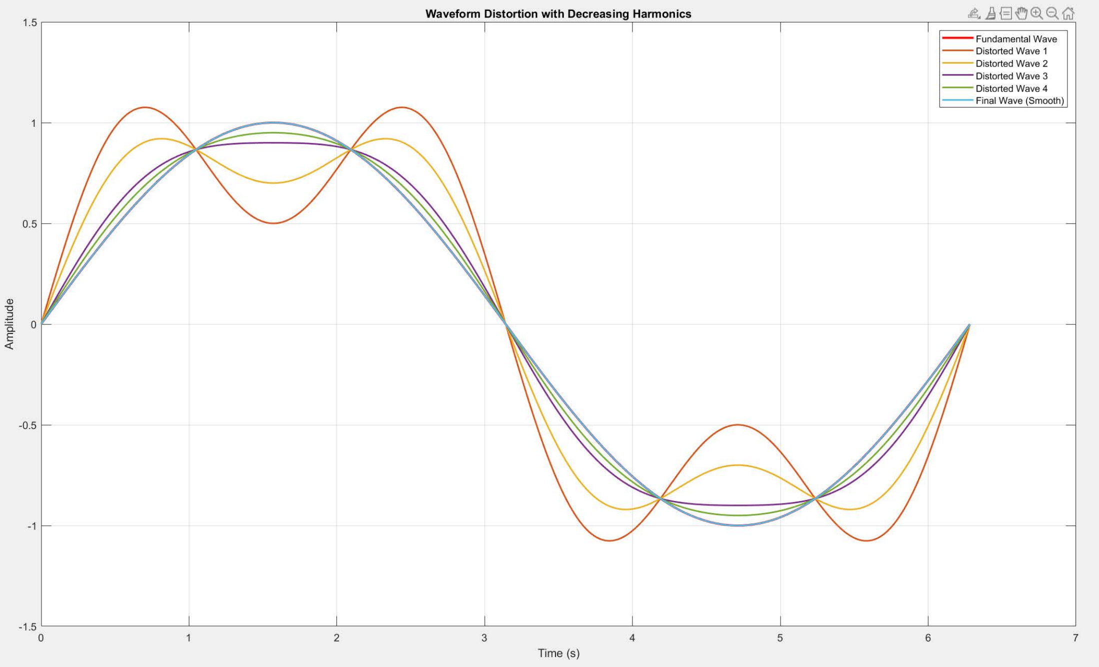


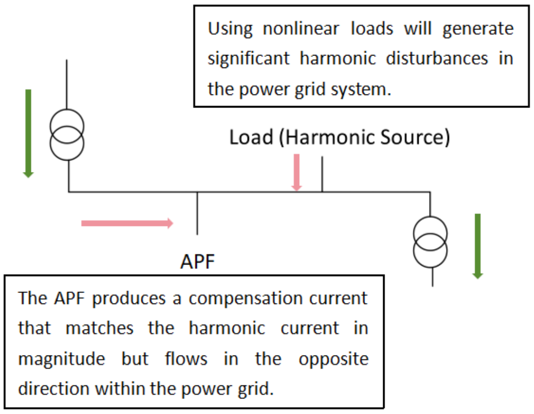
Fig. 1 Waveform Distortion with Decreasing Harmonics

3. Research on Existing Harmonic Mitigation Methods

3.1 Active Power Filter (APF)

Active Power Filters (APFs) solve the problem of harmonic disturbances by constantly observing the level of harmonics in the grid and generating compensating currents or voltages to neutralize their effects [3,4]. The core principle is that by detecting the harmonic components in the load current and using control algorithms to generate compensation currents opposite to the harmonics and injecting them into the grid, the impact of harmonics can be effectively reduced [3,5]. The APF is suitable for dealing with complex and changing environments because it automatically adjusts the compensation signal according to the harmonic frequencies in the system.

There are two main construction types of APFs: parallel and series [6,7]. The parallel type is often used to compensate for harmonic currents, while the series type is mainly used to compensate for harmonics in voltage [7]. Due to its ability to flexibly handle harmonics of different frequencies, APFs are often used in applications with high power quality requirements, such as complex power environments like industrial equipment and communication systems. Figure 2 illustrates the operation of a shunt-type active filter (SAPF) in a power system containing nonlinear loads. The shunt-type SAPF is connected in parallel with the load to compensate for the harmonic currents generated by the load. Nonlinear loads are harmonic sources that inject harmonic currents into the grid, leading to power quality problems. SAPF neutralizes the effects of harmonics and reduces the disturbance to the system by detecting the harmonic currents, generating a compensating current of the same amplitude as the harmonic current but in the opposite direction, and injecting it into the grid.



Using nonlinear loads will generate significant harmonic disturbances in the power grid system.

The APF produces a compensation current that matches the harmonic current in magnitude but flows in the opposite direction within the power grid.

Fig. 2 Operation of Active Power Filter (APF) in a Nonlinear Load System

The APF has the significant advantage of dynamically adjusting to the grid's frequency and amplitude of harmonics to ensure optimal filtering, making it adaptable to changing harmonic interference environments. In addition, APF possesses high accuracy and fast response and can maintain its system's stability in complex power environments [8,9]. In addition to harmonic suppression, APFs can perform reactive power compensation, thereby improving the power factor and overall operating efficiency of the power system [10,11]. However, APFs also have limitations in handling high-frequency harmonics, which restricts their application to specific frequency ranges [12]. Firstly, the relatively high cost of APF makes it more challenging to roll out, especially in small projects [12,13]. In addition, APF requires a continuous DC power supply, which increases the system's energy consumption. Furthermore, the complex control system design of the APF also makes maintenance more difficult, as it requires a high degree of precision.

APFs are widely used in industrial facilities, data centers, and renewable energy generation systems. For example, in industrial locations such as arc furnaces and inverters that generate large amounts of harmonics, APFs enhance power quality and ensure stable equipment operation by suppressing harmonics in real time [14,15]. Data centers rely on APFs to reduce harmonic interference and ensure the stable operation of critical equipment with high power quality. In renewable energy systems such as photovoltaic and wind power, APFs eliminate harmonics generated by inverters and power electronic equipment and safeguard grid stability [16,17].In addition to this, with the development of intelligent grids, APFs can also optimize power transmission through their fast response capability, ensuring a high-quality power supply.

For the future direction of optimization, the improvement of APF can be focused on several important aspects. First, optimizing the control algorithm is particularly important through adaptive control algorithms or artificial intelligence technology, which can improve the accuracy and response speed of harmonic detection and compensation. Secondly, energy consumption optimization is another primary focus. Using more efficient power conversion technologies and optimized controller design can effectively reduce the operational energy consumption of APFs [13]. At the same time, cost reduction is a crucial challenge for APFs, which can be made more economical by simplifying their design and using more cost-effective components. In terms of volume and weight optimization, especially in applications with high space requirements, improved designs can further extend the APF's range of applicability. In conclusion, by improving control algorithms, optimizing energy consumption, reducing costs, and improving physical structures, the application of APFs can be further expanded in complex power systems, and the economic benefits will be increased [13].

3.2 Passive Power Filter (PPF)

Passive Power Filter (PPF) mainly eliminates harmonics at specific frequencies by utilizing a filter network of passive components such as inductors, capacitors, and resistors. The principle of operation is to use the selectivity of inductance and capacitance for currents of different frequencies to filter out harmonics of specific frequencies with the help of resonant circuits, thus improving the power quality in the power system. Figure 3 shows the frequency response characteristics of the passive filter (PPF). PPFs resonate at a specific frequency mainly through the selectivity of their inductance and capacitance, thus effectively filtering out harmonics around that frequency. The filter has a lower impedance in the lower frequency bands, which means it filters best at those frequencies. As the frequency increases, the filter's impedance gradually increases, which indicates that its ability to filter high-frequency harmonics gradually decreases.

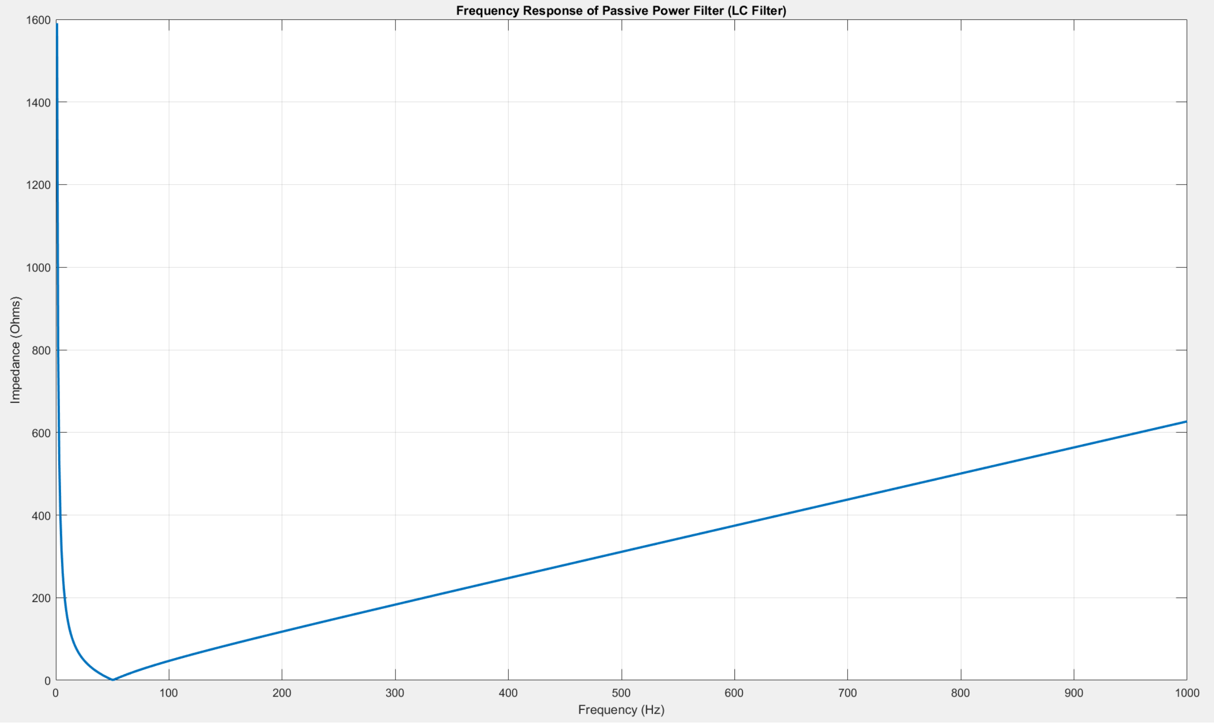


Fig. 3 Frequency Response of Passive Power Filter (LC Filter)

PPFs have been widely used in power systems due to their simplicity, low cost, and high reliability. By relying only on passive components such as inductors, capacitors, and resistors, PPFs are relatively inexpensive to design and manufacture and are particularly suitable for projects with limited budgets. In addition, the PPF does not require an external power supply, which reduces operational energy consumption and makes it easier to design and maintain [11]. In a stable harmonic environment, PPFs can efficiently filter out fixed-frequency harmonics and are suitable for systems with relatively fixed harmonic frequencies. However, the filtering effect of PPF has limitations in that it is restricted to fixed frequency harmonics and is, therefore, less resilient to frequency fluctuations [16]. Moreover, its filtering accuracy could be better and effectively deal with high harmonics or rapidly changing harmonic signals. The fixed structural design of PPFs limits their performance in complex or dynamic load environments, and they cannot be dynamically adjusted to real-time changes in the system.

The application scenario of PPF mainly focuses on power systems with relatively fixed harmonic frequencies. It is commonly used in small and medium-sized industrial settings, such as low harmonic environments generated by motors, inverters, and other equipment. PPFs are also widely used in power transformers and distribution systems to help improve power quality and reduce harmonic damage to equipment [17,18]. Due to its simple structure and low cost, the PPF is particularly suitable for applications where the load is relatively stable and essential harmonic suppression is required.

The future direction of PPF optimization will likely focus mainly on improving its filtering efficiency and adaptability. Improving the design of the filter to expand its ability to suppress higher harmonics is an important direction that can significantly enhance its filtering effect. In addition, the combination of automatic regulation technology enabling it to respond dynamically to harmonic changes in the power system will enhance its adaptability. Further reductions in energy consumption and equipment size through optimizing materials and manufacturing processes will also help increase the potential for PPF applications in complex systems while keeping costs low.

3.3 Hybrid Power Filter (HPF)

Hybrid filters combine the advantages of active and passive filters, which can dynamically adjust to compensate for harmonics and filter out fixed frequency harmonics at a low cost. Hybrid filters work on the principle that passive filters handle the lower harmonics, while active filters are responsible for the dynamic regulation and compensation of the higher harmonics [12]. The greater flexibility and accuracy of hybrid filters compared to passive filters alone and the ability of hybrid filters to reduce power consumption and cost while maintaining filtering effectiveness compared to active filters alone significantly optimize system economics and performance. Figure 4 illustrates the circuit structure of a hybrid filter, combining the advantages of an active filter (APF) and a passive filter (PF). Passive filters mainly filter out lower fixed-frequency harmonics, while active filters compensate for high-frequency harmonics dynamically. Active filters are responsible for dynamically compensating high-frequency harmonics. By combining these two filters, hybrid filters can efficiently and flexibly cope with harmonic disturbances of different frequencies, optimizing the power quality of the power system while reducing costs.

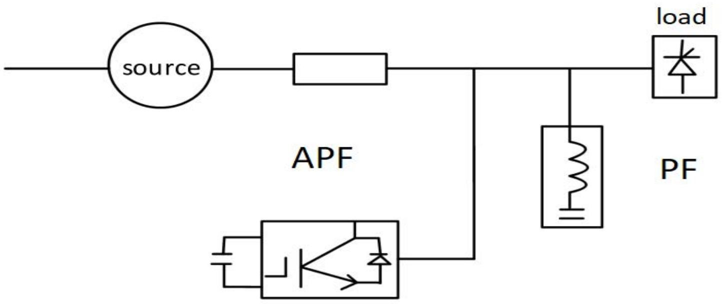


Fig. 4 Hybrid Power Filter Circuit with Active and Passive Filters

Hybrid filters show significant advantages in terms of harmonic suppression. It effectively filters out low harmonics at fixed frequencies and dynamically adjusts to compensate for higher harmonics, combining the advantages of the other two types of filters. Compared to separate APFs and PPFs, hybrid filters have lower cost and energy consumption and perform better in filtering accuracy and flexibility [13]. Because of their excellent performance and high economy, hybrid filters are widely used in complex and variable power environments to meet diverse harmonic suppression needs. However, it also has some obvious drawbacks. Firstly, the structure of hybrid filters is relatively complex and challenging to design and implement, especially when coordinating the work of the two filters. The design of the control system could be more precise [19]. Secondly, hybrid filters are more expensive to purchase and maintain later, potentially lowering overall cost-effectiveness when applied on a large scale [19]. Finally, although the hybrid filter can handle a wide range of harmonics, its filtering accuracy may still need to be improved in extremely complex power environments.

Hybrid filters are widely used in applications with high power quality requirements and complex harmonic sources, such as large industrial systems, inverters, and power electronics in manufacturing plants. It can significantly improve the system's power quality by simultaneously handling low and high harmonics. Hybrid filters are also used in smart grids and renewable energy generation systems to help optimize power transmission, reduce harmonic interference with the grid, and ensure stable system operation and efficient energy transfer.

The optimization of hybrid filters has focused on improving performance and reducing cost. Firstly, improving the control algorithm can enable more efficient cooperative work between the active and passive parts, thus enhancing the filtering accuracy. Secondly, the design structure of the system is optimized to simplify its complexity and reduce manufacturing and maintenance costs. Further enhancing the filter's response speed and dynamic adaptability will allow it to better cope with harmonic variations in complex power systems. Finally, using new materials and advanced processes helps improve the filter's efficiency and reduces the equipment's size and energy consumption.

4. Application Methods for Power System Optimization

In modern power systems, harmonic detection and optimization gradually incorporate the latest technological tools. Power systems can achieve more accurate harmonic detection and real-time compensation through cutting-edge technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) [4]. The AI algorithm can quickly analyze the harmonic distribution in the system and automatically adjust the working state of the filter to improve the harmonic suppression effect [5]. IoT, on the

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other hand, enables remote monitoring and data collection through a network of sensors, helping to optimize system responsiveness and flexibility. Future optimizations are centered around the limitations of the existing technology to improve the harmonic impact of these filters. However, existing technologies still face the challenges of responsiveness, adaptability, and cost when dealing with complex harmonic environments. In the future, the direction of improvement should focus on improving the system's adaptive ability and intelligent control level to enhance harmonic compensation's speed and accuracy further. Optimization recommendations include using more innovative control algorithms and artificial intelligence techniques for harmonic detection and regulation. At the same time, it should also reduce cost and volume by simplifying the design of the equipment and introducing new materials, which will increase the efficiency of the application of the equipment. These improvements will help enhance power system performance in complex scenarios such as renewable energy and smart grids.

5. Conclusion

This paper examines the effects of harmonics on power electronic equipment, and the study results show that harmonics can have several negative impacts on equipment, such as triggering instability, increasing losses and failures of equipment and its components. By analysing the characteristics of different types of harmonic sources and their specific effects on electronic devices, this paper reveals the potential threat of harmonics to the efficiency and lifetime of electronic components. In contemporary times, when electronic power equipment is increasingly widely used in complex power systems, it is crucial to understand how to control harmonic phenomena in practical applications effectively. By better understanding the mechanisms of harmonic generation and propagation, engineers can take more effective protective measures, such as designing more efficient filters or reducing the adverse effects of harmonics by improving the structure of power electronics. By doing so, the stability of the equipment can be improved, and on the other hand, energy losses can be reduced, and sustainable power applications can be advanced. Although this study reveals many effects of harmonics on power electronic equipment, many aspects still deserve further exploration. For example, novel harmonic filtering techniques, modelling and analysis of multi-harmonic source interactions can be a direction for further research in the future. In addition, with the rapid development of power electronics, studying the sensitivity and immunity of different novel materials to harmonics is also a promising topic.

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