Field-Validated Triplen Harmonic and Neutral Current Mitigation Using an Active Harmonic Filter

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Abstract: Nonlinear loads in commercial buildings increasingly distort low-voltage distribution systems and may cause excessive neutral-current loading. Third-order triplen harmonics are especially critical in three-phase four-wire systems because their zero-sequence components accumulate in the neutral conductor instead of cancelling among phases. Despite extensive harmonic research, few field-based studies jointly quantify triplen-driven neutral loading, verify Active Harmonic Filter (AHF) performance on an operating commercial site, and confirm IEEE Std 519-2022 compliance within a single case, leaving a practical evidence gap. This paper presents a field-validated assessment of triplen harmonic mitigation in a commercial building distribution system using a shunt Active Harmonic Filter (AHF). Field measurements were obtained at the incoming side of the SDP Amazon Atrium Senen distribution panel using a power quality analyzer, and the results were evaluated using IEEE Std 519-2022. A MATLAB/Simulink model was developed to represent the measured operating condition and support performance interpretation. The model was validated against the field data—accurate for voltage distortion and power factor but under-predicting current distortion—so it is positioned as a trend-analysis rather than a sizing tool. The pre-mitigation condition showed severe current distortion, with phase-current THDi values of 69.27%, 81.47%, and 56.28%, a voltage THD of 5.40%, a neutral current of 96.89 A, and a power factor of 0.82. After AHF operation, the THDi values decreased to 9.87%, 12.18%, and 8.46%, while THDv decreased to 3.35%, neutral current decreased to 23.41 A, and power factor increased to 0.99. Whereas conventional THDi and TDD indices quantify overall distortion but not the zero-sequence burden carried by the neutral conductor, this study introduces a dedicated metric for that burden. The proposed Neutral Harmonic Mitigation Ratio (NHMR) reached 75.84%, indicating

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substantial reduction of triplen-related neutral loading. Evaluated through Total Demand Distortion under the measured short-circuit ratio, the post-mitigation condition satisfied the IEEE Std 519-2022 current-distortion limit. The results show that a field-validated AHF approach can effectively mitigate triplen harmonic effects and improve power quality in commercial three-phase four-wire distribution systems. Beyond the numerical gains, the field-validated framework gives facility engineers a practical, standards-referenced basis for diagnosing neutral-current risk and planning AHF-based mitigation in commercial power systems.

Keywords: active harmonic filter, commercial building, IEEE 519-2022, neutral current, triplen harmonics.

Introduction

Commercial buildings increasingly rely on power-electronic and nonlinear loads such as LED lighting, uninterruptible power supplies, switching power supplies, variable-frequency drives, servers, computers, and electronic converters. These loads improve operational flexibility but draw nonsinusoidal current from low-voltage distribution systems. Consequently, harmonic distortion may increase conductor losses, overheat transformers and neutral conductors, reduce power factor, disturb protection devices, and degrade supply quality (Afonso, Brandao, Goncalves, & Monteiro, 2021; Michalec et al., 2021; Mishra, 2019; Phannil, Jettanasen, & Ngaopitakkul, 2018; Ramljak & Tokić, 2020; Remigio-Carmona et al., 2022). Recent power-quality reviews have emphasized that harmonic monitoring and mitigation remain important for modern distribution networks because load composition changes dynamically and field conditions are often more complex than idealized simulation cases (Arranz-Gimón, Zorita-Lamadrid, Morinigo-Sotelo, & Duque-Perez, 2021; Oubrahim, Amirat, Benbouzid, & Ouassaid, 2023; Remigio-Carmona et al., 2022; Samanta, Roy, & Chatterjee, 2023). Third-order triplen harmonics deserve special attention in three-phase four-wire commercial systems. Unlike the fundamental component and non-triplen harmonic components, third-order harmonic currents are zero-sequence components; therefore, their phase components add in the neutral conductor instead of cancelling. This can cause the neutral current to approach or exceed phase currents even when voltage magnitude remains acceptable (Akagi, Watanabe, & Aredes, 2017; Das, 2015; Gruzs, 1990; Lazar et al., 2026). For facility operators, this is not only a waveform-quality issue but also an operational reliability issue because excessive neutral current may accelerate insulation ageing, increase thermal stress, and raise the risk of nuisance tripping or equipment malfunction. Previous studies can be grouped into four streams. First, review and signal-processing studies summarize power-quality disturbance detection, feature extraction, and classification methods (Afonso et al., 2021;

Chawda et al., 2020; Mishra, 2019; Oubrahim et al., 2023; Remigio-Carmona et al., 2022; Samanta et al., 2023)these clarify the importance of harmonic monitoring but do not usually provide a site-specific neutral-current mitigation assessment. Second, passive-filter studies demonstrate harmonic reduction using tuned filters (Ishaya, Abu-Siada, & Islam, 2023; Park, Lee, Yoo, & Jang, 2021), but passive filters may be sensitive to load variation and resonance conditions. Third, active and hybrid filter studies report promising results using SAPF, AHF, or hybrid filter control strategies (Baliyan, Rizwan, & Jamil, 2021; Boopathi & Indragandhi, 2024; Chauhan & Chauhan, 2024; Iqbal et al., 2021; Khan et al., 2021), although many emphasize controller performance, simulation, hardware-in-the-loop, or laboratory validation. Fourth, standard-oriented studies and IEEE Std 519-2022 provide the compliance basis for harmonic control (IEEE, 2010, 2019, 2022), but compliance evaluation must still be translated into practical field-based decisions for commercial buildings. The remaining gap is therefore practical and methodological: previous work has not sufficiently connected field-measured triplen harmonic behavior, neutral-current loading, AHF mitigation performance, and IEEE Std 519-2022 compliance in a single commercial-building case study. This gap matters because building operators need evidence that a mitigation device does not merely reduce THDi numerically, but also reduces neutral-conductor loading and restores compliance under actual operating conditions. In practice, commercial buildings are a particularly challenging setting for triplen harmonics. Their load mix is dominated by single-phase electronic equipment—computers, LED drivers, uninterruptible power supplies, and variable-frequency HVAC—whose rectifier front ends inject strong third-order currents. Because these zero-sequence components add rather than cancel, the neutral conductor can carry currents approaching or exceeding the phase values, producing conductor and transformer overheating, additional losses, nuisance tripping, and elevated fire risk—often without any obvious voltage-level symptom. Facility operators therefore face a risk that is severe yet easily missed by conventional voltage-based monitoring. The novelty of this study is threefold. First, it provides field evidence—rather than simulation alone—linking measured triplen behavior to neutral-current loading in an operating commercial building. Second, it introduces the Neutral Harmonic Mitigation Ratio (NHMR), a metric that isolates the reduction of triplen-related neutral loading, which conventional THDi and TDD indices do not capture directly. Third, it couples this evidence to a formal IEEE Std 519-2022 compliance assessment based on Total Demand Distortion (TDD), closing the loop from measurement to a standard-referenced decision. These points motivate the research objectives stated below.

These findings should be read with several limitations that follow from the study design. First, the evidence comes from a single commercial building and a single operating window, so the absolute values are specific to that site and to daytime commercial operation; daily and seasonal load variation, not captured here, could change the magnitude—though not the mechanism—of the neutral loading. Second, field measurement carries inherent uncertainty from clamp accuracy and analyzer tolerance, and only a single measurement pass was available, so formal repeatability statistics could not be computed. Third, IL was approximated from the highest recorded load current, which affects the TDD magnitude as discussed above. Fourth, the study evaluates technical performance only; installation and operating economics, and a direct comparison with passive or hybrid alternatives, were outside its scope. Each of these bounds the generalization of the reported numbers rather than the qualitative conclusion that triplen harmonics dominate the neutral loading and that the AHF mitigates it.

To address this gap, this paper presents a field-validated case study of SDP Amazon Atrium Senen, a commercial low-voltage three-phase four-wire distribution system. The study evaluates severe harmonic distortion before mitigation, quantifies the reduction achieved after a shunt AHF is operated, and interprets the result from the perspective of triplen harmonic accumulation and IEEE Std 519-2022 compliance. The main contributions are: (1) a field-based power-quality assessment of a commercial three-phase four-wire system with severe harmonic distortion; (2) a gap-driven interpretation of third-order triplen harmonics as the mechanism behind neutral-current amplification; (3) quantification of neutral-current reduction using the proposed Neutral Harmonic Mitigation Ratio (NHMR); (4) evaluation of AHF effectiveness for THDi, THDv, neutral current, and power factor; and (5) compliance assessment against IEEE Std 519-2022 under the measured short-circuit-to-load-current ratio. The remainder of the paper is organized as follows: the Related Work and Research Gap section reviews prior studies; the Research Method section describes the methodology; the Result and Discussion section presents the findings; and the Conclusions section closes the paper.

Related Work and Research Gap

Power-Quality Monitoring and Harmonic Characterization

Power quality problems in distribution systems include voltage variation, waveform distortion, unbalance, transients, and interruptions. In harmonic studies, total harmonic distortion of voltage (THDv), total harmonic distortion of current (THDi), and total demand distortion (TDD) are widely used indicators (Arranz-Gimón et al., 2021; IEEE, 2019, 2022). Review papers (Afonso et al., 2021; Michalec et al., 2021; Oubrahim et al., 2023; Remigio-Carmona et al., 2022; Samanta et al., 2023) show that power-quality analysis increasingly combines signal processing, pattern recognition, and monitoring frameworks. Their limitation for the present problem is that they are broad reviews; they do not quantify how triplen-dominated distortion affects neutral current in a specific commercial three-phase four-wire installation. The THD of current and voltage are calculated as.

$$THD_I = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \times 100\% \tag{1}$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} \times 100\% \tag{2}$$

where $I_1$and V_1denote the RMS values of the fundamental current and voltage, respectively, while $I_h$and $V_h$represent the RMS values of the h-th harmonic current and voltage components, respectively

Triplen Harmonics and Neutral-Current Risk

Triplen harmonics include the 3rd, 9th, 15th, and higher integer multiples of the third harmonic. In a balanced three-phase system, the fundamental phase currents are separated by 120°. However, for the third harmonic, the phase displacement becomes 3 × 120° = 360°, which means that third-harmonic currents are effectively in phase. Therefore, they add arithmetically in the neutral conductor. If the dominant contribution is the third harmonic and the three phase harmonic magnitudes are approximately equal, the neutral current contribution can be approximated as.

$$I_N \approx 3I_3 \tag{3}$$

where I_N is the RMS neutral current and $I_3$is the RMS value of the third-harmonic current in each phase. This approximation is valid for balanced three-phase systems, in which the third-harmonic currents are zero-sequence components that are in phase and therefore add arithmetically in the neutral conductor. (Akagi et al., 2017; Das, 2015; Gruzs, 1990; Subjak & McQuilkin., 1990) however, many applied mitigation papers still report THDi reduction without making neutral-current loading a central evaluation metric. This paper directly addresses that limitation by treating neutral current as a primary operational outcome.

Passive, Active, and Hybrid Harmonic Mitigation

Passive-filter studies (Ishaya et al., 2023; Park et al., 2021) demonstrate that tuned passive filters can reduce selected harmonic orders, but their practical limitation is sensitivity to system impedance, resonance risk, and changing load conditions. Passive zero-sequence solutions such as zig-zag transformers can also reduce neutral-conductor current, but they are similarly fixed in nature and cannot follow rapid load variation (Jou, Wu, Wu, Chiang, & Chen, 2005). Active and hybrid approaches, including neural-network-based shunt hybrid APF (Iqbal et al., 2021), intelligent PI-based hybrid active filtering (Baliyan et al., 2021), hardware-in-the-loop hybrid shunt APF evaluation (Khan et al., 2021), and experimental SAPF implementations (Boopathi & Indragandhi, 2024), show stronger adaptability under nonlinear loading. Nevertheless, these studies are often controller-focused and do not always combine real commercial-building audit data, neutral-current risk, and IEEE 519 compliance recovery in one framework. An AHF mitigates harmonics by measuring the distorted load current, extracting the harmonic component, and injecting a compensating current with opposite phase. For a shunt AHF, the source current can be represented as.

$$i_s(t) = i_L(t) + i_c(t) \quad (4)$$

where $i_s(t)$is the instantaneous source current, $i_L(t)$is the instantaneous load current, and $i_c(t)$is the instantaneous compensation current generated by the active power filter. If the compensation current is properly controlled to cancel the harmonic components of the load current, the source current becomes nearly sinusoidal and remains in phase with the source voltage.

$$i_c(t) \approx -i_h(t) \quad (5)$$

If the compensation current satisfies (5), the source current approaches the fundamental component, $i_1(t)$, with most harmonic components effectively eliminated. Compared with passive filters, Active Harmonic Filter (AHF) technology provides adaptive harmonic compensation under varying load conditions, resulting in improved power quality. However, this capability is achieved at the expense of higher implementation cost and increased control complexity. (Afonso et al., 2021; Akagi, Kanazawa, & Nabae, 1984; Akagi et al., 2017; Boopathi & Indragandhi, 2024; Das et al., 2021; Singh, Al-Haddad, & Chandra, 1999).

Standards-Based Compliance and Remaining Gap

IEEE Std 519-2022 provides recommended harmonic limits at the point of common coupling (PCC). For current distortion, the allowable limit depends on the ratio ISC/IL, where ISC is the short-circuit current at the PCC and IL is the maximum demand load current (IEEE., 2022). In the evaluated SDP Amazon system, the measured ratio was ISC/IL = 171.41, placing the system within the 100 ≤ ISC/IL < 1000 range, for which the relevant current-distortion limit is 15%. This limit becomes the basis for before-and-after compliance evaluation. Table 1 summarizes how the paper responds to limitations in prior work, ensuring that the novelty is presented as a response to a specific gap rather than a generic AHF claim. The reviewed studies also provide extractable benchmark evidence, but the available variables are not uniform; Table 2 therefore keeps each metric explicit instead of forcing all studies into a single indicator.

Table 1 Gap-to-Contribution Mapping of This Study

Literature stream	Typical limitation	Response in this paper
PQ reviews (Afonso et al., 2021; Oubrahim et al., 2023; Remigio-Carmona et al., 2022; Samanta et al., 2023)	Broad monitoring focus; limited site-specific mitigation evidence	Field case study with before-after AHF data
Passive filters (Ishaya et al., 2023; Park et al., 2021)	Less adaptive to variable nonlinear loads	AHF under actual commercial loading
APF/SAPF studies (Baliyan et al., 2021; Boopathi & Indragandhi, 2024; Iqbal et al., 2021; Khan et al., 2021)	Often simulation, HIL, or controller focused	Neutral current and IEEE 519 as central outcomes
Standards references (IEEE, 2019, 2022)	Provide limits but not site-specific decision evidence	Compliance recovery from field data

Read together, Table 1 shows that prior work tends to treat monitoring, mitigation, or standards in isolation; the present study is positioned to connect these strands within a single field case rather than to add another device-level demonstration.

Table 2 Compact Benchmark Dataset from Prior Studies

Study	Metric	Extracted performance
Park et al. (2021)	ITDD	8.75% to 4.75%; 45.71% reduction
Ishaya et al. (2023)	THDi	14.93% to 4.87%; 67.38% reduction
Iqbal et al. (2021)	THDi avg.	58.98% to 3.64%; 93.83% reduction
Khan et al. (2021)	THDi	31.74% to 2.38%; 92.50% reduction
Boopathi & Indragandhi (2024)	THDi	26.0% to 1.5%; 94.23% reduction
This study	THDi max.	81.47% to 12.18%; 85.05% reduction

Interpreting Table 2, the reported reductions differ less in the devices used than in what they leave unverified. Monitoring-oriented work characterizes distortion but rarely tests a mitigation device on-site; passive-filter studies achieve reduction but adapt poorly to the changing load mix of commercial buildings; and active or hybrid-filter studies frequently remain at the simulation or hardware-in-the-loop stage, or emphasize controller design over field-confirmed neutral-current outcomes. Standards references define limits but not the site-specific evidence needed for an operational compliance decision.

Against conventional harmonic indicators, this distinction motivates the proposed metric. THDi expresses per-phase current distortion and TDD expresses demand-referenced distortion for compliance, but neither isolates how much of the neutral-conductor burden—the specific hazard of triplen harmonics—has been removed. The Neutral Harmonic Mitigation Ratio (NHMR) is defined to fill exactly this gap, expressing the fractional reduction of neutral current attributable to mitigation and thereby complementing, not replacing, THDi and TDD. In these terms the present framework extends previous field-based AHF studies in three ways: it validates AHF performance on an operating commercial site rather than a test bench; it reports neutral-current outcomes explicitly through NHMR; and it ties the result to an IEEE Std 519-2022 TDD compliance decision. Recent 2024–2026 studies from IEEE Transactions and IEEE Access on commercial-building harmonic mitigation should be cited here to situate these contributions among the latest work [recent references to be finalized by the authors per journal scope].

Research Method

Research Design Rationale

The study was designed as a field-measurement-driven engineering case study because the investigated problem is operational rather than purely theoretical. Triplen harmonic accumulation and neutral-current loading depend on actual load composition, phase imbalance, building operation, and the installed mitigation device. Therefore, a field audit was used as the primary evidence source, while Simulink modelling was used to support interpretation and reproducibility. This design follows a problem-to-evidence logic: the field audit identifies the severity of distortion, the harmonic mechanism explains why neutral current becomes excessive, the AHF intervention tests whether mitigation reduces the operational risk, and IEEE Std 519-2022 provides the compliance benchmark.

Implementation considerations. Deploying a shunt AHF entails capital cost broadly scaled to its harmonic-current rating, plus switchgear and installation, and ongoing requirements such as periodic inspection, ventilation/cooling, firmware maintenance, and verification measurements; these should be weighed against the avoided cost of neutral-conductor and transformer derating, downtime, and premature equipment aging. For facility maintenance, the same measurement-based framework supports planning: periodic recording of neutral current and NHMR provides an early, quantitative indicator of rising triplen loading, allowing filter servicing or capacity decisions to be scheduled before thermal limits are approached.

The approach is scalable. In larger facilities, filters can be applied per panel or per riser and coordinated, with the incoming-panel measurement method replicated at each monitored point. The methodology also transfers to environments where nonlinear loads dominate—hospitals, data centers, and light-industrial facilities—where neutral-current and continuity requirements are even more critical, although filter rating, redundancy, and compliance targets must be set case by case. A single operating commercial building was studied in depth because the objective is field verification of triplen-driven neutral loading and AHF mitigation under real load conditions, which requires access to an energized panel with an installed filter rather than a large sample of sites. The selected building—an active retail/commercial facility whose load mix comprises computers, lighting, UPS, and VFD-driven HVAC—is representative of the electronic-load-dominated profile typical of modern commercial buildings, so the mechanisms observed are expected to generalize qualitatively. The corresponding constraint on statistical generalization is stated explicitly in the Limitations.

Field Measurement Site

The case study was conducted at SDP Amazon Atrium Senen, Jakarta, Indonesia. The distribution system is a low-voltage three-phase four-wire system operating at 400/230 V and 50 Hz. The panel supplies commercial nonlinear loads, including computers, LED lighting, UPS equipment, switching power supplies, and other electronic devices. The field measurement was performed at the incoming side of the distribution panel using a Hioki PQ3100 power quality analyzer, following standard power-quality measurement practice (IEC, 2015; IEEE, 2019). The measurement was carried out on 30 July 2025 over an approximately two-hour window (09:28:15–10:43:14 local time), with the power quality analyzer logging trend data at a one-second interval (Hioki PQ3100 trend setting). The pre-mitigation condition (AHF bypassed) and the post-mitigation condition (AHF in normal operation) were recorded consecutively within the same operating window, so that both datasets reflect comparable load and system conditions.

Measurement Procedure, Sensor Placement, and Uncertainty

The measurement configuration and sensor placement are illustrated in Figure 1. Voltage leads and split-core current clamps (CTs) were connected to all four conductors (R, S, T, and neutral) at the incoming side of the SDP Amazon panel, upstream of the downstream commercial loads and at the same busbar where the shunt Active Harmonic Filter (AHF) was installed. This measurement arrangement captures the aggregate load current and the neutral current directly, which are essential for evaluating harmonic distortion, triplen harmonic accumulation, and the overall effectiveness of the AHF.

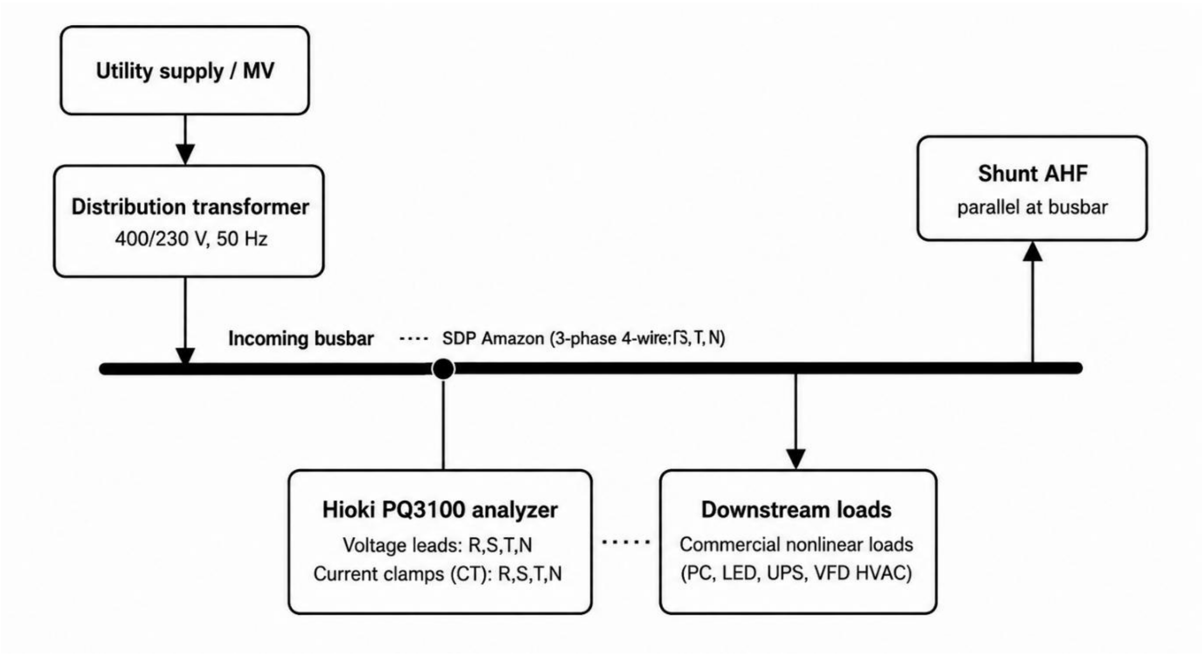

Figure 1 Measurement setup and sensor placement at the incoming panel (SDP Amazon)

Placing the analyzer at the incoming busbar rather than at individual feeders ensures that the recorded THDi, TDD, and neutral current represent the whole-panel operating condition seen by the utility and by the AHF—the level at which IEEE Std 519-2022 compliance is meaningful. Measurements were recorded with a Hioki PQ3100 power quality analyzer, an instrument oriented to the IEC 61000-4-30 measurement quantities, used within its valid manufacturer calibration interval with matched clamp sensors on each conductor. The dominant measurement uncertainties arise from current-clamp amplitude and phase response at higher harmonic orders and from the analyzer's amplitude accuracy; for the low-order components that dominate here (third and fifth), these contribute only a small percentage relative to the very large before-and-after differences reported, so they do not affect the qualitative conclusions. The instrument's calibration-certificate date and clamp accuracy class can be added if required by the journal. The measurement window (approximately two hours, 09:28–10:43) was selected to coincide with normal daytime commercial operation, when occupancy and the electronic load mix—and therefore triplen generation—are at their representative working level. Because the pre- and post-mitigation datasets were captured consecutively within this same window, the comparison isolates the effect of the AHF from load variation. This window characterizes the building's typical operating condition rather than its full 24-hour or seasonal envelope; longer-term monitoring is identified in the Limitations as future work.

Measurement Parameters

The measured parameters included phase-to-phase voltage, phase current, neutral current, system frequency, power factor, THDi, THDv, and harmonic spectrum. Measurements were conducted for the pre-mitigation condition and for the condition after the shunt AHF was operated. The key measured system parameters are summarized in Table 3.

Table 3 Measured System Parameters Used for Analysis

Parameter	Value
Nominal system voltage	400 V
Frequency	50 Hz
System configuration	3-phase 4-wire
Maximum initial THDi	81.47%
Initial THDv	5.40%
Initial neutral current	96.89 A
Initial power factor	0.82
ISC/IL	171.41

Table 3 shows the main electrical parameters measured before the Active Harmonic Filter (AHF) was implemented. The results of these measurements describe the operating condition of the electrical distribution system, with high current harmonic distortion (THDi), high neutral current and low power factor. The measured parameters are taken as the reference to assess the effectiveness of the AHF in enhancing the power quality under the same operating conditions.

Table 4 Operating and Measurement Conditions Before and After AHF Operation

Aspect	Before AHF	After AHF
Measurement date	30 July 2025	30 July 2025 (same day)
Measurement window	09:28:15–10:43:14 (consecutive)	within the same window
Trend logging interval	1 s	1 s
Measurement point	Incoming side, SDP Amazon	Incoming side, SDP Amazon
System configuration	3-phase 4-wire, 400/230 V, 50 Hz	3-phase 4-wire, 400/230 V, 50 Hz
Building load composition	Commercial nonlinear loads (computers, network	Same load base

Aspect	Before AHF	After AHF
	equipment, LED lighting, VFD air-conditioning, UPS)	
Occupancy / operating hours	Normal mall operating hours; commercial load active	Same operating hours
Equipment / AHF status	AHF bypassed (OFF)	AHF in normal operation (ON)
Current transformer	External CT at incoming feeder	External CT at incoming feeder

Because both datasets were acquired consecutively within a single, approximately two-hour operating window, the building load composition, occupancy, and operating hours were effectively unchanged between the two measurements; the only intentionally varied factor was the operating status of the AHF. This supports a valid before-and-after comparison in which the observed changes can be attributed to AHF operation rather than to differences in loading or building activity.

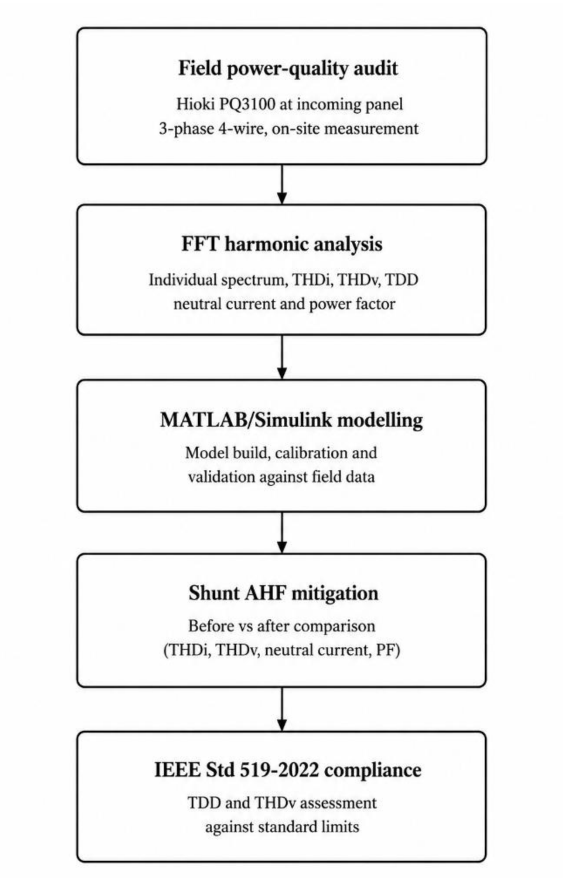

Figure 2 Field-validated harmonic assessment and mitigation workflow

As shown in Figure 2, the research methodology consists of five sequential stages, including field measurement, harmonic analysis, simulation modelling, AHF performance evaluation, and compliance verification with IEEE Std 519-2022.

Mitigation Configuration

The mitigation device was a shunt AHF installed in parallel with the distribution system. Current transformers were placed at the incoming feeder to detect harmonic currents. The AHF controller generated compensating currents that were injected into the system to cancel the measured harmonic components. The conceptual configuration is shown in Figure 1.

Evaluation Metrics

The AHF effectiveness was evaluated using THDi reduction, THDv reduction, neutral-current reduction, power-factor improvement, and compliance status. The percentage reduction for a parameter X is expressed as.

$$R_X = \left(X_{(before)} - X_{(after)}\right)/X_{(before)} \times 100 \tag{6}$$

To emphasize the neutral-current risk associated with triplen harmonics, this paper defines the Neutral Harmonic Mitigation Ratio (NHMR) as.

$$NHMR = \left(I_{(N,before)} - I_{(N,after)}\right)/I_{(N,before)} \times 100 \tag{7}$$

where $I_{N,\text{before}}$ and $I_{N,\text{after}}$are the RMS neutral currents measured before and after Active Harmonic Filter (AHF) operation, respectively. This metric directly quantifies the effectiveness of the AHF in reducing neutral-conductor current and mitigating harmonic-induced neutral loading.

Validation and Assumptions

The analysis assumes that the before-and-after measurements represent comparable operating conditions at the same distribution panel and that the dominant mitigation mechanism is harmonic-current compensation by the shunt AHF. The MATLAB/Simulink model was not used to replace the field data; instead, it was used to represent the measured system configuration and to support interpretation. The model reproduced the voltage distortion and power factor closely but underestimated the current distortion and neutral current; it is therefore positioned as a trend-analysis tool with stated limitations. The main field-validation criterion was agreement between the observed field trend and the expected behavior of a shunt AHF: reduction of harmonic current and harmonic voltage drop, reduction of neutral-current loading, and improvement of power factor. Longer monitoring periods would further strengthen statistical generalization.

Simulink Model and Validation

To support interpretation and reproducibility, a model of the distribution system was developed in Simulink R2024a using the Simscape Electrical and Powergui (FFT analysis) toolboxes. The model comprises a three-phase source, a distribution feeder, a nonlinear load, a neutral conductor, measurement blocks, a shunt Active Harmonic Filter, and a Powergui FFT-analysis block, and it was configured to follow the actual SDP Amazon installation, in which the AHF is connected in parallel (shunt) with a current transformer on the incoming side as the harmonic-current sensor. The nonlinear load was represented by a universal-bridge (three-phase rectifier) feeding an R–L load, which reproduces the dominant harmonic-generating behaviour of the commercial electronic loads at the site. The complete system model is shown in Figure 3, and the internal structure of the shunt AHF is shown in Figure 4.

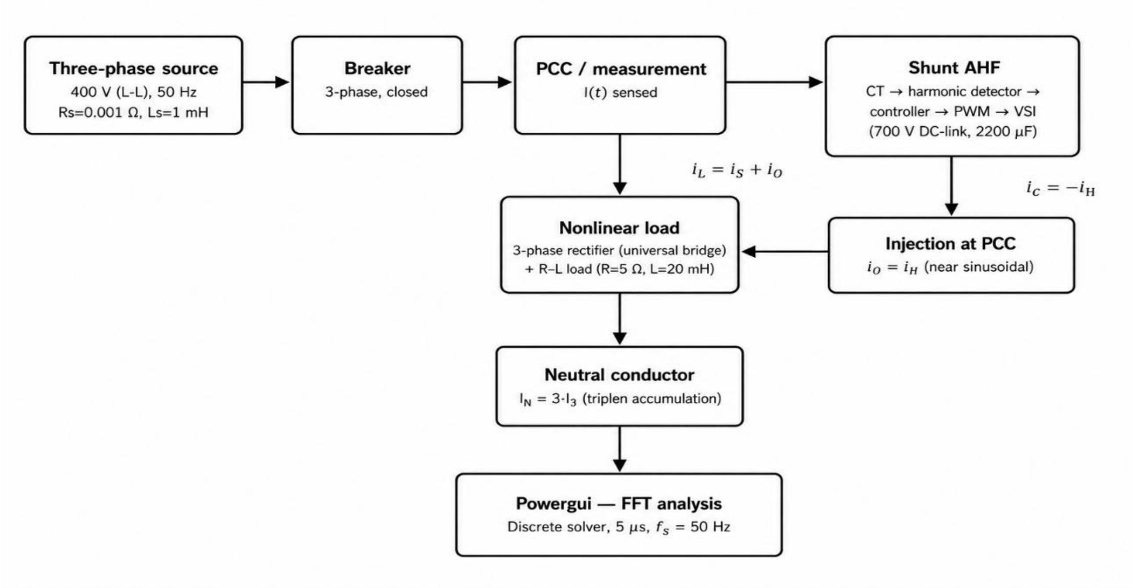

Figure 3 Simulink model of the three-phase four-wire distribution system with shunt AHF

As shown in Fig. 3 the proposed system consists of shunt AHF at the PCC to compensate the harmonic currents generated by the nonlinear load. The system consists of three-phase four-wire distribution network, a nonlinear load and a shunt AHF connected in parallel at the main busbar. The filter is able to inject compensating currents at the PCC to minimize harmonic distortion and to improve the overall power quality. The corresponding internal control structure of the shunt AHF is shown in Fig. 4. The load current is continuously measured and processed to extract the harmonic components, and the reference compensation current is generated from them. The controller and PWM generator injects the required compensating current to the voltage source inverter at the PCC. Thus, the source current approaches a near-sinusoidal waveform with minimum harmonic distortion.

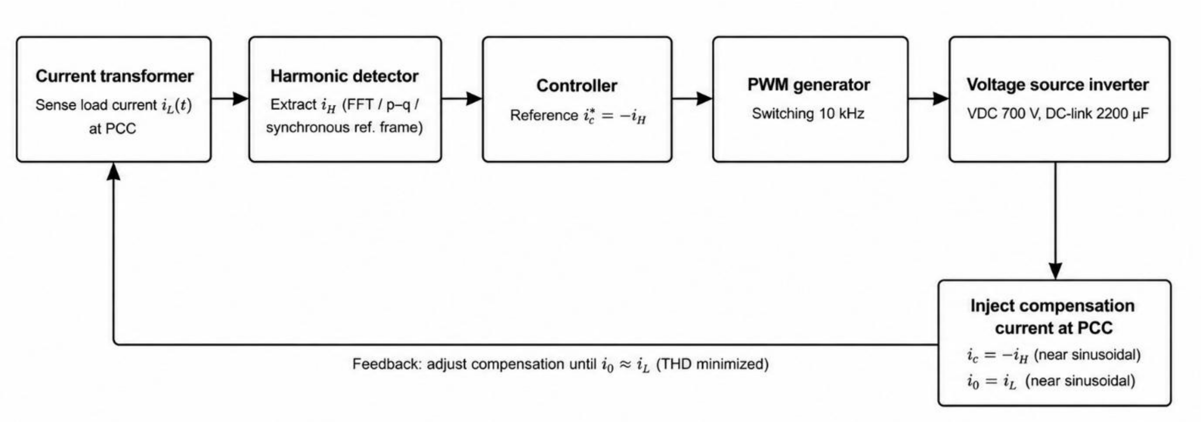

Figure 4 Internal structure of the shunt Active Harmonic Filter model

The internal control structure of the shunt AHF is illustrated in Figure 4. First, the load current is measured by the current transformer, and then, the harmonic detector finds the harmonic components. The reference compensating current is generated by the controller, and the PWM generator converts it into switching signals to drive the voltage source inverter. The inverter then injects the compensating current at the PCC to eliminate the harmonic distortion and improve the overall power quality.

The main model and solver parameters are summarized in Table 5. The model uses a discrete solver with a 5 µs sample time and a 0.1 s simulation duration (five cycles at 50 Hz); the source is set to 400 V, 50 Hz, and the shunt AHF injects a compensating current in anti-phase with the extracted harmonic component so that the source current approaches the fundamental.

Table 5 Key Simulink Model Parameters

Parameter	Value / Description
Software	MATLAB/Simulink R2024a
Toolbox	Simscape Electrical, Powergui (FFT analysis)
Solver type	Discrete (Powergui)
Sample time	5 µs
Simulation duration	0.1 s (5 cycles at 50 Hz)
Fundamental frequency	50 Hz
Source voltage	400/230 V, 3-phase 4-wire
Source impedance	R = 0.001 Ω, L = 1 mH
Nonlinear load	Universal bridge (3-phase rectifier) + R–L load (R = 5 Ω, L = 20 mH)
Modelled harmonic orders	3, 5, 7, 9 (dominant, order-3 emphasized at 150 Hz)
AHF model	Shunt AHF; injects ic(t) = $-i_h(t)$

Parameter	Value / Description
Validation criterion	Relative error < 10% per parameter, or overall MAPE < 10%

The model was validated by comparing its output with the field measurements for THDi of each phase, THDv, neutral current, and power factor, as summarized in Table 6. The model reproduces the voltage distortion and power factor closely (relative errors of 1.11% for THDv and 2.44% for power factor, both within the 10% tolerance), but it underestimates the current distortion and the neutral current (THDi errors of about 34% and a neutral-current error of about 48%). The deviation is systematic—the simulated THDi is consistently about 0.66 times the measured value and the simulated neutral current about 0.52 times the measured value—indicating that the simplified harmonic source captures the dominant third- and fifth-order components but underestimates the higher-order triplen content that contributes to the neutral current. With an overall MAPE of 25.63% (above the 10% threshold), the model is therefore positioned as a trend-analysis tool that explains the behaviour of voltage distortion and power factor and the direction of change, rather than as a fully quantitative predictor of current distortion. Accordingly, the empirical conclusions of this study rest on the field measurements, not on the simulation output; full quantitative validation of current distortion and neutral current would require adding higher-order harmonic sources, calibrating the injected harmonic amplitudes against the measured spectrum, and modelling inter-phase load unbalance in more detail.

Table 6 Model Validation: Field Measurement versus Simulation

Parameter	Measurement	Simulation	Error (%)	Decision
THDi phase R (%)	69.27	45.68	34.06	Not valid
THDi phase S (%)	81.47	53.73	34.05	Not valid
THDi phase T (%)	56.28	37.11	34.06	Not valid
THDv (%)	5.40	5.46	1.11	Valid
Neutral current (A)	96.89	50.32	48.07	Not valid
Power factor	0.82	0.84	2.44	Valid
MAPE (%)	—	—	25.63	Above 10% threshold

Model assumptions and calibration. The nonlinear load was represented by a three-phase diode rectifier (universal bridge) feeding an R–L branch (R = 5 Ω, L = 20 mH), chosen so that the simulated current waveform reproduces the characteristic harmonic signature—dominant third and fifth orders—observed in the field spectrum. The harmonic-source parameters were therefore selected by matching the modeled low-order spectrum to the measured one rather than fitted freely: the R–L values set the rectifier conduction angle and hence the relative magnitudes of the low-order harmonics, while the source impedance (Rs = 0.001 Ω, Ls = 1 mH) fixes the background distortion. The key assumptions are a stiff, balanced source, ideal switching in the AHF stage, and a single lumped equivalent for the aggregate building load rather than individually modeled feeders. Interpretation of the validation error. The overall MAPE of 25.63% exceeds the 10% acceptance threshold, driven almost entirely by the current-distortion and neutral-current channels (THDi and IN errors of roughly 34% and 48%), whereas the voltage-distortion and power-factor channels are accurate (1.11% and 2.44%). The model is retained for engineering interpretation because the deviation is systematic rather than random—the simulated THDi is consistently about 0.66 of the measured value and the neutral current about 0.52—so the model reproduces the correct trends, rankings, and direction of change even though it under-predicts absolute current distortion. In engineering terms, it is a conservative screening tool for waveform behavior, power factor, and the qualitative effect of the AHF, and should not be used to size a filter on absolute neutral-current values without correction.

Sources of error and possible refinement. The underestimation is attributable to the simplified harmonic source, which omits higher-order triplen content, inter-phase load imbalance, and the detailed nonlinear device characteristics (dc-side capacitance, control dynamics) of the real loads. Targeted calibration—adding higher-order harmonic injections, tuning the injected amplitudes to the measured spectrum, and representing per-phase imbalance—would be expected to reduce the discrepancy; because the empirical conclusions of this study rest on the field data, such refinement is left as future work. For reproducibility, the complete model configuration (the block structure and the parameters of Table 5) can be provided as supplementary material.

Result and Discussion

Baseline Voltage and Current Conditions

The pre-mitigation line-to-line voltages were 397.70 V, 400.24 V, and 397.02 V, close to the nominal 400 V rating. Therefore, the major power-quality problem was not voltage-magnitude deviation but current waveform distortion caused by nonlinear loads. The measured phase currents were 65.05 A, 56.78 A, and 76.55 A, showing moderate load unbalance. However, the neutral current of 96.89 A was larger than the individual phase currents, indicating a severe zero-sequence harmonic component rather than ordinary load unbalance alone.

Individual Harmonic Spectrum Before Mitigation

The individual harmonic spectrum was obtained from the FFT analysis of the Hioki PQ3100 at the incoming side of the panel. Figure 4 shows the measured current-harmonic spectrum before AHF operation, and Table 7 lists the average magnitude of each odd harmonic order per phase. The third-order harmonic (150 Hz) has the largest amplitude of all harmonic components in the three phases (32.19 A, 30.56 A, and 33.13 A for phases R, S, and T), followed by the fifth order; the seventh and ninth orders are markedly lower. This confirms that the distortion is dominated by the third-order triplen component, consistent with the large population of single-phase nonlinear loads typical of commercial buildings.

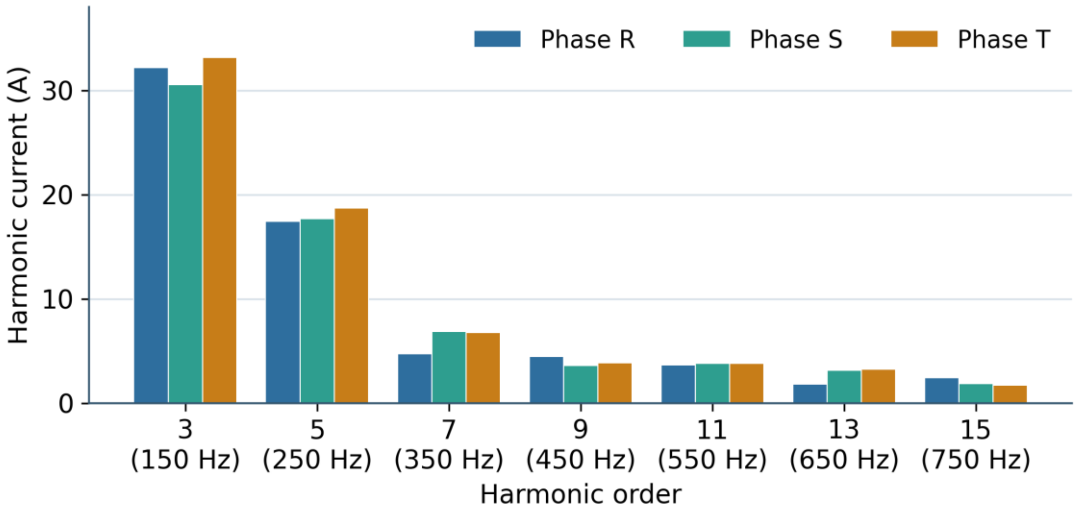

Figure 5 Measured current-harmonic spectrum before AHF operation

Figure 5 shows that the third harmonic dominates every phase while higher orders fall off rapidly, so the engineering priority is clearly the low-order zero-sequence content rather than broadband distortion.

Table 7 Individual Current-Harmonic Spectrum Before Mitigation (average, in ampere)

Harmonic order	Phase R (A)	Phase S (A)	Phase T (A)
3 (150 Hz)	32.19	30.56	33.13
5 (250 Hz)	17.41	17.67	18.71
7 (350 Hz)	4.70	6.88	6.78
9 (450 Hz)	4.45	3.59	3.86
11 (550 Hz)	3.67	3.80	3.79
13 (650 Hz)	1.84	3.16	3.26
15 (750 Hz)	2.45	1.86	1.70
Total harmonic RMS current, I_h (A)	37.47	36.53	39.20

The spectrum in Table 7 confirms that distortion is concentrated at the third order in every phase (about 32 A) with a secondary fifth-order contribution. Because this dominant order is zero-sequence, it is the physical reason the neutral—not the phases—carries the largest burden, and it explains why a device targeting low-order triplen content is effective at this site. The total harmonic RMS current per phase, $I_h = \sqrt{(\Sigma I_h^2)}$, computed from the spectrum above is 37.47 A, 36.53 A, and 39.20 A for phases R, S, and T. These values are used directly in the Total Demand Distortion (TDD) evaluation reported in the IEEE Std 519-2022 Compliance subsection, providing an explicit link between the measured spectrum and the compliance assessment.

Current Harmonic Distortion Before Mitigation

Table 8 presents the measured THDi values before and after AHF operation. Before mitigation, all phase THDi values were far above typical acceptable levels for a low-voltage feeder, indicating severe current distortion. It should be noted that the 15% current-distortion limit of IEEE Std 519-2022 applies to the Total Demand Distortion (TDD), not to THDi; the phase THDi values are therefore reported here only as operational indicators of distortion severity, whereas formal current-distortion compliance is evaluated separately through TDD in the IEEE Std 519-2022 Compliance subsection. The highest distortion occurred in phase S, where THDi reached 81.47%. Phases R and T also showed severe distortion at 69.27% and 56.28%, respectively, confirming that the system was operating under severe harmonic distortion.

Table 8 THDi Before and After AHF Operation

Phase	Before to after AHF	Reduction
R	69.27% to 9.87%	85.75%
S	81.47% to 12.18%	85.05%
T	56.28% to 8.46%	84.97%
Average	69.01% to 10.17%	85.26%

Beyond the numerical reduction, the fall from severe (up to 81%) to low THDi means the current waveform is restored close to sinusoidal, directly reducing heating and stress in conductors, terminations, and the upstream transformer. The residual THDi reflects the AHF's finite bandwidth at higher orders rather than a failure of low-order compensation, consistent with the model's under-prediction of high-order content noted earlier.

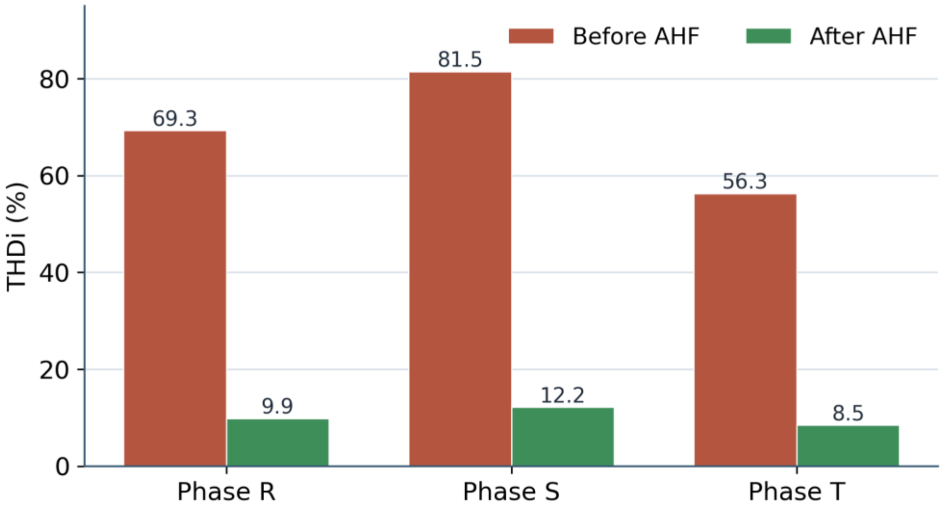

Figure 6 Comparison of phase-current THDi before and after AHF operation

Figure 6 shows the reduction is consistent across all three phases, indicating a systemic rather than phase-specific improvement.

Triplen Harmonic Interpretation and Neutral-Current Loading

The field result is consistent with the theoretical behavior of third-order triplen harmonics. In a three-phase four-wire system, third-order harmonic currents are in phase in the three phase conductors and accumulate in the neutral conductor. The measured neutral current before mitigation was 96.89 A, while the phase currents were between 56.78 A and 76.55 A, indicating that the neutral conductor was subjected to a higher current than the individual phase conductors. After AHF operation, the neutral current decreased from 96.89 A to 23.41 A. Applying (7), the NHMR is.

$$NHMR = \big((96.89 - 23.41)\big)/96.89 \times 100 \; = \; 75.84\% \qquad (8)$$

This reduction shows that AHF operation not only reduced current distortion but also substantially decreased neutral-conductor loading. From an operational perspective, this result is important because neutral overheating is one of the most direct risks associated with triplen harmonics in commercial installations (Gruzs, 1990; Lazar et al., 2026).

Voltage Harmonic Distortion and Power Factor

THDv decreased from 5.40% to 3.35%, a 37.96% reduction. The pre-mitigation THDv was slightly above the 5% reference limit for low-voltage systems, whereas the post-mitigation THDv satisfied the limit; this is explained by the reduction of harmonic current flowing through the system impedance, which reduces harmonic voltage drops. The power factor improved from 0.82 to 0.99, a 20.73% improvement, indicating that reducing harmonic current also reduced the distortion component of apparent power. Table 9 summarizes the main improvements.

Table 9 Summary of AHF Mitigation Performance

Parameter	Before to after	Improvement
Maximum THDi	81.47% to 12.18%	85.05%
THDv	5.40% to 3.35%	37.96%
Neutral current	96.89 A to 23.41 A	75.84%
Power factor	0.82 to 0.99	20.73%

Engineering significance: the simultaneous improvement of THDi, THDv, neutral current, and power factor means the AHF addresses several risks at once—thermal loading, voltage quality, and reactive burden—rather than trading one against another. For commercial operation and electrical safety, the reduction of neutral current from 96.89 A to 23.41 A is the most consequential result, because neutral overloading is a direct fire and derating hazard that conventional phase-based protection does not detect.

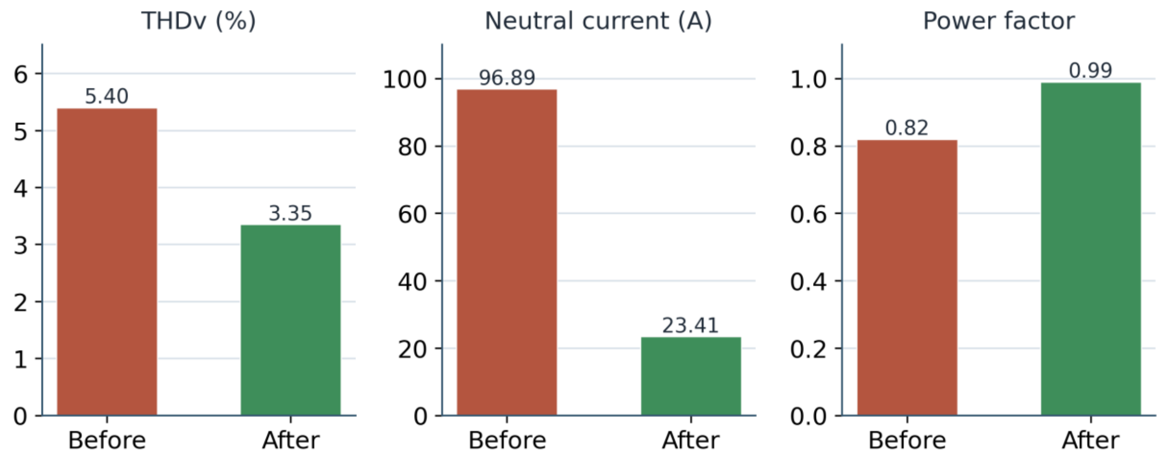

Figure 7. Reduction of THDv and neutral current and improvement of power factor. Neutral current is in amperes, THDv in percent, PF is dimensionless

Figure 7 confirms that the voltage-distortion and power-factor gains accompany the current-distortion improvement, consistent with the expected behavior of a correctly compensated three-phase four-wire system.

IEEE Std 519-2022 Compliance

The measured I_{SC}/I_L ratio was 171.41, placing the system in the $100 \le I_{SC}/I_L < 1000$ category, for which the current-distortion limit is 15%. Because IEEE Std 519-2022 evaluates current distortion through Total Demand Distortion (TDD) rather than THDi, the phase THDi values are treated here as operational indicators, whereas compliance is assessed using TDD. The maximum demand current I_L was not separately recorded in the audit; it was therefore approximated by the highest recorded load current, and this approximation is stated as a limitation. Using the individual harmonic spectrum, the per-phase harmonic rms current was computed and divided by I_L to obtain TDD. Before mitigation, the TDD values were 57.60%, 64.33%, and 51.21% for phases R, S, and T, all far above the 15% limit. After mitigation, the corresponding TDD values decreased to 8.21%, 9.62%, and 7.69%, all below the 15% limit, while THDv decreased from 5.40% to 3.35% (compliant). Therefore, under the stated I_L approximation, the post-mitigation condition satisfies the IEEE Std 519-2022 current and voltage distortion limits. Table 10 summarizes the compliance status.

Table 10 IEEE Std 519-2022 Compliance Summary

Parameter	Before to after	Limit	Status after
TDD phase R	57.60% to 8.21%	15%	Comply
TDD phase S	64.33% to 9.62%	15%	Comply
TDD phase T	51.21% to 7.69%	15%	Comply
THDv	5.40% to 3.35%	5%	Comply
Neutral current	96.89 A to 23.41 A	—	Reduced
Power factor	0.82 to 0.99	—	Improved

Interpretation and limits of the compliance assessment. The TDD values place all phases below the 15% limit after mitigation, so the compliance conclusion is robust to the exact demand figure. Because IL was approximated by the highest recorded load current rather than a 15-minute maximum demand, the computed TDD is a conservative estimate: a higher true IL would lower TDD and only strengthen compliance, whereas a substantially lower IL would raise it. Since ISC/IL sets the applicable limit band, a materially different ratio—for example if demand growth pushed ISC/IL below 100—would tighten the limit to 12%, and the margin should then be re-checked. If the load profile changes significantly, the compliance result should be re-evaluated with an updated demand measurement; the present conclusion applies to the measured operating condition.

Comparison with Previous Studies and Novelty Impact

The obtained results are consistent with previous studies reporting that AHF and SAPF systems can substantially reduce harmonic distortion under nonlinear loading (Baliyan et al., 2021; Boopathi & Indragandhi, 2024; Iqbal et al., 2021; Khan et al., 2021). However, the main novelty of this paper is not only the magnitude of THDi reduction; the added value is the explicit field-based linkage between triplen harmonic behavior, neutral-current mitigation, and IEEE Std 519-2022 compliance recovery. Compared with passive-filter studies (Ishaya et al., 2023; Park et al., 2021), the present work demonstrates an adaptive mitigation approach suitable for a commercial building where nonlinear load composition may change during operation. Compared with controller-oriented APF studies (Baliyan et al., 2021; Boopathi & Indragandhi, 2024; Iqbal et al., 2021; Khan et al., 2021), this work uses actual commercial-building measurements and treats neutral-current reduction as a primary performance indicator. Compared with broad power-quality reviews (Afonso et al., 2021; Oubrahim et al., 2023; Remigio-Carmona et al., 2022; Samanta et al., 2023), this paper provides quantitative field evidence showing how mitigation changes the operational risk profile of the neutral conductor. Only a limited subset of the reviewed studies provides neutral-current or power-factor evidence comparable with the present field case. (Khan et al., 2021) report neutral-current reduction from 12 A to 0.9 A and near-unity power factor in HIL operation, while (Boopathi and Indragandhi., 2024) report PF improvement from 0.93 to 0.99. In contrast, the present study reports field-measured neutral-current reduction from 96.89 A to 23.41 A, PF improvement from 0.82 to 0.99, and IEEE Std 519-2022 compliance recovery. Tables 11 and 12 consolidate the operational variables and the resulting novelty position.

Table 11 Operational Benchmark Variables

Study	Neutral / PF evidence	Standards and validation
Iqbal et al. (2021)	PF improved; neutral before-after not extractable	Simulation benchmark; standards based
Khan et al. (2021)	Neutral 12 A to 0.9 A; near-unity PF	IEEE 519-1992; HIL + simulation
Boopathi & Indragandhi (2024)	PF 0.93 to 0.99; neutral not reported	IEEE 519; experimental + simulation
This study	Neutral 96.89 A to 23.41 A; PF 0.82 to 0.99	IEEE 519-2022; commercial field audit

The comparative study presented in Table 11 summarizes the operational benchmark variables reported by previous studies and compares them with the results of the present work. Previous studies have mainly focused on power factor improvement and harmonic mitigation by simulation or laboratory-scale validation, while little evidence has been reported on the neutral-current reduction under real commercial operating conditions. On the other hand, the current work provides the field measurements of reduction of neutral current from 96.89 A to 23.41 A and improvement in power factor from 0.82 to 0.99 with the performance assessment based on latest IEEE Std 519-2022 standards.

After making this comparison, the novelty of the current study is positioned against the extracted literature in Table 12. The comparison shows that apart from the numerical THDi reduction, this work also demonstrates effective neutral-current mitigation, field validation in a commercial distribution system and compliance assessment according to IEEE Std 519-2022. The joint contributions help differentiate the proposed approach from previous studies relying mainly on simulation, laboratory experiments, or earlier versions of the IEEE standard.

Table 12 Novelty Positioning Against Extracted Literature

Capability	Previous literature	This study
Numerical THDi reduction	Yes	Yes
Neutral-current mitigation	Limited / partial	Yes
Triplen-harmonic interpretation	Limited	Yes
Commercial-building field validation	Rare	Yes
IEEE 519-2022 compliance recovery	Partial	Direct
NHMR as explicit metric	Not used	Proposed

The comparative analyses in Tables 11 and 12 show that most of the previous studies have focused on harmonic mitigation through simulation or lab-scale validation, with little focus on field-based neutral-current assessment and compliance with IEEE Std 519-2022. The identified gaps justify the need of the proposed research framework. The proposed research framework combines field measurements, harmonic compensation, and standards-based performance evaluation in a commercial three-phase four-wire distribution system. The next section explains the methodology used to fill these holes in research.

Practical Implications

The results have direct implications for commercial-building facility managers. First, neutral-current monitoring should be included in routine power-quality audits because high neutral current may indicate triplen harmonic accumulation, and sustained harmonic loading also reduces transformer capability (IEEE, 2018). Second, compliance assessment should not rely only on voltage conditions because the voltage profile may appear acceptable while current distortion and neutral loading are severe. Third, AHF operation can provide a practical solution for sites with variable nonlinear loads because it adapts to changing harmonic conditions more effectively than fixed passive filtering. In the Indonesian context, mitigation planning should also remain aligned with the national wiring regulation PUIL 2011 (SNI 0225:2011) (Badan Standardisasi Nasional, 2020) and with equipment-level harmonic emission limits such as IEC 61000-3-2 (IEC, 2018).

Limitations

This paper is based on a single commercial-building case study; the results should not be generalized to all commercial buildings without additional measurements under different loading profiles. The analysis focuses primarily on before-and-after AHF performance and does not include economic payback analysis or a direct field comparison with passive and hybrid filters. In addition, the MATLAB/Simulink model is a trend-analysis tool that underestimates current distortion and neutral current, so quantitative validation of those parameters requires model refinement. Future work should include longer measurement periods, harmonic spectra up to higher orders, and cost-benefit evaluation.

Conclusions

This paper presented a field-validated assessment of triplen harmonic mitigation and neutral-current reduction using a shunt Active Harmonic Filter in a commercial three-phase four-wire distribution system. The pre-mitigation condition showed severe harmonic distortion, with THDi values of 69.27%, 81.47%, and 56.28% for phases R, S, and T. The neutral current reached 96.89 A, exceeding the measured phase-current range and indicating significant triplen harmonic accumulation. After AHF operation, the THDi values decreased to 9.87%, 12.18%, and 8.46%; THDv decreased from 5.40% to 3.35%; neutral current decreased from 96.89 A to 23.41 A; and power factor improved from 0.82 to 0.99. The proposed NHMR reached 75.84%, demonstrating substantial mitigation of neutral-conductor loading, and the post-mitigation condition satisfied the IEEE Std 519-2022 current-distortion limit evaluated through TDD. The findings confirm that AHF technology is effective for reducing triplen harmonic effects in commercial low-voltage three-phase four-wire systems. Future research should extend the approach to longer-term monitoring, multi-site comparison, selective harmonic compensation, economic feasibility analysis, and adaptive control strategies.

Theoretically, the study's contribution is the explicit linkage of measured zero-sequence triplen behavior to neutral-conductor loading and its consolidation into a single interpretable indicator—the Neutral Harmonic Mitigation Ratio—that captures a hazard which THDi and TDD leave implicit. Practically, the field-validated, standards-referenced workflow gives facility engineers and consultants a repeatable basis for diagnosing neutral-current risk and justifying AHF-based mitigation in commercial power systems.

Future work should extend the approach along four directions that mirror the limitations above: long-term and multi-site monitoring to capture daily, seasonal, and building-type variation; economic feasibility analysis alongside the technical assessment; comparison with alternative mitigation technologies such as passive and hybrid filters and zig-zag transformers; and integration of the NHMR indicator into smart-building and online power-quality monitoring systems so that triplen-related neutral loading can be tracked continuously. Together, these steps would develop the NHMR framework from a single-site demonstration into a broadly validated tool with direct impact on the safety and efficiency of commercial electrical distribution.

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