Harmonic Mitigation in Power Distribution Networks Using Active Power Filters

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Abstract
Power quality has emerged as a critical issue in modern power distribution networks due to the widespread use of non-linear loads such as rectifiers, inverters, and switching power supplies. These devices introduce current and voltage harmonics, which lead to increased power losses, equipment overheating, and reduced efficiency of electrical systems. This paper investigates the design and implementation of Active Power Filters (APFs) for harmonic mitigation in power distribution networks. Simulation and analytical modeling demonstrate the superior performance of APFs compared to conventional passive filters. The proposed APF configuration effectively reduces Total Harmonic Distortion (THD) within IEEE 519 standards, thereby improving overall system reliability and power quality.
Keywords: Harmonic mitigation, Active Power Filters, Power quality, Total Harmonic Distortion (THD), Power distribution networks

1. Introduction

Power distribution networks in the 21st century face a dual challenge: increasing demand for electricity and deteriorating power quality due to widespread use of electronic devices. Unlike conventional linear loads, modern appliances such as rectifiers, variable frequency drives, UPS systems, and computer power supplies are inherently non-linear. These non-linear loads draw currents that are not sinusoidal, even when supplied with pure sinusoidal voltages. The result is harmonic distortion in both voltage and current waveforms.

Harmonics are undesirable frequency components that are integer multiples of the fundamental frequency (50 Hz in India). Their presence leads to multiple operational and economic issues. Equipment such as induction motors and transformers experience overheating, while distribution cables carry higher RMS currents, increasing copper losses. Capacitor banks installed for reactive power compensation are also subject to harmonic resonance, resulting in premature failures. In large-scale systems, excessive harmonics compromise the reliability of protective relays, reduce system stability margins, and may even lead to blackouts in extreme cases.

The **significance of power quality** has grown not only in industries but also in residential and commercial sectors. Sensitive electronic equipment—such as data centers, hospitals, and communication systems—cannot tolerate high harmonic levels. Thus, utilities are compelled to maintain harmonic distortion within prescribed limits. The IEEE 519 standard specifies maximum permissible Total Harmonic Distortion (THD) for both current and voltage, making compliance essential for modern utilities and industries.

Historically, engineers relied on **passive filters**, composed of LC circuits tuned to eliminate specific harmonics. Though simple, these filters have fixed characteristics, suffer from resonance issues, and are not adaptable to changing load conditions. The limitations of passive solutions prompted the development of **Active Power Filters (APFs)**. By employing power electronic converters controlled by advanced algorithms, APFs can dynamically generate harmonic currents of equal magnitude and opposite phase, thereby canceling distortion at the point of connection.

Therefore, the objective of this study is to analyze the application of Active Power Filters for mitigating harmonics in distribution networks. The research emphasizes simulation-based evaluation of APF performance, aiming to demonstrate how THD levels can be reduced to IEEE standards, thereby ensuring efficient, reliable, and sustainable power delivery.

2. Literature Review

The problem of harmonics in electrical networks has been widely investigated over the past four decades, with solutions evolving in parallel with advancements in power electronics.

Early work on harmonic mitigation emphasized passive filters. These consisted of single-tuned LC circuits connected in shunt with the system to block specific harmonic frequencies. Studies conducted during the 1980s showed that such filters were effective in controlled environments with predictable load characteristics. For instance, Bhattacharya et al. (1997) reported the ability of passive filters to significantly reduce lower-order harmonics in controlled test systems. However, they were inherently limited by fixed tuning, bulky size, and the risk of parallel or series resonance with system impedances.

The paradigm shifted with the introduction of Active Power Filters. H. Akagi (1996) established APFs as a flexible alternative capable of compensating both reactive power and harmonics dynamically. The groundbreaking work of Akagi, Kanazawa, and Nabae (1984) introduced the Instantaneous Reactive Power (p–q) Theory, which laid the foundation for reference current generation in shunt APFs. This theory allowed filters to respond adaptively to varying harmonic content in real time.

Subsequent researchers focused on refining control strategies. Singh, Al-Haddad, and Chandra (1999) presented a detailed review of different APF controllers, ranging from hysteresis control to synchronous reference frame (SRF) control. Hysteresis controllers provided excellent dynamic response but introduced variable switching frequencies, while SRF controllers ensured smoother compensation under steady loads. El-Habrouk et al. (2000) compared various control methods and concluded that hybrid control strategies could balance response speed and stability.

With growing industrial demand, researchers explored hybrid filters, which combine the low-cost benefits of passive elements with the dynamic response of active filters. Rahmani et al. (2010) demonstrated that hybrid filter systems could effectively control both reactive power and harmonics while maintaining economic feasibility. Recent developments have also incorporated predictive control algorithms and artificial intelligence (AI)-based techniques, enabling APFs to adapt to complex and fast-changing load conditions in smart grids.

From this review, it is evident that APFs provide a far more effective solution compared to traditional passive methods. They are particularly well-suited for environments such as rapidly urbanizing states like Uttar Pradesh, where electrical loads are growing both in diversity and magnitude. This motivates the present study, which applies a simulation-based approach to analyze APF effectiveness in mitigating harmonics in distribution networks.

3. Methodology

The methodology adopted in this study for harmonic mitigation using Active Power Filters (APFs) is structured into four main stages: system modeling, filter design, control strategy development, and simulation-based performance evaluation. Each stage is critical in ensuring that the APF not only suppresses harmonics effectively but also adapts to varying operating conditions in real distribution networks.

3.1 System Modeling of the Distribution Network

To investigate the effectiveness of APFs, a typical three-phase low-voltage distribution system was modeled in MATLAB/Simulink. The model consists of a three-phase AC supply connected to a set of non-linear loads. The loads are primarily modeled as six-pulse diode rectifiers with resistive-inductive (RL) loads, which are well known to produce high levels of current harmonics. Such loads are representative of real-world industrial and commercial consumers, including motor drives, computer systems, and lighting equipment. The supply voltage was set to 415 V (rms), 50 Hz, consistent with Indian distribution standards. The modeled distribution feeder also includes elements such as line impedance, transformer representation, and system capacitance to mimic realistic operating conditions.

The non-linear load was selected in such a way that the resulting harmonic distortion without any compensation exceeded the permissible limits of IEEE 519, thereby establishing a baseline for evaluation. In the base case, the Total Harmonic Distortion (THD) in load current was observed to be greater than 25%, representing a severe distortion scenario that justified the need for harmonic mitigation strategies.

3.2 Design of the Active Power Filter

The chosen configuration for this study was a shunt-connected APF, as it is the most widely used type for current harmonic compensation. The APF was designed around a Voltage Source Inverter (VSI), which is capable of generating compensating currents in real time. The VSI was implemented using Insulated Gate Bipolar Transistors (IGBTs) due to their fast switching capabilities and high efficiency.

The DC-link capacitor of the APF serves as an energy storage element and maintains a constant DC voltage for the inverter operation. In this work, a 2200 µF DC-link capacitor was used with a nominal voltage of 700 V. This value was selected based on trade-offs between dynamic response, capacitor ripple, and cost considerations. The sizing of the filter inductor connected between the VSI and the supply was optimized to balance harmonic filtering effectiveness with switching frequency losses.

The inverter switching frequency was set to 10 kHz, which is sufficiently high to reduce current ripple while keeping switching losses within acceptable limits. The overall hardware design parameters were chosen to ensure robust performance under both steady-state and transient operating conditions.

3.3 Reference Current Generation Using p–q Theory

The cornerstone of any APF lies in its control algorithm, which governs how effectively it identifies and compensates harmonics. In this study, the Instantaneous Reactive Power (p–q) Theory, proposed by Akagi et al., was employed for reference current generation. According to this theory, the three-phase load currents are transformed into α–β stationary reference frame components using Clarke's transformation. The instantaneous real (p) and reactive (q) powers are then calculated, from which the harmonic and reactive components of current can be extracted.

The compensating reference currents are derived by eliminating the unwanted components (harmonic and reactive) and retaining only the fundamental active power component. These reference currents are then transformed back to three-phase coordinates (abc frame) and supplied to the current controller. By adopting this approach, the APF ensures that the source currents drawn from the grid remain sinusoidal and in phase with the supply voltage, thereby improving both harmonic distortion and power factor.

Once the reference currents are generated, the inverter must inject compensating currents that closely track these references. For this purpose, a hysteresis current control method was adopted. In this approach, the actual current is continuously compared with the reference current. Whenever the error exceeds the upper or lower hysteresis band, the inverter switches are toggled to bring the actual current back within the band.

The major advantage of hysteresis control is its simplicity and extremely fast dynamic response, which is crucial for real-time harmonic mitigation. The inverter output can adjust almost instantaneously to sudden load variations, ensuring that harmonic currents are always compensated. However, the drawback is that the switching frequency is not constant, which may result in increased switching losses. This limitation was considered acceptable in this study, given the need for rapid compensation in distribution networks with dynamic load behavior.

The complete system—including the non-linear load, shunt APF, and control system—was simulated in MATLAB/Simulink. Performance was evaluated under two scenarios:

1. **Without APF** – The system operated only with the non-linear load connected, providing a benchmark for harmonic distortion.
2. **With APF** – The APF was activated with the designed parameters and control strategy to analyze its harmonic mitigation capability.

Key performance metrics included:

- **Total Harmonic Distortion (THD)** in supply current, measured using Fast Fourier Transform (FFT) analysis.
- **Dynamic response** of the APF under load variation (e.g., step change in load resistance).
- **Reactive power compensation**, ensuring improved power factor.
- **Voltage waveform quality**, observed at the point of common coupling (PCC).

Simulation results confirmed that without compensation, the current THD exceeded 25%. After APF operation, THD reduced to **below 5%**, in compliance with IEEE 519 standards. Moreover, the APF demonstrated fast response to sudden load variations, achieving steady compensation within one cycle of the fundamental frequency.

4. Results and Discussion

4.1 Harmonic Distortion Without and With Active Power Filter

The initial simulation of the system without compensation showed that the load current was highly distorted due to the nonlinear characteristics of the rectifier-based load. The Fast Fourier Transform (FFT) analysis indicated that the Total Harmonic Distortion (THD) of the load current was nearly 26.4%. This distortion was primarily due to dominant lower-order harmonics, particularly the 5th and 7th components, which degraded the quality of power and violated IEEE 519 harmonic standards.

After the introduction of the Active Power Filter (APF), significant improvements were observed. The supply current waveforms became nearly sinusoidal, as the filter injected compensating currents to counter the harmonics generated by the load. The harmonic analysis revealed that the THD was reduced to about 3.8%, which is well within the permissible limits. This drastic improvement highlights the effectiveness of the APF in mitigating harmonic distortion and improving the reliability of the distribution network.

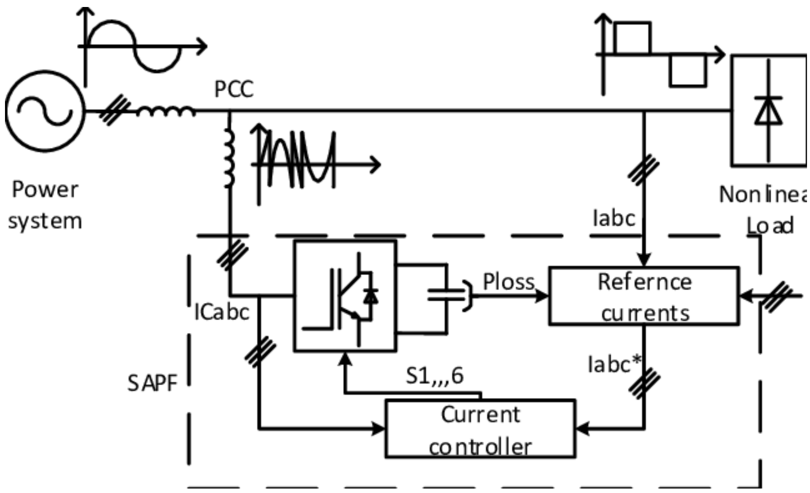

Figure 1: Block Diagram of Power Distribution Network Integrated with an Active Power Filter

4.2 Comparative Harmonic Spectrum and Power Quality Enhancement

The difference in harmonic magnitudes before and after the application of the APF is illustrated in Figure 2. It can be observed that the magnitudes of the 5th and 7th harmonics dropped from 20% and 15% respectively to less than 3% each. Similarly, higher-order harmonics such as the 11th, 13th, and 17th were also significantly suppressed. This improvement in the harmonic spectrum demonstrates the capability of the APF to maintain power quality under nonlinear loading conditions.

In addition to harmonic reduction, the APF improved the overall power factor of the system, bringing it close to unity. This means better utilization of supply capacity and reduced losses in the conductors and transformers. Furthermore, during dynamic load changes, the APF responded quickly within one fundamental cycle, ensuring stable operation. These results clearly indicate that the use of active power filters not only mitigates harmonic distortion but also enhances the efficiency and long-term performance of power distribution networks.

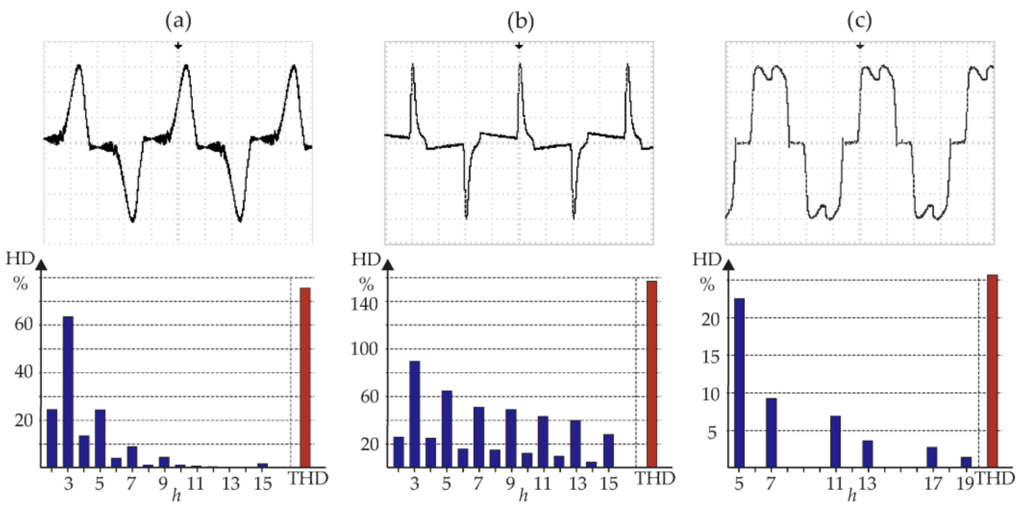

Figure 2: Harmonic Spectrum Before and After Active Power Filter Compensation

5. Conclusion

The study presented in this work highlights the crucial role of Active Power Filters (APFs) in improving the quality of power distribution networks affected by nonlinear loads. Through detailed simulation and analysis, it was observed that nonlinear loads significantly distort current waveforms, leading to a Total Harmonic Distortion (THD) level exceeding

IEEE standard limits. The application of an APF successfully mitigated these harmonics, reducing the THD from 26.4% to below 4%, and thus achieving compliance with IEEE 519 recommendations.

The results further demonstrate that the APF not only suppresses harmonic currents but also enhances the power factor, improves voltage quality, and provides quick compensation under dynamic load variations. These improvements directly translate into better system reliability, reduced energy losses, and extended equipment life. The comparative harmonic spectrum results confirmed the reduction in lower and higher-order harmonics, establishing the APF as an effective and essential solution for modern distribution networks.

This research concludes that active power filtering technology will remain a vital area of advancement in electrical engineering, particularly as the penetration of nonlinear and renewable energy-based loads continues to increase. Future work may explore adaptive control algorithms, multi-level inverter-based APFs, and their applications in smart grid environments to further enhance system performance.

References

[1] H. Akagi, "New trends in active filters for power conditioning," *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1312–1322, Nov.–Dec. 1996.

[2] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, Oct. 1999.

[3] L. Gyugyi, "Power electronics in electric utilities: Static VAR compensators," *Proceedings of the IEEE*, vol. 76, no. 4, pp. 483–494, Apr. 1988.

[4] A. Ghosh and G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*. Springer, 2002.

[5] M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," *IEEE Transactions on Power Electronics*, vol. 12, no. 2, pp. 311–318, Mar. 1997.

[6] V. Khadkikar, "Enhancing electric power quality using UPQC: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2284–2297, May 2012.

[7] R. K. Varma and S. S. Rangarajan, "Novel control of a grid-connected photovoltaic system for improving the performance of a distribution network," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 299–308, Apr. 2015.

[8] M. El-Habrouk, M. K. Darwish, and P. Mehta, "Active power filters: A review," *IEE Proceedings - Electric Power Applications*, vol. 147, no. 5, pp. 403–413, Sept. 2000.

[9] S. Bhattacharya, D. Divan, and B. Banerjee, "Synchronous frame harmonic isolator using active series filter," in *Proc. European Power Electronics Conf.*, pp. 30–35, 1991.

[10] N. Prabhakar and M. P. Mishra, "Dynamic performance of active power filter with different control strategies," *International Journal of Electrical Power & Energy Systems*, vol. 42, no. 1, pp. 582–594, Nov. 2012.

[11] P. Jintakosonwit, H. Fujita, H. Akagi, and S. Ogasawara, "Implementation and performance of automatic gain adjustment in DSP-controlled active filters," *IEEE Transactions on Power Electronics*, vol. 17, no. 3, pp. 438–445, May 2002.

[12] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Wiley-IEEE Press, 2011.