

# Intelligent Diagnostics and Mitigation of Supraharmonics in Converter-Interfaced Smart Grids: Critical Assessment and Future Direction

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## Abstract

*The drastic shift towards low carbon power networks has been driving the integration of converter interfaced technologies, including Solar Photovoltaic Systems, wind energy converters, Electric vehicle, Battery Energy Storage Systems and charging infrastructure. Therefore, a power quality and electromagnetic compatibility (EMC) issue has become an important problem of high frequency perturbations often referred to as supraharmonics ranging from 2 - 150 kHz. These emissions are produced by semiconductor switching, pulse width modulation (PWM) techniques, interactions between components and complex network impedances. This paper gives a detailed analysis of comparative study of conventional and intelligent techniques for supraharmonic analysis, source identification and*

**Keywords:** Supraharmonic, Renewable Energy, Smart Grids, Power Quality, Artificial Intelligence,

*mitigation for renewable energy integrated smart grid. Signal processing tools, machine learning (ML) and artificial intelligence (AI) methodologies, active power filters (APF), hybrid architectures, adaptive control, and intelligent inverter modulation strategies are critically analysed with regard to parameters like computational complexity, real time applicability and robustness. Key findings include the fact that current research is fragmented, with numerous gaps in standardized monitoring (2-150 kHz), dynamic multi source tracking, representative AI training sets and real time coordinated converter control. A single, intelligent end to end solution that integrates advanced signal processing, predictive AI diagnostics, and adaptive mitigation is proposed to address these gaps, improve operational resilience, and provide comprehensive observability in converter dominated power systems.*

Machine Learning, Signal Processing, Active Power Filter, Converter Interaction.

## 1. Introduction

Today, the power grid is undergoing revolutionary changes due to the growing number of renewable energy resources and loads connected to the power grid via the power electronics [1]. The main components are solar Photovoltaic generators, wind turbine converters, battery energy storage systems, and electric vehicle chargers. On the other hand, new digital paradigm tools like the Internet of Things (IoT), Edge Computing, Digital Twins and Artificial Intelligence (AI) are being increasingly used to monitor grid health, classify power quality disturbances, and take automatic control actions [1].

Smart grid features enhance system flexibility, observability and efficiency but the significant number of converter interfaced devices brings in power quality issues which are complex and mainly centred on low order integer multiples of the fundamental power frequency 50 - 60Hz, typically

in the range of the 40<sup>th</sup> and 50th harmonic up to 2 kHz. Today, however, the switching frequency of the power electronic converters is in the kHz range, from several kilohertz to tens of kilohertz [2].

The voltage and current deviations in the frequency range of 2–150kHz are considered as supraharmonics [3]. Supraharmonic emissions are observed in both the narrowband and broadband noise. Narrowband emission can be seen as discrete switching frequency and sideband emissions, while the broadband noise can be seen in wider spectra [4]. The high frequency emissions have adverse impacts such as thermal stress and premature failure of grid connected equipment, degradation of insulation in cables and transformers, high power losses, acoustic noises and malfunction or disruption of Power Line Communication (PLC) systems [5].

Although the topics of isolated parts of supraharmonics have been the subject of recent

research, the picture is fragmented [3]. The synthesis of these sources, measurement needs, signal processing capabilities, AI based source identification and adaptive mitigation of the sources under dynamic multi converter interactions is a highly desirable system that is needed urgently. This review critically analyses traditional and intelligent techniques highlighting accuracy, real time support, computational load, adaptability and viability for implementation in the grid [3].

## 2. Smart Grid Architecture & Power Electronics Interactions

Smart grids integrate advanced sensing, communication, automation, and distributed energy resources to enable the optimal operation of the power system [6]. The converter interfaces which are a key component for grid connected operations, however, are the major sources of supraharmonic disturbance [7].

### 2.1 Renewable Energy Integration

Systems using renewable energy use a variety of converter topologies (AC/DC, DC/DC, and DC/AC) to process power. These power electronic interfaces feature semiconductor switching devices with high frequency emissions that are influenced by switching frequency, control topology, pulse width modulation (PWM) techniques, output filter design and dynamic grid impedance are illustrated [8].

### 2.2 Inverter Topologies and Modulation

Inverters can be used in the grid following or grid forming [9]. mode Switching pulses for the semiconductor devices are controlled by PWM schemes such as Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), Discontinuous Pulse Width Modulation (DPWM) and Variable Frequency Pulse Width Modulation (VFPWM) [9].

The high frequency spectrum is directly determined by parameters like carrier frequency, modulation index, dead time, switching pattern, etc. [8]. If several converters are working simultaneously, mutual coupling caused by the grid impedance can lead to resonance amplification and cross talk, making emission characterisation very complicated [10].

## 3. Fundamentals of Supraharmonics

The supraharmonic spectra 2-150 kHz are dominated by switching frequency components, harmonic sidebands, interharmonics, resonant peaks and broadband noise [11]. The emissions from the individual device converter, self-generated by its internal operation. Emissions that come from other emissions sources in the network and pass-through a given device because of the low high frequency input impedance.

Propagation of supraharmonics through network components such as capacitors, cables, transformers, filters is highly non-stationary and depends on local system impedance, system topology, dynamic loading and interactions between parallel converters [3], [12].

## 4. Standard Frameworks and Measurement Approaches

### 4.1 Assessment Standards

Standardisation in the 2–150 kHz range is evolving. Table 1 summarises key international standards and guidance documents

**Table 1: Comparison of Standards and Guidelines for Supraharmonic Assessment**

| Ref      | Standard/<br>Guideline | Frequency Focus        | Main Purpose                                 | Existing Limitations                                                  |
|----------|------------------------|------------------------|----------------------------------------------|-----------------------------------------------------------------------|
| [1<br>3] | IEC 61000 Series       | Power Quality / EMC    | Measurement methods and compatibility levels | Limited formal regulatory frameworks above 9 kHz                      |
| [1<br>4] | IEEE 519-2022          | Power System Harmonics | Recommended harmonic limits                  | Focused predominantly on conventional low order harmonics up to 2 kHz |

|      |                        |                        |                                                     |                                                                 |
|------|------------------------|------------------------|-----------------------------------------------------|-----------------------------------------------------------------|
| [15] | CIGRE Technical Papers | >2 kHz emissions       | Technical assessment and field measurement guidance | Informative guidance; not an enforceable regulatory standard    |
| [16] | CISPR Standards        | EMC and High Frequency | Equipment emission limits                           | Device-level orientation; lacks network interaction perspective |

### 5. Source Classification of supraharmonic

Modern power networks are associated with many types of supraharmonic sources, which have different mechanisms and impacts, are classified in Table 2 [17].

**Table 2: Comparative Analysis of Supraharmonic Sources**

| Source /Ref                  | Primary Mechanism                                       | Typical Impact                                | Key Research Challenge                                           |
|------------------------------|---------------------------------------------------------|-----------------------------------------------|------------------------------------------------------------------|
| PV Inverters, [18]           | High frequency switching and PWM patterns               | Current and voltage supraharmonics            | High dependence on variable solar irradiance and operating state |
| Wind Energy Converters, [19] | Multi stage converter switching and control interaction | High frequency voltage and current distortion | Dynamic converter grid resonance and impedance variation         |

|                              |                                                     |                                                       |                                                           |
|------------------------------|-----------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------|
| BESS Converters, [20]        | Bidirectional AC/DC and DC/DC switching             | Conducted emissions across modes                      | Shift in emissions during charge versus discharge modes   |
| Electric Vehicle Charger [5] | High power AC/DC and DC/DC stage conversion         | High magnitude supraharmonic current injection        | Cumulative impacts of simultaneous multi vehicle charging |
| Parallel Converters [21]     | Inter converter resonance and mutual coupling       | Amplification of background high frequency distortion | Complex interaction through varying network impedance     |
| LEDs & SMPS Loads, [3]       | Mass distributed low power switching supplies       | Collective broadband conducted emissions              | Aggregated impact of massive numbers of distributed units |
| PLC Devices [3]              | Intentional high frequency carrier signal injection | Discrete narrowband voltage and current emissions     | Crosstalk, signal attenuation, and impedance mismatch     |

### 6. Intelligent Classification Method

The Signal Processing and Intelligent Diagnostic Techniques. However, the Fast Fourier Transform (FFT) is not suitable for processing supraharmonic signals, which are often non-stationary, intermittent and dynamic [22]. The use of advanced signal processing in conjunction with machine learning (ML) and deep learning (DL) brings improved diagnostic capability [23].

Table 3 compares the diagnostic performance of the signal processing, classical ML and deep learning architectures.

Table 3: Comparative Assessment of Supraharmonic Detection and Diagnostic Techniques

| Technique         | Principal Strengths                            | Primary Limitations                                 | Preferred Grid Application                                |
|-------------------|------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------------|
| FFT [24]          | Simple, low computational overhead             | Fails on non-stationary signals, no time resolution | Stationary, steady state baseline spectral analysis       |
| STFT [22]         | Provides time frequency localised information  | Fixed resolution trade-off determined by windowing  | Time varying, non-stationary signal analysis              |
| Wavelet, [25]     | Multi resolution analysis for fast transients  | High computational load and parameter sensitivity   | Transient detection and non-stationary profiling          |
| S-Transform, [26] | Excellent phase and time frequency tracking    | High computational complexity                       | High precision offline and power quality characterisation |
| ANN, [27]         | Strong non-linear modelling capability         | Sensitive to training data and black box nature     | Automated pattern detection and event classification      |
| CNN, [24]         | Automatic feature extraction from spectrograms | Requires large high quality labelled datasets       | Image based automated and time frequency classification   |

|                               |                                                     |                                                             |                                                      |
|-------------------------------|-----------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------|
| ANFIS, [28]                   | Combines neural learning with fuzzy logic reasoning | High training complexity under high feature dimensions      | Adaptive diagnosis under uncertain system models     |
| Deep Learning (ResNet ), [29] | Superior feature extraction and accuracy            | Requires high computational resources and big training data | High density grid monitoring and automated analytics |

7. Supraharmonic Mitigation Methods

The range of mitigation strategies includes passive filtering, active power filters (APF), hybrid configurations and converter-level control modifications [21]. A comparison of these mitigation strategies is given in Table 4.

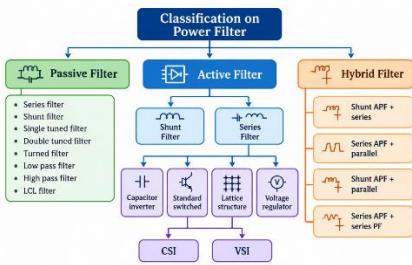


Fig. 1. classification of Power Filters [30].

Table 4. The Table Below Compares the Different Types of Supraharmonic Mitigation Techniques.

| Topology/ Ref.        | Structural Strengths                         | Key Operational Limitations                    | Practical Grid Applicability            |
|-----------------------|----------------------------------------------|------------------------------------------------|-----------------------------------------|
| Passive Filters, [31] | Low cost, high reliability and simple design | Fixed tuning and potential resonance with grid | Static and predictable single frequency |

|                                     |                                                  |                                                          |                                                        |
|-------------------------------------|--------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------|
|                                     |                                                  | impedanc<br>e                                            | emission<br>s                                          |
| Active Power Filters, [32]          | Dynamic compensa<br>tion and adaptive response   | Higher hardware cost and limited bandwidth               | Variable dynamic emission s and localized mitigation n |
| Hybrid Active Filters, [33]         | Reduced APF rating and superior HF attenuation n | Design complexit y and tuning interactio ns              | Medium to high voltage RE grid connecti on points      |
| Converter Control Mitigation , [34] | Software based, zero added hardware cost         | Requires accurate modelling , grid impedanc e dependent  | Embedde d inverter modulati on and firmware updates    |
| Adaptive Control, [34]              | Tracks dynamic grid impedanc e variations        | Control stability proof required under transients        | Variable RE penetrati on microgri ds and weak grids    |
| AI-Based Control, [23]              | Predictive mitigatio n and self-optimisin g      | Requires extensive training, Explainab ility challenge s | Next generatio n smart inverters and edge controlle rs |

8. Comparative Synthesis of AI Techniques

Intelligent algorithms offer distinct performance trade-offs with respect to smart grid deployment parameters [35].

Table 5: Synthesis of AI Diagnostic and Control Techniques

| Techniques                        | Technical Characteristics and Main Comparison                                                                      |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Artificial Neural Networks, [29]  | Good non-linear pattern recognition, moderate computational load and requires clean training datasets.             |
| Support Vector Machines [23]      | High classification accuracy on small datasets and performance depends on kernel hyperparameter tuning.            |
| Decision Trees, [24]              | Computationally fast and interpretable and prone to overfitting under noisy conditions.                            |
| Random Forest [35]                | High resistance to noise and overfitting and increased computational memory footprint.                             |
| Extreme Learning Machine, [36]    | Ultrafast training time and highly sensitive to feature selection and input data quality.                          |
| Convolutional Networks, [36]      | Superior automated feature extraction from 2D spectral images and high computational demands.                      |
| Transfer Learning, [37]           | Excellent generalization across domain shifts and high resource footprint during training.                         |
| Hybrid AI and DSP Frameworks [23] | Combines DSP feature extraction with AI classification and yields an optimal balance of speed and precision.       |
| AI Inverter Control [38]          | Enhances grid stability through adaptive control and harmonic reduction and dynamic response to grid fluctuations. |

## 9. Performance Evaluation of Conventional and Intelligent Techniques

Table 6: show the Performance evaluation comparing conventional and intelligent techniques across operational power system metrics.

**Table 6: Comparative Evaluation of Conventional and Intelligent**

| Performance criterion | Conventional Techniques                            | Intelligent and AI-Driven Techniques                           |
|-----------------------|----------------------------------------------------|----------------------------------------------------------------|
| Accuracy              | High for stationary, continuous signals            | Superior for complex and time-varying emission patterns        |
| Computational cost    | Low to moderate and deterministic                  | Moderate to high during training, low during inference         |
| Real-Time Capability  | Well established and low latency                   | Fast post training, depends on hardware execution              |
| System Adaptability   | Poor and requires manual component redesign        | Excellent and continuously retrainable and self-tuning         |
| Noise Robustness      | Susceptible to dynamic grid background noise       | High and capable of learning under noisy backgrounds           |
| Data Requirement      | Minimal and relies on direct analytical formulas   | Moderate to extensive and requires significant training data   |
| Interpretability      | High and explicit deterministic mathematical basis | Lower and machine learning models present black box challenges |

|                  |                                                |                                                  |
|------------------|------------------------------------------------|--------------------------------------------------|
| Grid Scalability | Low and localized hardware bound installations | High and scalable via distributed edge computing |
|------------------|------------------------------------------------|--------------------------------------------------|

## 10. Future Research Directions

To transition supraharmmonic management from reactive filtering to proactive, real-time control, future research should prioritize:

1. **Coordinated Multi Inverter Modulation:** Implementing distributed reinforcement learning (DRL) to adaptively shift 1. Unified Monitoring Frameworks: Creating consistent, ongoing monitoring guidelines for distribution infrastructures in the 2–150 kHz range.
2. Edge-AI Analytics: For low latency, real time source identification, lightweight machine learning models are directly applied to smart meters and inverter controllers.
3. Digital Twins for High Frequency Grid Modelling: Creating dynamic digital twins to simulate cross talk between many converters and anticipate resonance events prior to control instability.
4. carrier frequencies across interconnected PV and storage inverters, preventing cumulative spectral peaks.

## 11. Conclusion

Supraharmonics 2–150 kHz represent an important power quality and EMC challenge in converter-dominated smart grids [17]. Traditional fixed passive filtering approaches are increasingly inadequate for dynamic, non-stationary grid operating states. While advanced signal processing (Wavelets, S-Transform) provides robust feature extraction, integrating AI and ML techniques enables real-time disturbance classification, dynamic source tracking, and predictive mitigation [23] Future power quality architectures must adopt an integrated approach combining edge-driven AI analytics with adaptive smart inverter modulation and active filtering to ensure system resilience and power quality in renewable-dominated grids.

### Authors' Contribution

All authors contributed to the interpretation of the reviewed literature, critically revised the paper, approved the final version for publication and agreed to be held responsible for the entire contents.

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### Conflicts of Interest

There are no conflicts of interest for the authors to disclose.

### Generative AI Statement

Throughout the creation of this work, the authors used Quillbot and ChatGPT to rephrase the content and correct grammar. The authors then reviewed and edited the text and accept sole responsibility for the content of this publication.

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