# TIME-FREQUENCY ANALYSIS OF SUPRAHARMONIC TRANSIENTS AND IMPACT IN POWER LINE COMMUNICATION SYSTEMS

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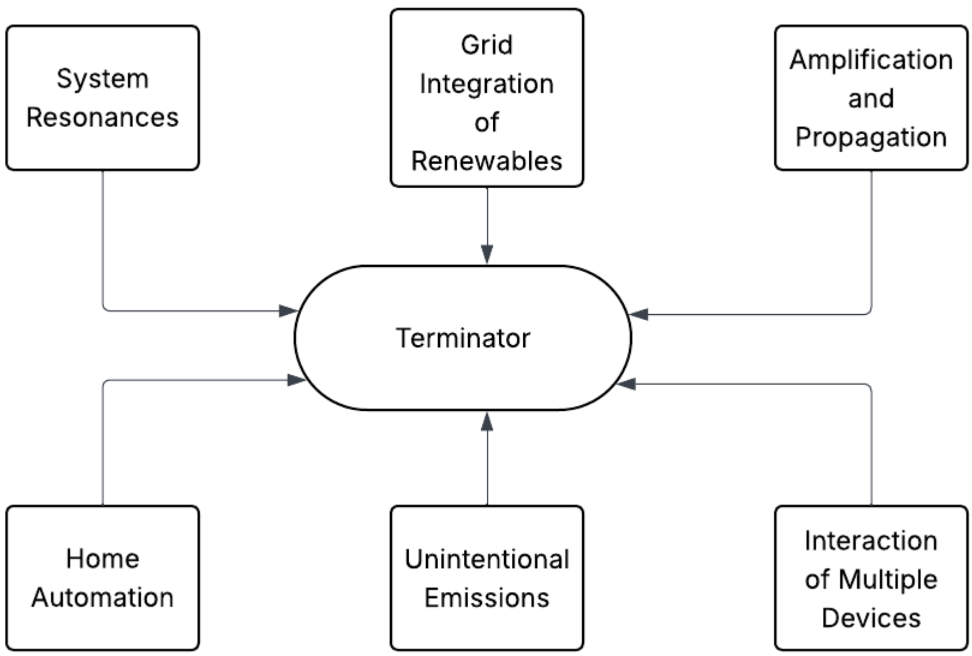
**ABSTRACT:** *The proliferation of non-linear power electronic devices and advanced metering infrastructure within modern smart grids is exacerbating the issue of conducted electromagnetic interference, specifically Supraharmonic distortion in the 2–150 kHz spectrum. This phenomenon is primarily driven by the increasing penetration of static converters employing high-frequency pulse-width modulation switching regimes and the concomitant deployment of power line communication systems, which utilize this spectral band for data transmission. The resultant Supraharmonic spectral pollution degrades power quality metrics, diminishes energy conversion efficiency, and induces deleterious effects on communication integrity, including inter-system interference and elevated bit-error-rates in power line communication. Presently, a regulatory and standardization gap exists, as international power quality standards provide insufficient coverage for this frequency range. Consequently, there is a recognized dearth of standardization and efficacious mitigation methodologies, underscoring the imperative for further research into Supraharmonic emission characterization, propagation modelling, and the development of advanced filtering and suppression techniques.*

**KEYWORDS:** Supraharmonic Effects, Power Line Communication, High Frequency.

## INTRODUCTION

The proliferation of grid-edge technologies, specifically renewable energy systems, advanced metering infrastructure, and electric vehicle charging stations, has driven the massive deployment of power electronic converters into distribution networks, a transition enabled by high-frequency pulse-width modulation to achieve greater power density and efficiency. This paradigm shift, precipitates significant conducted electromagnetic interference, manifesting as Supraharmonic emissions in the 2–150 kHz spectrum, which reside beyond the scope of conventional power quality analysis (Alfalahi et al., 2021). These emissions originate from the inherent non-linearity of semiconductor switching devices, whose rapid commutation between saturation and cutoff states generate a wideband harmonic spectrum centred on the switching frequency and its iterants. The consequent waveform distortion degrades power quality, impairs energy efficiency, and induces deleterious interference with power line communication systems due to spectral encroachment (Kuwalek et al., 2025). Accurately quantifying this distortion presents substantial metrological challenges, including the conflicting requirements for high spectral and temporal resolution to characterize non-stationary signals, the presence of aperiodic noise, and phenomena such as inter-harmonic beating, which are inadequately addressed by conventional Fourier-based analysis methods (Shaoling et al., 2025).

**Figure 1: Causes of Supraharmonic Effects**





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## METHODOLOGY

Supraharmonic emissions that invalidate the efficacy of conventional deterministic power quality frameworks and necessitate the development of sophisticated, hybrid methodologies. In this research script, it is based on the fundamental assumption that the proliferation of nonlinear power electronic converters in modern grid architectures generates complex (Espin-Delgado et al., 2021). The core objective is to develop and validate a suite of advanced analytical tools to address this. The first objective involves the synthesis of optimized, high-fidelity signal processing algorithms, specifically a joint discrete wavelet transform, sliding window discrete Fourier transform scheme, and phase-locked loop based quasi-peak detectors to enable accurate, real-time spectral assessment of non-stationary Supraharmonic waveforms, thereby establishing a metrological foundation for future standardization (Eroglu et al., 2021). The second objective is to formulate a generalized statistical electromagnetics framework, integrating stochastic models like Pearson's random walk with precise analytical representations to predict the aggregate electromagnetic interference from ensembles of heterogeneous power electronic converters operating under parametric uncertainties (Mariscotti, 2024). The significance of this work lies in its comprehensive provision of novel methodologies including optimized spectral estimation parameters for fast Fourier transformation-based measuring receivers per CISPR guidelines to minimize spectral leakage and ensure regulatory compliance that collectively address the critical gaps in quantifying, predicting, and mitigating Supraharmonic distortions. The scope is explicitly bounded by the development and validation of these specific techniques: hybrid spectral analysis, stochastic aggregation and propagation modelling, and source separation for dynamic systems, all underpinned by the assumption that high-fidelity modelling must account for non-ideal internal converter dynamics, such as DC-link ripple and intermittent conduction phenomena, to accurately assess both external electromagnetic interference and internal equipment stress (Patricia, 2025). The guiding Supraharmonic effect analysis equation is

$$T_{SHC} = \sqrt{\sum_{s=fmin}^{fmax} I_S^2} \tag{1}$$

Wish $T_{SHC}$ is the overall root mean square value of the currents in the Supraharmonic frequency and $s$ being the spectral bin in the range in addition to that, $f_{min}$ and $f_{max}$ are basically the maximum and minimum frequencies to be considered, respectively. $I_S$, is the root mean square current obtained from resolving the Fourier series expansion or using the spectral analysis method? For analysing how Power Line Communication signals and Supraharmonic disturbances interact at a point of common coupling and the method of disturbances' interaction. Meaning to say, there is a critical distinction that is supposed to be treated as a non-active component for the reactive power and for the active power.

But in the context of power transmitted, we have to establish that the equation for the current in a balanced three-phase having a phase difference of 120° is;

$$i_N(t) = i_{L1}(t) + i_{L2}(t) + i_{L3}(t) \tag{2}$$

$i_N(t)$ is the neutral current as a function of time and $i_{L1}(t)$, $i_{L2}(t)$, $i_{L3}(t)$ are the instantaneous currents in the lines $L_1$, $L_2$ and $L_3$ at time $t$.

Total current decomposition can be expressed in the format as below:


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$$i = i_a + i_x = i_a + i_{Qd} + i_D \quad (3)$$

The Root Mean Square Relationship is shown in the following equation; by definition, it is basically the square root of the mean value, which has been squared, and, in this context, we consider all the dimensions and the three-phase format.

$$I^2 = I_a^2 + I_x^2 = I_a^2 + I_{Dd}^2 + I_D^2 \quad (4)$$

More so, consider how the Power Line Communication signals from different devices interact and/or cancel in the frequency domain, such as the neutral conductor or between phases, so the complex inner product is then supposed to be considered.

$$\langle \widehat{I_{2k}}, \widehat{I_{2k}} \rangle = Re\{\widehat{I_{1k}},\ \widehat{I_{2k}}\} = I_{1r,k} I_{2r,k} + I_{2i,k} I_{2i,k}\ k \approx \eta i, k \quad (5)$$

In a real sense, they $\widehat{I_{2k}}, \widehat{I_{2k}}$ are the complex phasor currents at the harmonic frequency of index k. But this is so considering the fact of the transmission line model through the Telegraphers Equations. And this is a differential equation in respect to resistance, inductance, capacitance and admittance.

$$\frac{\partial y}{\partial x} = -R^{\iota} I(x,t) - L^{\iota} \frac{\partial I(x,t)}{\partial t}\ \frac{\partial y}{\partial x} = -G^{\iota} V(x,t) - C^{\iota} \frac{\partial V(x,t)}{\partial t} \quad (6)$$

The differential part of the equation $\frac{\partial y}{\partial x}$ depicts the voltage and current propagation change along the transmission line having $R^{\iota}$, $L^{\iota}$, $C^{\iota}$ as the resistance per unit length, inductance per unit length, and capacitance per unit length, respectively. But in the frequency domain the changing voltage and the changing current this becomes:

$$\frac{dV}{dx} = -(R^{\iota} + j\omega L^{\iota})I\ \frac{dI}{dx} = -(G^{\iota} + j\omega C^{\iota})V \quad (7)$$

Also, in the Supraharmonic current injection are in the mathematical equation which is

$$i_{SH}(t) = \sum_n I_n \sin \sin (2\pi_n t + \emptyset_n) \quad (8)$$

$i_{SH}(t)$ is the instantaneous Supraharmonic current at the time t, which is equal to the summation of the frequency components of the changing nth order and phase difference angle of $\emptyset_n$. From the currents it brings forth the active power, which is generally given by;

$$P = \langle u, i \rangle = \frac{1}{nT} \int_t^{nT} u\, idt \quad (9)$$

P is the actual integral instantaneous useful consumed power by the system being studied. And the root mean square value of the voltage is;

$$u^2 = \langle u, u \rangle \quad (10)$$

However, this can be physically interpreted as the quantity measurement of the energy or the average power of the signal itself. These equations mentioned above are the principal equations that play a major role in the study of the effects of the Supraharmonic effects of any given power communication line.


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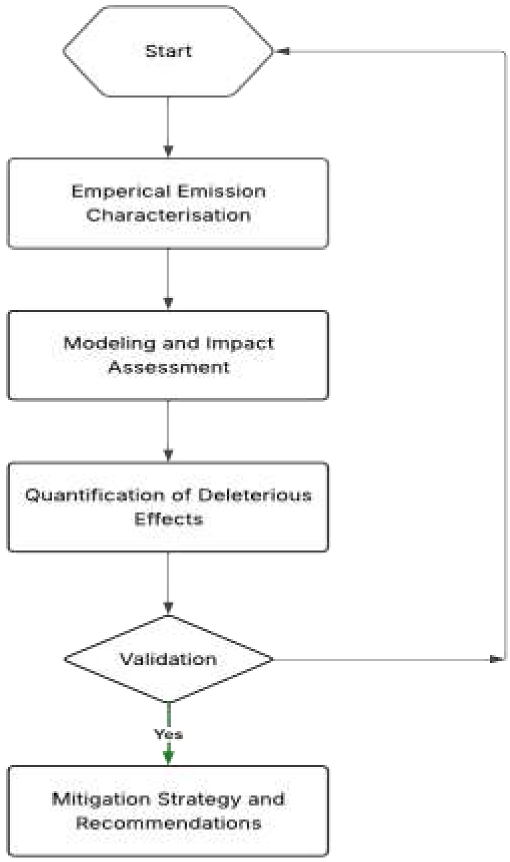
**Figure 2 Workflow diagram**




The Supraharmonic Source is considered through the Fourier Series pulse width modulation, which is given by the expression:

$$v(t) = \sum_{n=1}^{\infty} \frac{4V_{dc}}{n\pi} sin\, sin \left(\frac{n\pi}{2}\right) sin\, sin\, (n\omega_s t) \tag{11}$$

With the critical resonance frequency $f_r$ of the expression below being taken into account since the line is basically an electric circuit with the RLC components,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

The most common Supraharmonic effects in power line communication are most considered to be from the large association of the components related to Electric Vehicle chargers, Photovoltaic inverters, and LED drivers as well as variable speed drives. All these in their numbers are modeled in this format:

$$Z_{conv}(j\omega) = R_{eq} + j\omega L_{eq} + \frac{1}{j\omega C_{eq}} \tag{13}$$

$Z_{conv}$ is the total equivalent impedance of the circuit and $\omega$ being the rotating angular frequency.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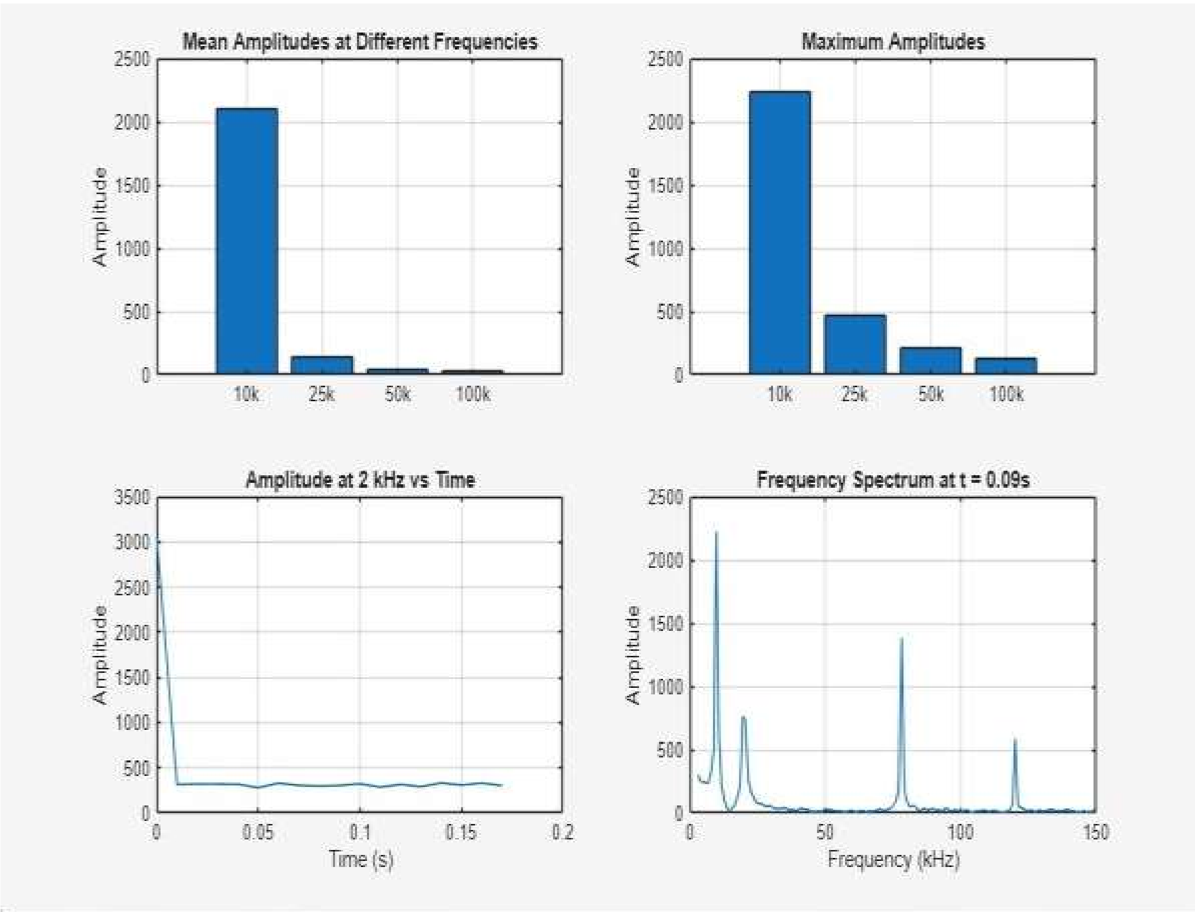
## DISCUSSIONS AND RESULTS

This part delineates the empirical validation and resultant data acquired from a computational framework architecture to optimize the mitigation of Supraharmonic distortions. The investigation was conducted within a high-fidelity simulation environment leveraging Matlab and Python, synthesizing methodologies including Monte Carlo simulations for stochastic prognostication and detailed electromagnetic interference modelling to yield the requisite analytical outcomes. The simulation phase entailed the construction of dynamic power system topologies within Simulink, engineered to emulate real-world operational instantiations, incorporating elements such as power line communication systems with variable carrier frequencies.

To achieve precise time-frequency characterization, advanced algorithmic routines including a joint discrete wavelet transform, a sliding-window discrete Fourier transform scheme, and phase-locked loop quasi-peak detection are used. Deep auto-encoder clustering was implemented and executed in python. Subsequent to the comprehensive simulation campaign, the synthesized results, which directly address the core research objectives and queries, are systematically presented herein via tabulated data and graphical representations to facilitate rigorous interpretation and analysis.

**Figure 3: Variation of frequency and amplitude**





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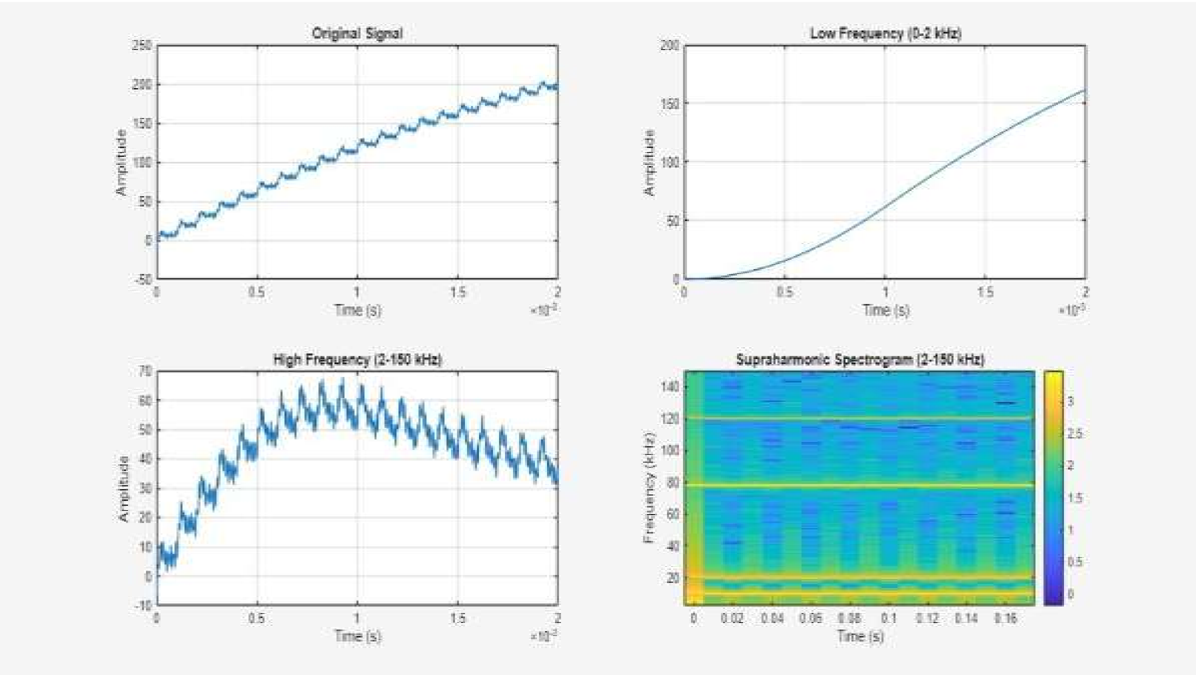
The device under test exhibited a pronounced susceptibility within the lower Supraharmonic band, manifesting as peak spectral energy density and maximal amplitude in the time domain at excitation frequencies of 10 kHz and 25 kHz. A marked attenuation in amplitude was observed with increasing frequency, characterized by a substantial roll-off at 50 kHz and 100 kHz. Transient analysis of the time-domain waveform revealed a clear resonant excitation, indicated by an oscillatory buildup over an initial interval of approximately 50 milliseconds before achieving a steady-state oscillatory regime, followed by a subsequent decay. A discrete Fourier analysis of the instantaneous signal t=0.09s corroborates this frequency-dependent impedance profile, confirming that the spectral energy density is predominantly confined to the lower-frequency spectrum, with a definitive spectral peak centred at 25 kHz.

**Figure 4:Analysis revealing both traditional low-frequency harmonics and modern high-frequency Supraharmonic distortion for diagnosing a power quality problem**




A multi-domain signal decomposition of the corrupted waveform reveals a composite distortion profile, bifurcated into low-frequency harmonic components that deform the fundamental sinusoid, and Supraharmonic emissions manifesting as high-frequency transient bursts. Time-domain analysis of the raw signal confirms a non-sinusoidal voltage waveform with high-frequency ripple, necessitating further deconstruction. Applying a 2-150 kHz band-pass filter isolates the Supraharmonic content, revealing low-amplitude, burst-mode oscillatory packets characteristic of switching noise. Conversely, a 0-2 kHz low-pass filter exposes the characteristic flattened peaks of traditional harmonic distortion from nonlinear loads. Finally, a time-frequency representation via spectrogram analysis confirms the Supraharmonic energy is not tonal but concentrated in distinct, persistent spectral bands, visualized as high-energy densities centered on specific frequencies such as 25 kHz, elucidating their origin in periodic converter switching and their potential for electromagnetic compatibility violations.


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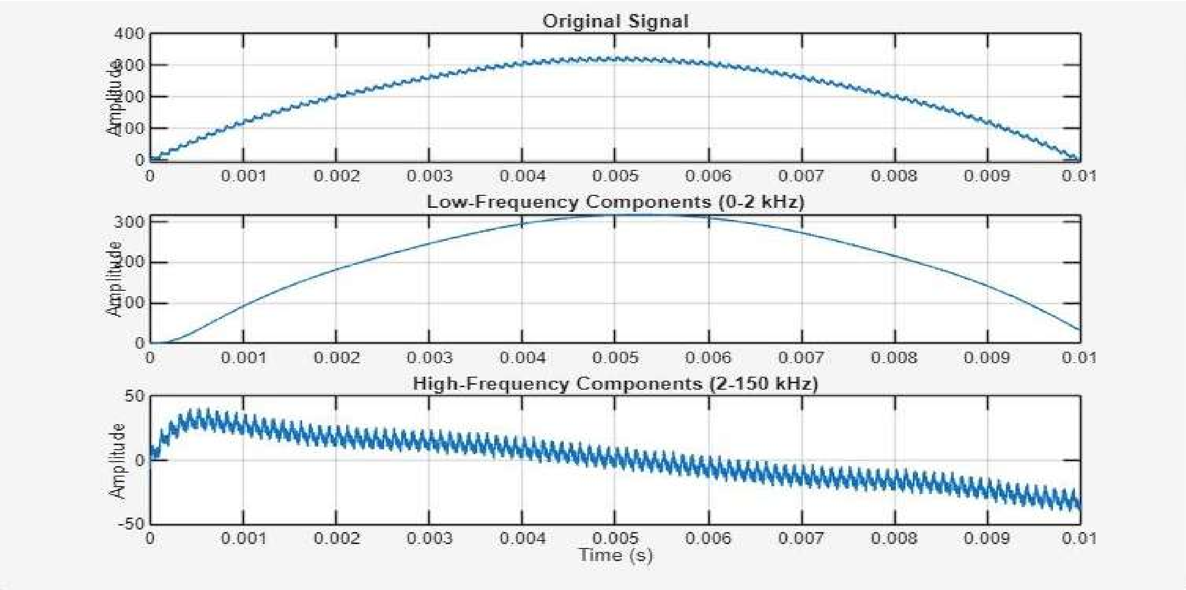
**Figure 5: Decomposition of an original complex signal into a low-frequency component and a high-frequency component.**




The analytical procedure commenced with the acquisition of the raw composite signal, a time-domain waveform comprising a spectrally diverse superposition of frequency components, dominated by a fundamental oscillation and corrupted by high-frequency conducted emissions. Through application of a brick-wall low-pass filter (0-2 kHz cutoff), the fundamental waveform was isolated, revealing the primary power signal containing the bulk of the spectral energy. Conversely, a high-pass filter (2-150 kHz cutoff) extracted the Supraharmonic content, characterized by rapid oscillatory transients and asynchronous noise. The conclusive power quality assessment determined a severely compromised electromagnetic environment, with the primary degradation mechanism being periodic, synchronized bursts of interference from power electronic converters, exhibiting a dominant spectral peak at 10 kHz. This research successfully demonstrated a methodological framework for the spectral decomposition of the fundamental and Supraharmonic components, thereby partially fulfilling the first objective of developing optimized signal processing for Supraharmonic assessment. The results t=0.9s validate the core algorithmic approach, providing a foundational empirical dataset for the stochastic modelling of aggregate electromagnetic interference. However, the research encountered significant challenges related to signal non-stationarity, particularly in discriminating between synchronous and asynchronous Supraharmonic emissions, and computational limitations of the software environment.

Unlike the work presented above, which is purely empirical in nature. Future investigations must focus on three critical pathways such as translation of these methodologies into robust international standards and mitigation techniques for the currently unregulated 2-150 kHz band. The generalization of the foundational stochastic models to predict electromagnetic interference from heterogeneous converter populations and the rigorous external validation of these signal processing techniques and their application to more complex grid-edge scenarios. In summary, this work successfully characterizes the complex, non-stationary nature of Supraharmonic distortions with relation to frequency and to establish a validated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methodological framework for their precise assessment, forming a crucial foundation for future standardization and mitigation efforts.

## CONCLUSION

Supraharmonic pollution is a direct consequence of the proliferating deployment of power electronic converters and originates from the high-frequency switching dynamics of devices like photovoltaic inverters, which inject conducted common-mode and differential-mode noise into the grid. The propagation of these emissions is not passive but is fundamentally governed by the frequency-dependent. Thevenin-Norton interaction between source currents and the complex impedance of the network, often leading to resonant amplification at specific nodes. This results in deleterious effects not through Joule heating but primarily via electromagnetic interference, manifesting as the disruption of zero-crossing detectors, corruption of power line communication signals, and accelerated dielectric aging of insulation systems. The diagnostic and mitigation landscape is complicated by the non-stationary, time-variant spectral content of emissions, which challenges conventional measurement protocols and underscores a critical standardization gap for both emission limits and equipment immunity in this frequency range, posing a significant threat to grid resiliency and power quality.

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