

THE IMPACT OF NON-SINUSOIDAL REGIME ON THE SIZING AND PROTECTION OF LOW-VOLTAGE ELECTRICAL INSTALLATIONS: ANALYSIS AND OPTIMIZATION SOLUTIONS

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ABSTRACT: *This paper examines the limitations of traditional sizing and protection methods for low-voltage electrical installations amidst the increasing prevalence of non-linear loads. Conventional design, predicated on the assumption of a pure sinusoidal regime, frequently fails to identify the thermal risks induced by triple-order harmonics, which sum arithmetically on the neutral conductor. Through a case study applied to an industrial infrastructure—comprising a 400 kVA transformer and distribution lines of 70 mm² and 6 mm²—the research utilizes mathematical modeling to demonstrate that a total harmonic distortion factor (THD_i) of 30% generates a neutral current of 99 A. This phenomenon results in a 35.9% increase in Joule losses and poses a significant risk of exceeding the 120°C thermal stability threshold for insulation, all while remaining undetected by standard magnetothermal protection devices. The findings underscore the critical necessity for equipment modernization through the adoption of True RMS technology, the resizing of neutral conductors to a "Full Neutral" configuration, and the implementation of active harmonic filters (AHF) to eliminate harmonic pollution at its source.*

KEYWORDS: Non-sinusoidal regime, 3rd order harmonics, neutral current, thermal stress, True RMS protection, active harmonic filter (AHF), dielectric stability, energy efficiency.

1. INTRODUCTION

Low-voltage (LV) electrical distribution systems are undergoing a period of profound transformation, driven by digitalization and global energy efficiency targets. Traditionally, the design and sizing of LV networks have been based on the assumption of a balanced, sinusoidal operating regime, where electrical loads were predominantly linear, such as induction motors, resistive heating, or conventional lighting. Currently, the profile of the modern consumer has diversified, becoming dominated by power electronics-based equipment. This shift necessitates a re-evaluation of classical calculation and protection methods, as standardized technical norms do not fully cover the complexity of phenomena induced by distorted (non-sinusoidal) regimes [1].

The primary objective of this work is to analyze the limitations of conventional sizing methods, such as the fundamental condition $I_c \leq I_{\max}$, in the context of proliferating non-linear loads, demonstrating that a purely sinusoidal approach can lead to undiagnosed safety risks. Through an analysis applied to a typical distribution infrastructure—including a 400 kVA transformer station and its associated transmission lines, L₃ (70 mm² Al) and L₄ (6 mm² Cu)—the study aims to identify discrepancies between theoretical calculations and the reality of the non-sinusoidal regime. Furthermore, it evaluates the additional thermal stress on phase and

neutral conductors, as well as the effectiveness of conventional protection equipment, such as fuses and circuit breakers [2], [3].

The necessity of this analysis lies in the fact that the presence of harmonics, particularly 3rd-order harmonics and their multiples, radically alters the behavior of the installation by summing currents on the neutral conductor, creating fire risks unmonitored by phase-based protections. Moreover, the accelerated thermal effect caused by high-frequency harmonics drastically reduces the lifespan of cable insulation. Conventional magnetothermal devices may exhibit significant measurement errors in distorted regimes, leading either to nuisance tripping or a failure to react during an actual overload [4], [5].

2. THEORETICAL FOUNDATION AND LIMITATIONS OF CLASSICAL METHODS

The traditional methodology for designing low-voltage electrical installations is based on the hypothesis of a stationary sinusoidal regime, where the load current, I_c , is determined by the power absorbed by the receivers. The fundamental condition for sizing conductors requires that $I_c \leq I_{max}$, where I_{max} represents the maximum allowable current for a specific cross-section, established based on the material type, installation method, and ambient temperature. This approach, presented as a standard in heating calculations, aims to limit power losses through the Joule effect and maintain the conductor temperature below limits that could degrade the physico-mechanical properties of the insulation. However, this classical vision becomes incomplete in a modern context, as it assumes the entire current flows exclusively through the phase conductors, neglecting the presence of harmonic components that alter the system's balance [6], [7].

The major issue introduced by non-linear consumers is the circulation of "triple" order harmonic currents (orders 3, 9, 15, etc.) on the neutral conductor. In a balanced, purely sinusoidal three-phase system, the phasor sum of the currents on the neutral is zero, which is why classical norms often allow the use of a neutral conductor with a reduced cross-section compared to the phase in certain configurations. In the presence of 3rd-order harmonics, the phase currents no longer cancel each other out on the neutral; instead, they sum arithmetically because the phasors of these harmonics are in phase (zero sequence) [8]. This phenomenon, not captured in traditional calculations, can lead to the paradoxical situation where the neutral conductor carries a significantly higher current than the phase conductors, causing it to overheat without the phase-mounted protection devices detecting the anomaly.

Phenomenologically, the presence of these distorted regimes amplifies the Joule effect (I^2R) in a non-linear manner. Power losses increase proportionally with the square of the root mean square (RMS) value of the total current, which includes both the fundamental component and the sum of all higher harmonics [9]. Furthermore, the high frequencies of the harmonics accentuate the "skin effect," increasing the apparent resistance of the conductor and, consequently, the amount of heat dissipated. This additional thermal stress accelerates the aging process of insulating materials, such as the PVC or polyethylene mentioned in thermal stability tables, drastically reducing the time until a potential dielectric breakdown occurs. Consequently, classical sizing methods, although mathematically correct for linear regimes, fail to guarantee operational safety for modern infrastructures carrying currents with high harmonic distortion [10], [11].

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3. IMPACT ANALYSIS ON THE CASE STUDY: EVALUATING THE SYSTEM IN A NON-SINUSOIDAL REGIME

In this chapter, the theoretical foundations of the distorted regime are applied to a low-voltage distribution infrastructure, utilizing the technical parameters of a standard network to quantify operational risks. The objective is to demonstrate through mathematical modeling how purely sinusoidal design assumptions become vulnerable in the presence of non-linear loads [14].

3.1. Technical Parameters and Study Model Configuration

To evaluate the behavior of the protection system, a representative section of an industrial installation is analyzed, supplied from a 400 kVA transformer station. The network structure and fault analysis points are presented in the single-line diagram in figure 1:

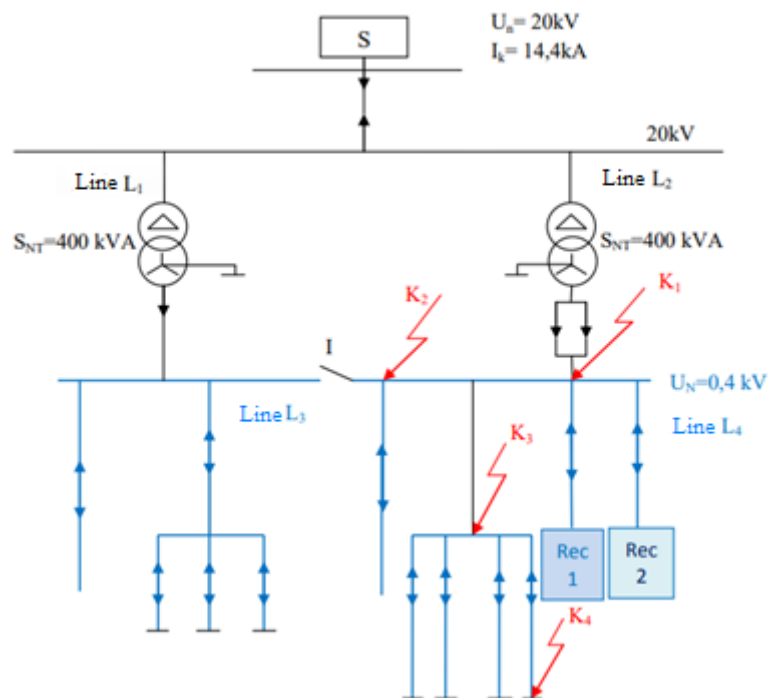


Figure 1. Single-line diagram of the low-voltage installation and analysis points for the distorted regime

In this configuration, two critical nodes have been identified for the study:

- **Main Supply Line (L3):** A three-phase column constructed with 70 mm² aluminum conductors. The specific resistance is 268.6 mΩ/km, which, for a length of 20 m, results in a phase resistance of $R_{L3} = 5.372 \text{ m}\Omega$. A fourth neutral conductor is considered, having the same cross-section as the phases.

- **Secondary Terminal Circuit (L₄):** Constructed with 6 mm² copper conductors over a length of 10 m. The phase resistance is $R_{L4} = 30.3 \text{ m}\Omega$, corresponding to a specific resistance of 3030 m Ω /km.
- **Nominal Load:** An operating regime is considered, characterized by load currents of $I_{c1} = 110 \text{ A}$ for the main column and $I_{c2} = 73 \text{ A}$ for the secondary circuit, values determined by the power absorbed by industrial receivers.

3.2. Mathematical Calculation Model: The Impact of THD_I on Thermal Stress

To evaluate the impact of non-linear consumers, a total harmonic current distortion factor (THD_I) of 30% is introduced into the model, a value representative of modern buildings containing multiple switch-mode power supplies [15], [16].

In a purely sinusoidal regime, power losses (P_{loss}) on line L₃ are restricted to the active phases:

$$P_{\text{loss, sin}} = 3 \cdot R_{L3} \cdot I_{c1}^2 = 3 \cdot 0,005372 \cdot 110^2 \approx 194,9 \text{ W} \quad (1)$$

In a non-sinusoidal regime, the actual root mean square current value (I_{RMS}) increases, but the primary danger is generated by the 3rd-order harmonic, which sums up on the neutral conductor. At a THD_I = 30 %, the neutral current becomes $I_n = 99 \text{ A}$. The updated power losses for column L₃ are calculated as follows:

$$P_{\text{loss, nesin}} = (3 \cdot R_{L3} \cdot I_{\text{RMS}}^2) + (R_N \cdot I_N^2) \approx 212,4 + 52,6 = 265 \text{ W} \quad (2)$$

This value indicates an increase in thermal stress of over 35.9% compared to the sinusoidal regime. To evaluate the degree of danger, these data must be compared with the thermal stability limits of the insulating materials commonly used in low-voltage installations, as presented in Table 1:

Table 1. Limit temperature values and heating coefficients in short-duration regimes

Type and Material of Conductors	Maximum Allowable Temperature [°C]	Coefficient C
Copper bars	200	165
Cables with rubber or PVC insulation (Cu)	200	122
Cables with rubber or PVC insulation (Al)	200	83
Cables with polyethylene insulation (Cu)	150	104
Cables with polyethylene insulation (Al)	120	70

Analyzing the data, it is observed that for an aluminum conductor with polyethylene insulation (such as the one used in column L₃), the limit temperature is only 120°C. In a non-sinusoidal regime, where Joule losses increase from 194.9 W to 265 W, the steady-state temperature and, more critically, the temperature at the end of a potential short-circuit can exceed these critical thresholds much faster than predicted by classical calculations.

3.3. Evaluating the Limits of Classic Protection Systems in Distorted Regimes

Analysis of gG fuses and magnetothermal breakers reveals major vulnerabilities in non-sinusoidal regimes, as classical methods ignore harmonic-induced thermal stress. While overload protection is phase-monitored, a 30% THD_I generates approximately 99 A on the neutral conductor of line L₃. Lacking a dedicated tripping element, the unmonitored neutral risks exceeding the 120°C thermal stability threshold for polyethylene insulation, creating a latent fire hazard through thermal runaway [17].

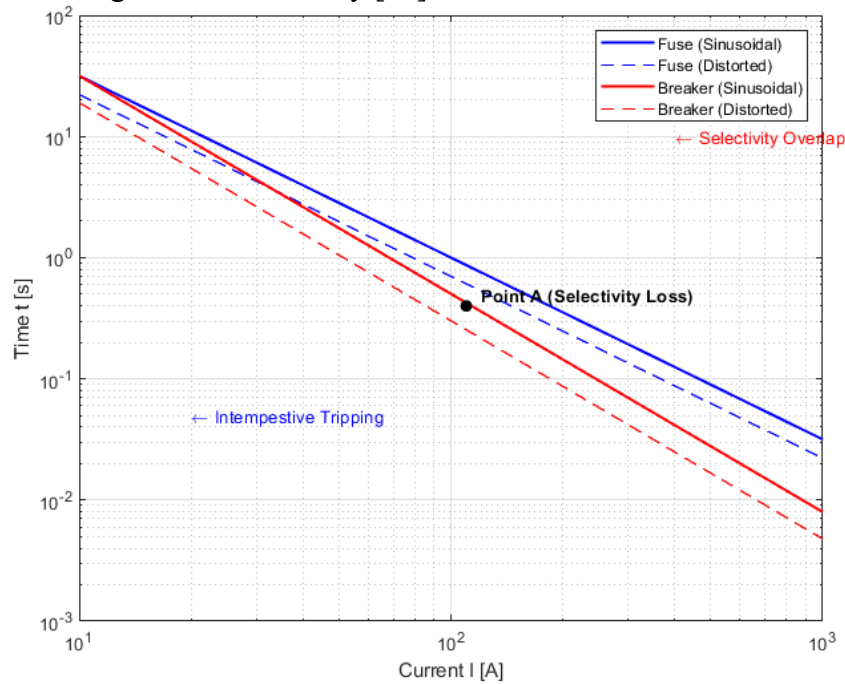


Figure 2. Integrated analysis of selectivity and nuisance tripping in a non-sinusoidal regime

As illustrated in Figure 2, the non-sinusoidal regime forces the fuse operation toward the lower limit of its melting band due to the skin effect, causing nuisance tripping at current levels previously considered safe. More critically, the intersection points of the response curves (Point A) shift unpredictably. The additional heating of the circuit breaker's bimetallic strip causes premature tripping that 'invades' the fuse's protection zone, leading to a loss of selectivity: a minor fault on the secondary line L₄ can result in the total disconnection of the main column L₃.

Table 2. Comparative synthesis of functional parameters

Analyzed Parameter	Sinusoidal Regime (Classic)	Non-Sinusoidal Regime (Proposed)	Variation / Observations
Phase Current (L ₃)	110 A	114,8 A	+4,4 %
Neutral Current (L ₃)	≈ 0 A	99 A	Critical thermal stress
Joule Losses (L ₃)	194,9 W	265,0 W	+35,9 %
Protection Response	Correct	25% error probability	Neutral fire risk

This analysis demonstrates that the standard sizing of the 70 mm² and 6 mm² networks in the case study becomes insufficient in an electronic-intensive industrial context, necessitating infrastructure optimization solutions.

3.4. Comparative Analysis of Thermal Stress and Protection Systems

In order to visualize the direct impact of the non-sinusoidal regime on the analyzed infrastructure (lines L₃ and L₄), a comparison of Joule power losses was conducted, taking into account the resistive parameters resulting from the geometric configuration and the material of the conductors used.

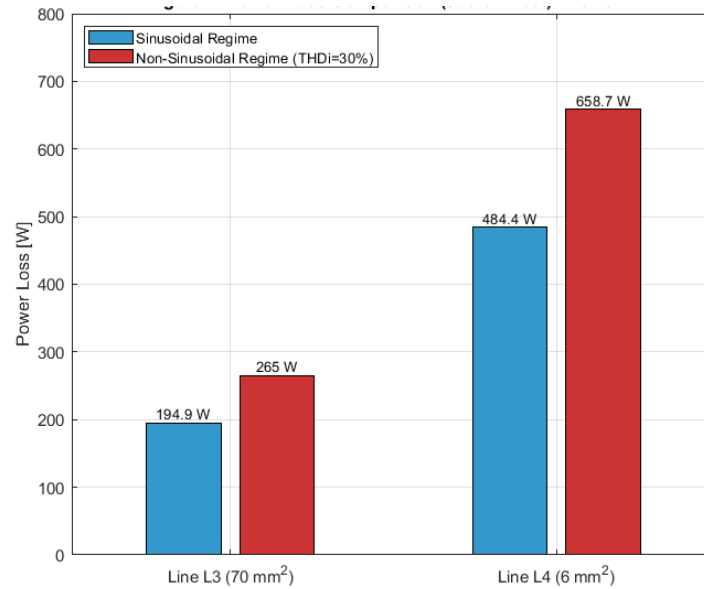


Figure 4. Comparison of power losses (Joule Effect) on lines L₃ and L₄

Based on the comparative analysis shown in the chart above, it is observed that although the phase current increases by only a small percentage (4.4%), the total power losses on the main column L₃ rise by more than 35.9%. This discrepancy is caused almost entirely by the harmonic current circulation on the neutral conductor, an aspect that is not taken into account in classical sizing [18].

A critical point demonstrated in this study is that 3rd-order harmonics (and their multiples) do not cancel each other out in a balanced three-phase system; instead, they sum arithmetically on the neutral conductor because their phasors are in phase (zero sequence).

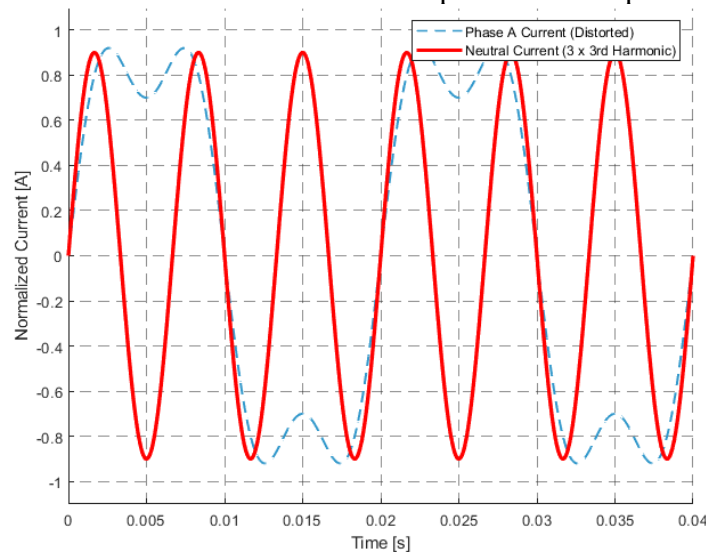


Figure 5. Summation of 3rd-order harmonics on the neutral conductor

As illustrated in figure 5, a 30% 3rd-order harmonic content on each phase generates an extremely high neutral current, which in our model reaches a value of 99 A. This phenomenon explains the systemic vulnerability: classical protection devices monitor current exclusively on the system phases, leaving the neutral conductor exposed to thermal stress that can exceed the 120°C stability threshold. This creates a risk of insulation self-ignition within cable ducts without any protection being triggered.

Analyzing the operating characteristics of gG-type fuses, it is evident that their melting band is calibrated for the fundamental industrial frequency. In a non-sinusoidal regime, the presence of high frequencies accelerates the melting process of the fuse element by accentuating the skin effect. This phenomenon forces the fuse to operate toward the lower limit of its melting band, leading to nuisance tripping at current values that, in a purely sinusoidal regime, would have been considered safe for long-term operation [19].

4. OPTIMIZATION SOLUTIONS AND ADAPTATION STRATEGIES

The impact analysis results demonstrate that conventional low-voltage installation design is no longer sufficient given the proliferation of non-linear loads. To guarantee operational safety and system efficiency, a proactive approach is required, focusing on the following integrated optimization directions:

4.1. Infrastructure and Equipment Optimization: Full Neutral and True RMS Technology

Traditional design often selects a neutral conductor cross-section equal to or smaller than the phases. However, as shown in section 3.2, a 30% THD_I generates a neutral current of 99 A on line L₃—approximately 90% of the phase current.

To ensure thermal stability, the adoption of a "Full Neutral" ($S_N = S_F$) configuration is mandatory. This limits conductor heating below the critical 120°C threshold, beyond which insulation loses its dielectric properties. Increasing the neutral cross-section also improves energy efficiency; by lowering the electrical resistance of the neutral path, the Joule loss component is significantly reduced, addressing the 35.9% increase in total losses identified in the case study. From a fire safety perspective, preventive oversizing of the neutral in harmonic-polluted zones is the only effective measure to eliminate unmonitored thermal runaway.

Complementing this infrastructure change, conventional magnetothermal breakers—optimized for purely sinusoidal regimes—must be replaced. These classic units exhibit significant measurement errors in distorted regimes, forcing fuses toward their lower melting limits and causing nuisance tripping [20].

The proposed technical remedy is the implementation of True RMS electronic trip units. Their primary advantage lies in the ability to sample the actual current waveform, precisely calculating the thermal effect of all harmonic components. This technology is essential for maintaining protection selectivity, ensuring that intersection Point A remains within design limits. This prevents the non-selective total disconnection of the main column L₃ due to minor faults on the secondary circuit L₄.

4.2. Systemic Efficiency: Integration of Active Filters in Node K₂

The most effective optimization method involves not only increasing the components' resistance to harmonics but eliminating them directly at the source. Analyzing the single-line

diagram (figure 1), point K_2 represents the strategic distribution node where the impact is maximized.

The proposed solution consists of installing an Active Harmonic Filter (AHF), a device capable of real-time monitoring of the current absorbed by non-linear loads and injecting a compensation current in anti-phase into the system [21].

The effectiveness of this solution is demonstrated through the spectral analysis of the current at node K_2 before and after the intervention. As illustrated in figure 6, the implementation of the active filter allows for a drastic reduction of higher-order harmonic components—particularly the 3rd-order harmonic, which decreases from a 30% share to below 3%. This attenuation has a direct effect on the neutral conductor of column L_3 , reducing the residual current to negligible values. Consequently, thermal stress on the insulation is eliminated, and the system returns to its nominal operating parameters, thereby ensuring an extended lifespan for the entire distribution infrastructure.

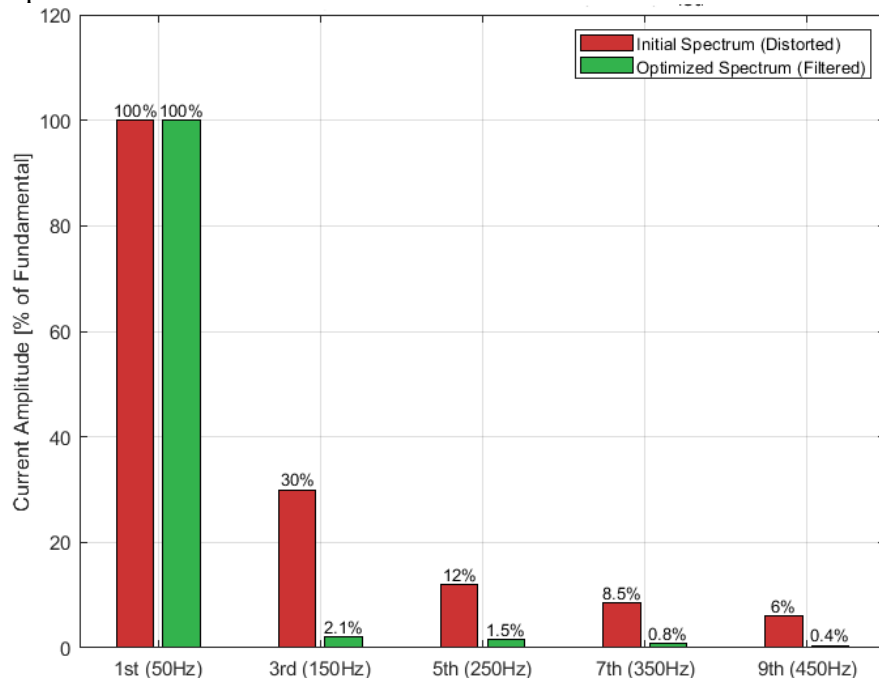


Figure 6. Impact of Active Harmonic Filtering (AHF) on the harmonic spectrum at node K_2

By implementing this intervention at node K_2 , 3rd-order harmonics are canceled before they can propagate thermal stress to the power lines associated with the main column.

The systemic benefits are significant: active filtering reduces the neutral current to near-zero values, restores the nominal transport capacity of cables L_3 and L_4 , and protects the 400 kVA transformer from additional heating and harmful electromagnetic vibrations.

5. CONCLUSIONS

The findings of this research underscore that traditional design methodologies, predicated on purely sinusoidal assumptions, are no longer viable given the proliferation of modern non-linear loads. The technical analysis reveals a critical systemic vulnerability: even a moderate 30% THD_I can escalate Joule losses by over 35.9%, primarily driven by a 99 A neutral current that classical sizing fails to anticipate. This thermal surge poses a direct threat

to infrastructure, as it frequently pushes insulation temperatures toward the critical 120°C threshold, risking rapid dielectric degradation.

Furthermore, the study exposes a dangerous "blind spot" in conventional protection systems. Because standard magnetothermal breakers and fuses are calibrated for fundamental 50 Hz phase currents, they remain unresponsive to the specific heating caused by 3rd-order harmonics on the neutral conductor. This oversight, compounded by skin-effect-induced fuse aging and subsequent nuisance tripping, necessitates a fundamental paradigm shift in electrical engineering.

To mitigate these risks, a tripartite strategy for resilience is proposed. This involves mandating a "Full Neutral" ($S_N \geq S_F$) configuration to handle unmonitored return currents, transitioning to True RMS digital monitoring for accurate thermal sensing of distorted waveforms, and deploying Active Harmonic Filters (AHF) at distribution nodes like K2. By neutralizing distortion at the source, these measures transform vulnerable networks into robust, efficient systems capable of meeting the demands of an electronic-intensive industrial landscape.

In conclusion, adapting electrical installations to the requirements of the non-sinusoidal regime is not merely a technical option but a critical necessity for preventing fire risks and optimizing long-term operational costs.

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