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Finite Impulse Response Filter–Based Active Power Filter for Harmonic Reduction in a 33 KV Power Line

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Abstract- ***This paper presents the design and implementation of a finite impulse response (FIR) fil-ter–based shunt active power filter for har-monic reduction in a 33 kV distribution pow-er line supplying nonlinear industrial loads. The increasing use of power electronic–based equipment in medium-voltage networks in-troduces significant harmonic distortion, lead-ing to poor power quality and non-compliance with established standards. To address this challenge, an FIR filter–based control strategy is proposed for accurate har-monic extraction and reference current gener-ation in an active power filtering system. A detailed model of a practical 33 kV distribution network was developed in the MATLAB/Simulink environment, incorporating nonlinear load characteristics representative of industrial applications. The FIR filter was designed to suppress the fundamental frequency component and selectively ex-tract harmonic currents, which were used to generate compensating current references for a voltage source inverter–based shunt active power filter. The system performance was evaluated under both uncompensated and compensated operating conditions using time-domain and frequency-domain analyses. Simulation results demonstrate that the pro-posed FIR-based active power filter effective-ly mitigates harmonics and improves overall power quality. The source current total harmonic distortion was reduced from 17.77% in the uncompensated system to 0.87% after compensation, achieving full compliance with IEEE 519 harmonic limits. In addition, significant improvements in current wave-form quality and power factor were observed. The results confirm that FIR filter–based active power filtering provides a stable, accurate, and robust solution for harmonic mitigation in medium-voltage distribution systems.***

Keywords: Finite impulse response filter, Shunt active power filter, Harmonic mitigation, Power quality improvement, Frequency response.

I. INTRODUCTION

The increasing penetration of nonlinear loads in modern power systems has made harmonic distortion a major power quality concern, particularly in medium-voltage distribution networks supplying industrial consumers (Chang & Ho, 2000). Equipment such as induction furnaces, variable speed drives, rectifiers, and switched-mode power supplies draw non-sinusoidal currents from the grid, leading to the injection of harmonic components into the power system. In 33 kV distribution networks, these harmonics propagate through transformers and transmission lines, causing voltage distortion, increased losses, overheating of power apparatus, misoperation of protective devices, and reduced overall system efficiency (Jain & Agarwal, 2003; Arpaia, 2014). Ensuring compliance with established power quality standards such as IEEE 519 therefore requires effective and adaptive harmonic mitigation techniques.

Conventional harmonic mitigation methods in medium-voltage systems have largely relied on passive filters due to their simplicity and cost-effectiveness. However, passive filters suffer from several inherent limitations, including fixed compensation characteristics, susceptibility to detuning, and the risk of resonance with system impedance (Rahmani et al., 2010). These drawbacks become more pronounced in distribution networks with variable loading conditions and evolving system configurations. As a result, active power filters have gained significant attention as a more flexible and robust solution for harmonic compensation and reactive power control in power systems. Shunt active power filters operate by injecting compensating currents that are equal in magnitude and opposite in phase to the harmonic currents produced by nonlinear loads (Stones & Collinson, 2007). The effectiveness of an active power filter depends largely on the accuracy and speed of its harmonic detection and reference current generation scheme. Various control techniques have been proposed in the literature, including instantaneous reactive power theory, synchronous reference frame methods, adaptive control, and artificial intelligence–based approaches (Sanusi & Bisiriyu, 2007). Despite their effectiveness, some of these methods involve complex transformations, high computational burden, or sensitivity to noise and parameter variations, which can limit their practical deployment in medium-voltage applications.

Finite impulse response (FIR) filters offer a compelling alternative for harmonic detection and reference signal generation in active power filter control (Salam et al., 2006; Ferdi et al., 2010). FIR filters are inherently stable, possess linear phase characteristics, and can be designed to selectively attenuate unwanted harmonic components while preserving the fundamental frequency component. These features make FIR filters well suited for power system applications where accurate phase alignment and robustness against disturbances are critical. By appropriately designing the filter coefficients, FIR-based controllers can effectively extract harmonic components from measured currents and generate precise compensation signals for active power filtering (Tiwari et al., 2010; Kaur, 2014).

This paper presents the design and implementation of a finite impulse response filter–based shunt active power filter for harmonic reduction in a practical 33 kV distribution power line. The study builds on detailed harmonic characterization of the network and proposes an FIR-based control strategy to generate compensation currents and switching pulses for a voltage source inverter–based active filter. The proposed approach is modeled and evaluated in the MATLAB/Simulink environment under realistic operating conditions. The performance of the FIR-based active power filter is assessed in terms of total harmonic distortion reduction, waveform quality improvement, and compliance with IEEE power quality standards. The results demonstrate the effectiveness of the proposed method in mitigating harmonics and enhancing power quality in medium-voltage distribution systems.

II. THEORY OF WORK

A finite impulse response (FIR) filter–based active power filter (APF) is an advanced harmonic mitigation technique designed to improve power quality in electrical power systems by dynamically compensating for harmonic and reactive currents generated by nonlinear loads (Adams et al., 2012). In medium-voltage networks such as 33 kV distribution systems, the increasing use of power electronic–based industrial equipment has made FIR-based APFs an attractive solution due to their stability, accuracy, and robustness under varying operating conditions. The basic operating principle of an FIR filter–based active power filter involves sensing the load currents at the point of common coupling and processing these signals through a digital FIR filter to extract the harmonic components (Bollen, 1995; Arpaia, 2014). Unlike infinite impulse response filters, FIR filters have a finite duration impulse response and are inherently stable, since they do not rely on feedback. This property makes them particularly suitable for real-time power system applications where stability and predictable behavior are critical (Das, 2011). The linear phase characteristic of FIR filters ensures that all frequency components experience the same time delay, which is essential for maintaining correct phase alignment between the compensating current and the harmonic current to be eliminated.

In a typical configuration, the FIR filter is designed as a high-pass or band-stop digital filter that suppresses the fundamental frequency component while allowing harmonic components to pass through. The filtered signal represents the harmonic current content of the load (Ghosh & Ledwich, 2012). This signal is then used as a reference to generate compensating currents through a voltage source inverter (VSI). The inverter injects currents of equal magnitude and opposite phase into the power system, effectively canceling the harmonic currents drawn by the nonlinear load (Rahmani et al., 2010; Kaur, 2014). A simplified block representation of this process is commonly illustrated in Figure 1, showing the interaction between current sensing, FIR filtering, reference current generation, inverter control, and current injection at the point of common coupling.

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The FIR-based APF control scheme typically includes a pulse-width modulation unit to convert the reference compensating currents into appropriate switching signals for the inverter. Because FIR filters can be precisely tuned to target specific harmonic orders, the controller is able to adapt to different harmonic spectra without requiring complex coordinate transformations (Bollen, 1995; Stones & Collinson, 2007).

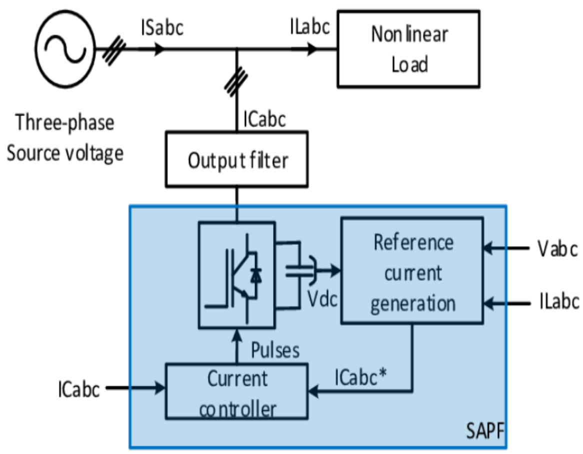

Figure 1: Block diagram of FIR filter–based shunt active power filter

This advantage reduces computational complexity when compared to synchronous reference frame or instantaneous power theory–based controllers, making FIR-based approaches suitable for medium-voltage applications with limited control bandwidth. The performance of FIR filter–based active power filters has been widely evaluated in terms of harmonic reduction, power factor improvement, and dynamic response (Ramya & Arpitha, 2013). Simulation and experimental studies reported in the literature consistently show substantial reductions in current total harmonic distortion when FIR-based APFs are employed. Typical results demonstrate a reduction of current THD from values exceeding 15% in uncompensated systems to below 5% after compensation, in compliance with IEEE 519 recommendations. Another important characteristic of FIR-based APFs is their immunity to parameter variations and noise. Since FIR filters do not use feedback, they are less sensitive to changes in system impedance and frequency drift (Seymour & Horsley, 2005; Tiwari et al., 2010).

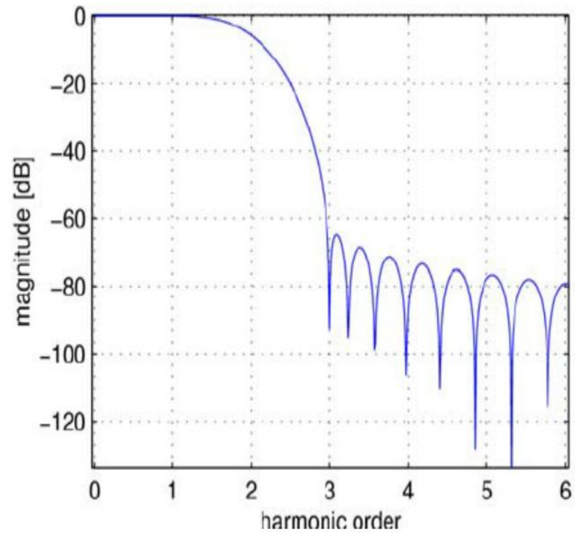

Figure 2: Magnitude response of FIR filter designed for harmonic extraction in power systems

This makes them suitable for practical power networks where operating conditions vary continuously. The frequency response of a typical FIR filter used for harmonic extraction is usually presented in the literature to illustrate its selectivity, as shown in Figure 2, where strong attenuation at the fundamental frequency and high gain at harmonic frequencies can be observed.

Overall, FIR filter–based active power filters provide an effective and reliable solution for harmonic mitigation in 33 kV distribution systems. Their inherent stability, linear phase response, and flexible design capability enable accurate harmonic detection and compensation under diverse operating conditions. These features make FIR-based APFs a strong candidate for improving power quality in medium-voltage networks supplying nonlinear industrial loads.

III. METHODOLOGY

The methodology adopted in this study is centered on the design, modeling, and performance evaluation of a finite impulse response (FIR) filter–based shunt active power filter for harmonic reduction in a 33 kV distribution power line. The approach integrates power system modeling, digital filter design, active filter control implementation, and simulation-based performance assessment within the MATLAB/Simulink environment. The first stage of the methodology involves modeling the 33 kV distribution system supplying nonlinear industrial loads. The network is represented by a three-phase balanced source, transmission lines, a step-down transformer, and a dominant nonlinear load modeled using a controlled rectifier and induction furnace equivalent. System parameters such as line impedance, transformer ratings, and load characteristics are selected to reflect practical operating conditions of a medium-voltage distribution feeder. This model serves as the baseline system for harmonic analysis and mitigation. Harmonic current detection and reference signal generation are achieved using a digital FIR filter. The measured three-phase load currents at the point of common coupling are sampled and passed through the FIR filter to extract the harmonic components. The FIR filter is designed to attenuate the fundamental frequency component while allowing harmonic frequencies to pass with minimal distortion. The filter coefficients are obtained using a window-based design method, ensuring linear phase response and stable operation. The general output of the FIR filter is expressed as

$$i_h(n) = \sum_{k=0}^{N-1} h(k) i_L(n-k)$$

Where $i_h(n)$ is the extracted harmonic current, $i_L(n)$ is the sampled load current, $h(k)$ represents the FIR filter coefficients, and N is the filter order. The extracted harmonic currents form the reference compensating signals for the active power filter.

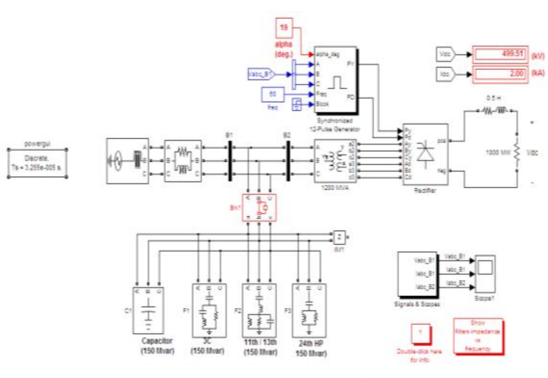

Figure 3: Simulink model of Three-Phase Harmonic Filter with FIR filter

The shunt active power filter is implemented using a three-phase voltage source inverter connected to the system through coupling inductors. The reference compensating currents generated by the FIR filter are compared with the actual filter currents, and the resulting error signals are processed by a hysteresis current controller to generate switching pulses for the inverter. This control strategy ensures fast dynamic response and accurate tracking of the reference currents. The inverter injects compensating currents of equal magnitude and opposite phase to the detected harmonic currents, thereby canceling harmonics at the point of common coupling. To maintain the dc-link voltage of the voltage source inverter at a constant level, a proportional–integral controller is incorporated into the control loop. The dc-link voltage regulator ensures that sufficient energy is available for harmonic compensation while minimizing steady-state voltage fluctuations. The interaction between the FIR filter, current controller, and dc-link voltage controller provides coordinated control of both harmonic and reactive power components.

The performance evaluation of the proposed FIR-based active power filter is carried out through time-domain and frequency-domain simulations. System behavior is analyzed under two operating conditions: without harmonic compensation and with the FIR-based active power filter in operation. Key performance indices such as source current waveform quality, voltage and current total harmonic distortion, and power factor are computed using Fast Fourier Transform analysis. The harmonic spectra obtained before and after compensation are used to quantify the effectiveness of the proposed approach. Finally, compliance with IEEE 519 harmonic limits is assessed by comparing the simulated total harmonic distortion values with standard thresholds. The simulation results provide a clear basis for evaluating the suitability of the FIR filter–based active power filter for harmonic mitigation in medium-voltage distribution systems and demonstrate its effectiveness under realistic operating conditions.

IV. RESULTS

The performance of the proposed finite impulse response (FIR) filter–based shunt active power filter was evaluated through detailed simulations carried out in the MATLAB/Simulink environment. The results are presented and discussed by comparing system behavior under uncompensated conditions and with

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the FIR-based active power filter in operation, with emphasis on waveform quality, harmonic distortion, and compliance with power quality standards. Under uncompensated operation, the nonlinear industrial load connected to the 33 kV distribution feeder drew highly distorted currents from the source. The time-domain simulation results show that while the supply voltage remained nearly sinusoidal due to the stiff upstream network, the source current exhibited significant waveform distortion characterized by sharp peaks and notches. Frequency-domain analysis using the Fast Fourier Transform revealed the presence of dominant low-order harmonics, particularly the 3rd and 5th harmonics, with appreciable contributions from higher-order components. The total harmonic distortion of the source current was measured at 17.77%, significantly exceeding the IEEE 519 recommended limits for medium-voltage systems.

When the FIR filter–based active power filter was introduced into the system, a substantial improvement in current waveform quality was observed. The compensated source current became nearly sinusoidal and closely aligned with the supply voltage, indicating effective harmonic cancellation and reactive power compensation. These improved waveforms are shown in Figure 4. The linear phase and stability properties of the FIR filter enabled accurate extraction of harmonic components and precise generation of compensating currents by the voltage source inverter.

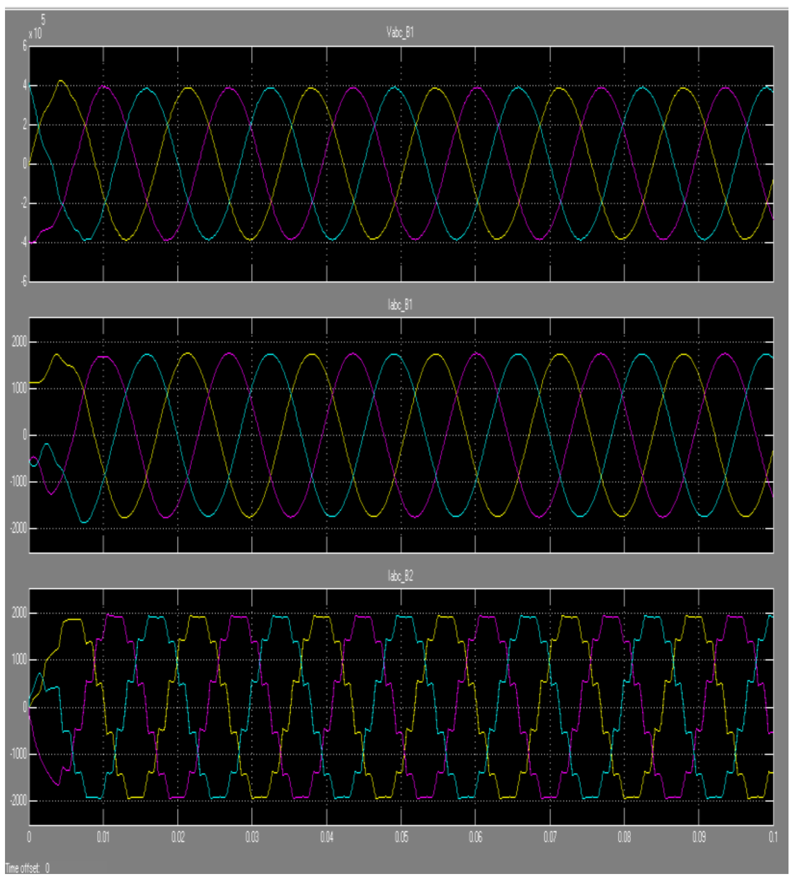

Figure 4: Source voltage and current waveforms with FIR-based active power filter.

The harmonic spectra obtained after compensation demonstrate a significant reduction in both low- and high-order harmonics. As shown in Figure 5, the amplitudes of the dominant harmonic orders were drastically reduced. The total harmonic distortion of the source current was reduced from 17.77% to 0.87%, representing a harmonic reduction of over 95%. This level of distortion is well within the limits specified by IEEE 519, confirming the effectiveness of the proposed FIR-based control strategy. A Plot the impedance vs. frequency of the harmonic filters presented in Figure 6.

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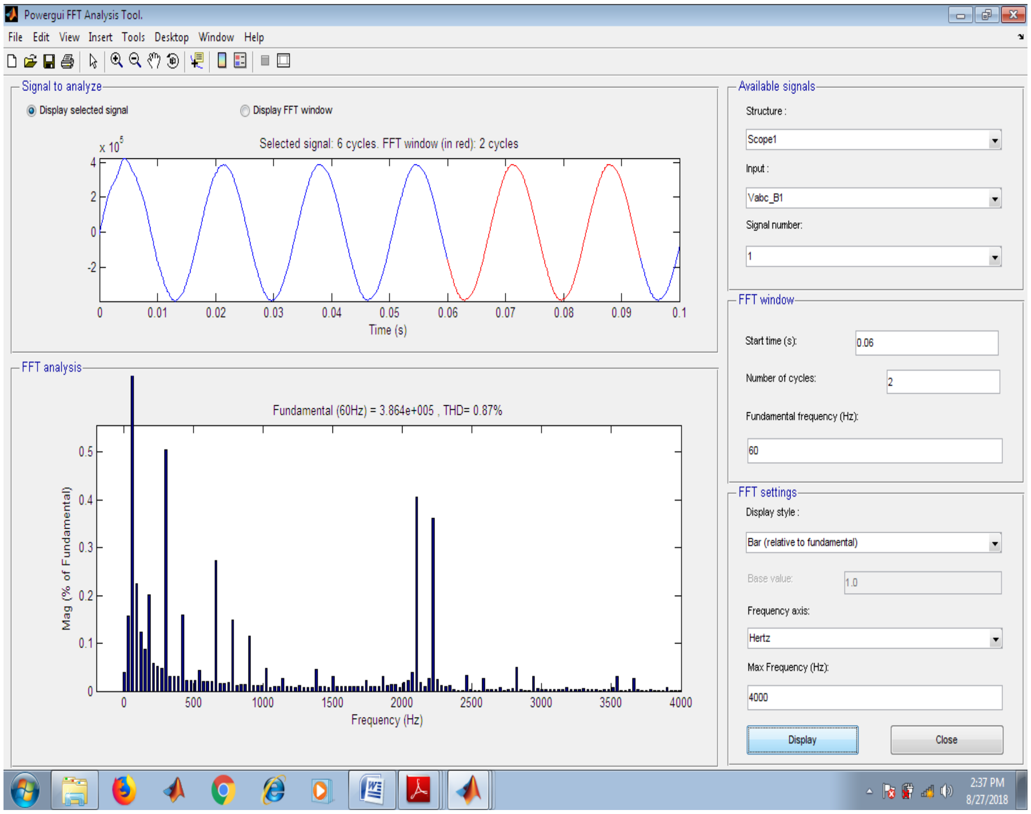

Figure 5: Harmonic spectrum of source current after FIR-based compensation

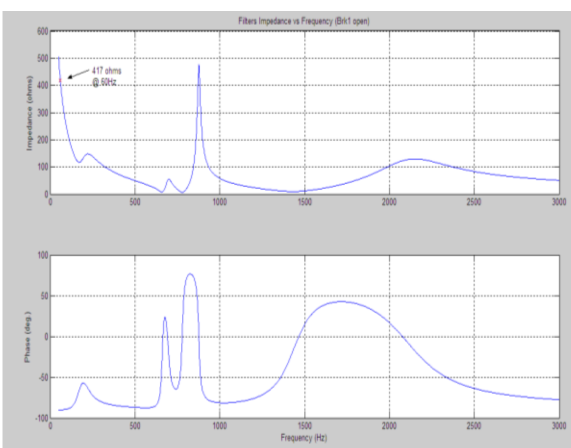
Figure 6: Plot the impedance vs. frequency of the harmonic filters

In addition to harmonic mitigation, the FIR-based active power filter significantly improved the power factor of the system. The near in-phase relationship between the source voltage and current under compensated conditions indicates that reactive power demand was effectively minimized. This improvement contributes to reduce current loading of network components and lower system losses. The dc-link voltage of the voltage source inverter remained stable throughout the simulation, demonstrating the effectiveness of the implemented dc-link voltage control scheme in maintaining energy balance during compensation. The dynamic response of the FIR-based active power filter was also examined under sudden load variations. Simulation results showed that the compensating currents adjusted rapidly to changes in load conditions, with minimal transient distortion. This fast response can be attributed to the feedforward nature of the FIR filter and the hysteresis current control technique, which together provide high bandwidth and robustness against system disturbances.

Table 1: Total Harmonic Distortion of System with and without FIR filter

System without FIR Filter	System with FIR filter
17.77%	0.87%

Overall, the results confirm that the FIR filter–based shunt active power filter provides effective harmonic

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mitigation and power quality enhancement in a 33 kV distribution system. Compared to uncompensated operation, the proposed approach significantly reduces total harmonic distortion, improves power factor, and ensures compliance with IEEE harmonic standards. The findings demonstrate that FIR-based active filtering is a technically viable and efficient solution for harmonic reduction in medium-voltage power networks supplying nonlinear industrial loads.

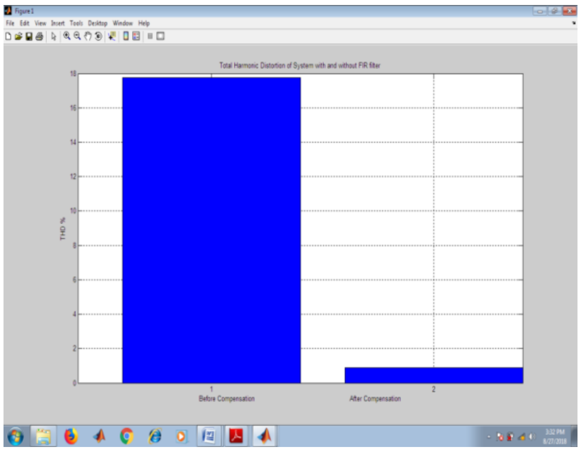

Figure 7: Comparative Graphical analysis between System without and with Filter

V. CONCLUSION

This paper has presented the design, modeling, and performance evaluation of a finite impulse response (FIR) filter–based shunt active power filter for harmonic reduction in a 33 kV distribution power line supplying nonlinear industrial loads. The proposed approach utilizes the inherent stability and linear phase characteristics of FIR filters to accurately extract harmonic components and generate precise compensating current references for active power filtering. Simulation results obtained from the MATLAB/Simulink environment demonstrate that the uncompensated system experiences severe harmonic distortion, with source current total harmonic distortion exceeding recommended IEEE 519 limits. The dominant low-order harmonics introduced by nonlinear loads significantly degrade current waveform quality and adversely affect overall power system performance. With the implementation of the FIR-based active power filter, a substantial improvement in power quality was achieved. The source current THD was reduced from 17.77% to 0.87%, representing a harmonic reduction of more than 95% and ensuring full compliance with IEEE harmonic standards. In addition to effective harmonic mitigation, the proposed control scheme improved power factor and reduced reactive power demand, thereby lowering current stress on system components and minimizing losses. The dc-link voltage regulation and current control strategy ensured stable and reliable operation of the voltage source inverter under both steady-state and dynamic load conditions. The fast transient response observed during load variations further confirms the robustness and suitability of the FIR-based approach for practical medium-voltage applications.

The findings validate the effectiveness of FIR filter–based active power filtering as a reliable and efficient solution for harmonic reduction in 33 kV distribution systems. The proposed methodology provides a solid foundation for the deployment of advanced digital filtering techniques in active power filters and can be extended to other medium- and high-voltage networks with significant nonlinear load penetration.

Authors Contributions
The first author supervised the research, reviewed the methodology, and contributed to the interpretation of the findings. The Second author conceptualized the study, developed the research methodology, carried out the modelling and simulation, analysed the results, and prepared the initial manuscript. The third author assisted with data collection, validation, and manuscript review. All authors reviewed and approved the final manuscript.

Potential Conflicts of Interest
The Authors declare that there are no conflicts of interest, and the study has not received any funding.

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