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Intelligent Supraharmonic Analysis and Mitigation in Renewable Energy-Integrated Smart Grids: A Comprehensive Review

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Abstract

Smart grids have introduced more power quality issues as a result of the integration of renewable energy resources, battery energy storage systems, electric vehicle chargers and other converter-interfaced technologies. These technologies produce high-frequency perturbations or frequencies higher than the fundamental frequency, called supraharmonics, in the range 2–150 kHz resulting from switching operations, pulse width modulation, power electronic device interactions and network impedance. In this study, the authors provide a complete comparison of intelligent supraharmonic analysis and mitigation techniques for renewable-energy-integrated smart grids. Supraharmonic sources, measurement techniques, signal processing techniques, AI and ML, and mitigation techniques such as active power filters, hybrid filters, adaptive filtering, and intelligent control of inverter and modulation-based suppression are examined. The results suggest that the existing body of work is still disjointed with gaps in standardized monitoring of 2–150 kHz, the identification of sources during dynamic and multi-source conditions, representative AI datasets and the real-time intelligent mitigation and coordinated management of converter interactions. This study therefore suggests an intelligent supraharmonic management view coordinated through real-time monitoring, advanced signal processing, disturbance identification using AI, predictive analysis, adaptive filtering and intelligent inverter control in a source-to-mitigation perspective. This can improve the observability, power quality, electromagnetic compatibility, reliability and operational resilience of converter-dominated smart grids.

Keywords: Supraharmonic, renewable energy, smart grids, artificial intelligence, source identification, intelligent mitigation, power electronic converters.

1. Introduction

The world of energy is in a state of rapid change, with the rise and growth of renewable energy technologies and distributed energy sources. The modern smart grid increasingly uses power electronic converters to support the deployment of solar photovoltaic systems, wind energy, battery energy storage systems and electric vehicles [1].

Emerging digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Edge Computing, Digital Twins and Data Analytics are now being used in smart grid

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monitoring and control. These technologies offer power quality monitoring, power quality disturbance classification, power quality disturbance prediction and adaptive control opportunities that can be automated [1].

The shift towards low-carbon electricity generation is driving the implementation of renewable energy technologies. Additionally, power electronic converters are widely used for interfacing renewable energy resources with the power grid, which generate high-frequency switching and are sources of power grid supraharmonics, typically solar photovoltaics and wind power [2], [3].

Smart grids increase the resilience and efficiency of the power distribution and transmission systems, especially in the integration of renewable energy (RE) systems. Smart grids are a combination of distributed generation, communication, energy storage, automation, sensing, and advanced control. While these features increase the observability and flexibility opportunities, the growing number of devices interfaced by converters brings new power quality challenges, especially in the high-frequency range [4] [5].

The introduction of solar photovoltaic (PV) systems, wind turbines and other distributed energy sources (DER) into the modern power grid has resulted in recent developments in renewable energy integration. However, the change has created new problems with harmonic distortion and system stability. The presence of significant harmonic contributions in large solar PV grid-connected plants, particularly at high irradiance conditions and in changing inverter operating modes, as exemplified by the study of a solar power plant connected to an unstable grid, which highlights problems of harmonic stability, including resonance phenomena and voltage distortion, which may affect the stability of the system [5]. The installation of renewable energy sources and the smart use of digital data are significant contributions to environmental sustainability and the efficiency of power systems, but at the same time they create new challenges in maintaining the stability and quality of electrical power systems [5], [6].

Conventional harmonics are frequency components of voltage and current that are unwanted and cause a degradation of the quality of electricity service and that result in the following: equipment overheating, insulation breakdown, and an increase in energy losses. Harmonic currents or voltages are also known as high frequencies or low frequencies at integer multiples of the fundamental frequency (50–60 Hz). However, traditional harmonics analysis cannot completely account for the high-frequency disturbances produced by modern power electronics converters [5].

The spectral components of voltage and current conducted above the frequency of about 2–150 kHz are usually referred to as supraharmonics, and are typically taken into account in power-quality and EMC investigations. Due to their adverse effects, this frequency range has gained greater importance because the converter switching pulse modulation width network resources and control interactions can generate high-frequency disturbances that affect the operation of the equipment and the network [7] [8].

Narrowband emission is generally referred to as supraharmonic emission, which means narrowband disturbances and Broadband emission which means emission over wide ranges of wider frequency. They are influenced by the nature of converter topology and operating

conditions, converter network impedance and mutual interactions between the various power electronic devices [9].

The current research has been pursued mostly along different streams, related to supraharmonic measurement and characterization, signal processing and intelligent detection and mitigation. However, these lines of research are not sufficiently linked. Systematically relating supraharmonic sources with the measurement requirements, signal processing, intelligent source identification and selection of appropriate mitigation strategies under changing renewable generation conditions, and multiple converter interactions, has not been addressed [10], [11], [12], [13].

3. Smart Grid Architecture

The smart grid is an advanced development of the traditional electrical power system by combining sensing, communication, automation, digital control, distributed energy resources (DERs), energy storage and intelligent data processing technologies. With the rapid development of the converter-interfaced renewable energy sources, new power quality issues such as high-frequency emission in the supraharmonics range [15] are posing a new challenge.

3.1 Renewable Energy Integration

Photovoltaic, wind, hydropower, battery energy storage systems, and electric vehicle charging systems are among the technologies included in renewable energy integration. For PV cells and wind turbines, the power electronic converter is typically used for interfacing with the grid, and for battery energy storage systems and electric vehicle chargers, the power electronic converter is also used to convert and control energy. These devices are able to produce high-frequency switching components whose characteristics are determined by the converter topology, switching strategy, operating conditions, filter configuration and network impedance. Hence, the introduction and growth of supraharmonic perturbations are directly related to the integration of renewable energy systems [2], [16].

3.2 Power Electronic Converters

DC/AC inverters are devices used to convert DC energy to AC energy for connection to the grid or load, and they are the most important components in the PV, BESS, and many wind energy systems. They are used to regulate voltage, frequency, phase, active power, reactive power and current quality. Modern inverters are typically grid-following or grid-forming. Inverters which follow the grid are used when there is an existing grid, while inverters which form the grid are used when there is no existing grid and become more critical in systems with high inverter penetration [17].

However, inverter switching produces high-frequency components. The combination of the switching frequency, the pulse width modulation strategy, grid resonance, grid impedance, and other converters may result in complex disturbances. Furthermore, converter switching is a major

4. Fundamentals of Supraharmonics

With the rising share of power electronic converters, renewable energy sources, Battery Energy

Storage Systems (BESS), Electric Vehicle (EV) chargers and other converter-interfaced devices, a new power quality issue has emerged: supraharmonics [9]. Not all components within 2–150 kHz are integer harmonics. Switching frequency components, sidebands, interharmonic components, resonant responses, and broadband emissions can all be found in supraharmonic spectra. One of the main sources of unintentional supraharmonic emission is power electronic switching. PWM switching creates the spectral components (due to the switching frequency and its harmonics), in addition to the modulation-related sidebands [19].

Supraharmonics can travel through the grid and affect network elements like the capacitors, cables, filters, transformers, and other converters. The propagation and size of these disturbances are dependent on network impedance, resonance, topology, measurement, load, and load interaction between converter-based sources [20].

5. Measurement Techniques

To identify the sources of supraharmonic propagation, interaction and requirements for mitigation, accurate measurement and characterization are required. Emissions above 150 kHz are studied for their relevance to measurement instrumentation or emissions at such high frequencies and are included in this review, though not the primary focus. Supraharmonic emissions can be narrowband, broadband, intermittent, time-varying and non-stationary, in contrast to conventional harmonics. They may be very dependent on the operating conditions of the converter and on the network impedance. Thus, no single measurement or signal processing approach is applicable to all cases [9], [21].

5.1 Guidelines and standards for assessment of supraharmonic structures.

Standards and technical guidelines offer a means of measuring, assessing and mitigating power quality disturbances in modern electrical networks. As more and more photovoltaic inverters, wind converters, battery energy storage systems, electric vehicle chargers and other power electronic devices have been adopted, the interest has shifted from normal harmonics to the supraharmonic range from 2 kHz to 150 kHz [9]. The IEC 61000 series, IEEE 519 and CIGRE technical publications include important guidelines for measurement, compatibility levels, emission limitations and power quality evaluation.

Table 1: Comparison of Standards and Guidelines for Supraharmonic Assessment

No.	Standard/Guideline	Frequency focus	Main purpose	Limitations
1	IEC 61000	PQ/EMC	Measurement/compatibility	Limited high-frequency framework
2	IEEE 519-2022	Harmonics	Harmonic limits	Mainly conventional harmonics
3	CIGRE	>2 kHz	Technical guidance	Not a complete regulatory standard

4	CISPR	EMC/high frequency	Emission limits	Equipment-oriented

6. Comparative Analysis of Supraharmonic Sources

Several sources of supraharmonic emissions have been found in renewable energy integrated smart grid: PV inverters are the most common sources to be investigated due to their switching operations, which develop voltage and current components of high frequencies. Wind energy converters are also able to contribute due to their power electronic interfaces, especially if various converter stages work in parallel [20].

Table 2 Comparative Analysis of Supraharmonic Sources

Ref.	Source	Main mechanism	Typical impact	Major research challenge
[22],[23], [24], [25]	PV inverter	High-Frequency Switching and PWM	Current and Voltage Supraharmonics	Variable Operating Conditions
[6], [26]	Wind converter	Converter Switching and Control Interactions	High-Frequency Distortion	Converter Grid Interaction
[23], [27]	BESS	Bidirectional Converter Switching	Conducted Disturbances	Operating Mode Dependency
[7], [28]	EV charger	DC/DC and AC/DC Conversion	Supraharmonic Current Injection	Large-Scale Simultaneous Charging
[16], [28]	Multiple converters	Resonance and Interaction	Amplification of Disturbances	Complex Network Impedance
[20]	LED/SMPS loads	High-Frequency Switching	Conducted Emissions	Large Numbers of Distributed Devices

7. Intelligent Analysis Techniques

With the extensive use of the PV systems, wind energy converters, battery energy storage systems, electric vehicle chargers and other power electronic interfaces, there is a growing requirement for intelligent power quality analysis in the smart grid. Supraharmonic emissions, between 2 and 150 kHz, can be generated by converter switching and interactions between power electronic devices. It is more difficult to detect and characterize these emissions than traditional harmonic emissions because the emissions can be narrowband, broadband or time-

varying. Traditional techniques, such as the Fast Fourier Transform, STFT and wavelet transforms are useful for extracting features, but intelligent techniques are also crucial for automatic detection, classification, identification and prediction of disturbances [29].

Table 3 Comparative Analysis of Supraharmonic Detection and Analysis Techniques

Ref.	Technique	Strength	Limitations	Suitability
[30], [31]	FFT	Simple and computationally efficient	Limited time information and qualification of stationary	Basic spectral analysis
[31]	STFT	Provides time frequency information	Resolution depends on window	Non-stationary analysis
[32], [33]	Wavelet/time frequency	Good multi resolution analysis	Computational complexity	Transient disturbances
[34]	S-transform	Joint time frequency localization	Higher computational burden	Detailed PQ analysis
[35]	ANN	Strong nonlinear classification	Requires training data	Intelligent detection
[36]	CNN	Effective automatic feature extraction	Requires substantial datasets	Automated classification
[29]	ANFIS	Combines fuzzy reasoning and learning	More complex training	Adaptive diagnosis
[36]	Deep learning	High pattern recognition capability	High computational and data requirements	Large-scale intelligent monitoring

8. Intelligent Supraharmonic Mitigation Techniques

The emergence of solar photovoltaic, wind power, battery energy storage systems, electric vehicle chargers, and other power electronic resources in the smart grid domain has led to greater demand for high-level mitigation of harmonic and supraharmonic disturbances. Switching with a converter and interaction with grid impedance can create intricate power quality issues. Intelligent mitigation techniques control parameters, switching actions, or compensation signals and operating modes to react to changes in the grid and detected disturbances. Active power filters, hybrid filters, smart inverters, adaptive filters, and predictive control are among the major techniques considered [37].

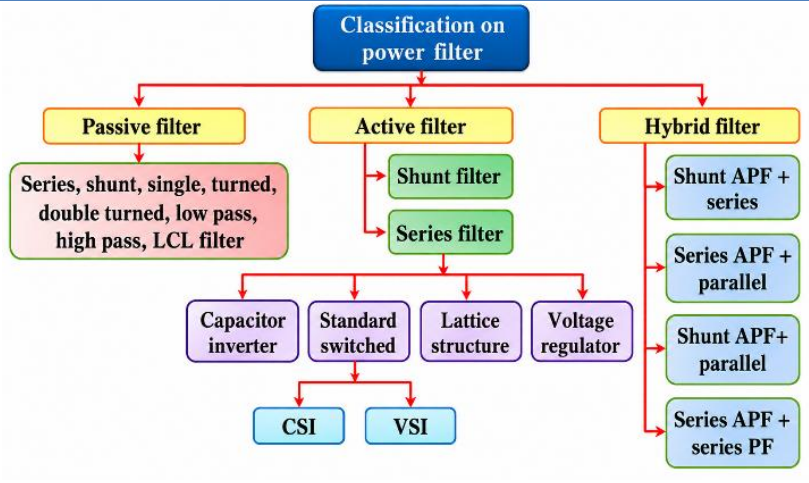


Fig: Subdivision of Power Filters.

Table:4 Comparative Analysis of Supraharmonic Mitigation Techniques

Ref.	Technique	Strengths	Limitations	Suitability
[37]	Passive Filters	Simple, reliable, relatively low cost and free of complex control.	➢ Fixed compensation characteristics ➢ Component size can become large ➢ Possible resonance with grid impedance.	Suitable for fixed frequency and relatively predictable supraharmonic emissions from PV, wind and converter systems.
[38]	Active Power Filters	Dynamic compensation, adaptable to changing loads and grid conditions and smaller passive components.	➢ Higher cost ➢ switching losses ➢ control complexity limited compensation capability at very high frequencies.	Suitable for dynamic and variable supraharmonic disturbances where fast compensation is required.
[39]	Hybrid Active Filters (HAPF)	Lower active filter rating, improved high-frequency attenuation, and better cost effectiveness than a fully active solution.	➢ More complex design ➢ Passive filter resonance and parameter selection remain important.	Highly suitable for supraharmonic mitigation because high frequency compensation can be shared between passive and active components.

[40]	Converter Control-Based Mitigation	Mitigation is integrated into the converter and avoids additional external filtering hardware.	➢ Requires accurate modelling and careful controller design ➢ performance can be affected by grid impedance and parameter variations.	Highly suitable for grid-connected PV, wind and BESS converters where mitigation can be incorporated into existing control systems.
[40]	Adaptive Control	Better response to changing grid impedance, renewable generation and load conditions.	➢ Higher control complexity and computational requirements ➢ stability must be carefully maintained.	Suitable for smart grids with variable renewable generation and changing network conditions.
[29]	Intelligent Based Mitigation	Adaptive decision making, nonlinear modelling and potential for predictive mitigation.	➢ Requires high quality training data, computational resources and ➢ appropriate validation Explainability can be limited.	Highly promising for future intelligent supraharmonic monitoring, prediction and adaptive mitigation in smart grids.

9. Comparative Analysis of Intelligent Techniques

There are different levels of accuracy, computational complexity, interpretability, adaptability and data requirements for supraharmonic analysis using intelligent methods. While conventional machine learning methods like support vector machines, decision trees and extreme learning machines offer effective classification with significantly lower computing demands, deep learning approaches like convolutional neural networks and transfer learning models offer more powerful automatic feature extraction and classification of complex power quality disturbances [29], [41].

Table 5 Comparative Analysis of Intelligent Techniques

Author /ref	Technique	Main comparison
[29]	ANN	Good nonlinear pattern recognition, requires representative training data, moderate computational demand
[29]	SVM	Strong classification with smaller datasets, sensitive to kernel/parameter selection

[29]	Decision Tree	Simple and interpretable, can suffer from overfitting
[41]	Random Forest	Better robustness than a single tree; higher computational complexity
	ELM	Very fast training and high classification capability, sensitive to feature/data quality
[42]	CNN	Effective automatic feature extraction from signal/time-frequency representations
[43]	ResNet/Transfer Learning	High accuracy and improved generalization for supraharmonic detection
[41]	Deep Learning	Strong performance for complex/nonlinear PQ pattern, requires large datasets and computational resources
[29]	Hybrid AI + DSP	Combines signal-processing feature extraction with intelligent classification
[39]	AI-based control/optimization	Enables intelligent monitoring, control, optimization and energy management
[44]	Intelligent converter control	Relevant to power-quality mitigation in renewable smart grids

10. Comparative Discussion and Performance Evaluation

Accuracy, computational cost, real-time capability, robustness, and scalability are some of the criteria used to compare the performance of the conventional and intelligent techniques of supraharmonic analysis and mitigation. This comparison is especially crucial for renewable energy smart grids because the emissions from PV inverters depend on the operating conditions, environmental factors, converter characteristics, and interactions with other power electronic devices [24], [23].

Table 6: Performance Comparison of Conventional and Intelligent Techniques

Performance criterion	Conventional methods	Intelligent methods
Accuracy	High for well-defined or stationary signals	Potentially very high for complex patterns
Computational cost	Generally low moderate	Moderate high, especially during training
Real-time capability	High and well established	High after training, hardware dependent

Robustness	Moderate, affected by changing conditions	Potentially high if trained with diverse data
Scalability	Moderate, data volume can become a limitation	High potential with distributed/edge implementation
Adaptability	Limited without parameter modification	High
Data requirement	Relatively low	Moderate to high
Interpretability	Generally high	Often lower, especially for deep learning
Suitability for renewable smart grids	Good for measurement and baseline analysis	Strong for adaptive detection and mitigation

The conventional techniques are useful in terms of simplicity, computational efficiency, measurement procedures and interpretability, while the intelligent techniques have the potential to be more accurate, adaptable, robust and scalable for automated analysis. This study proposes a hybrid structure using traditional signal processing techniques for obtaining reliable measurement and feature extraction and intelligent algorithms for detection, classification, prediction and adaptive mitigation [23].

11. Future Research Trends

Future intelligent supraharmonic analysis research is likely to be towards real-time, adaptive, distributed and data-driven power quality management.

An important trend is the integration of Artificial Intelligence (AI) with advanced signal processing. Future systems can leverage the features extracted using machine learning models and other time-frequency representations such as FFT, STFT and wavelets to enhance feature extraction and classification.

Edge intelligence is yet another key area. Performing supraharmonic monitoring near the converter or grid node avoids communication delay and enables fast mitigation.

The development of digital twins of power-electronic-dominated grids is another promising area. Digital twins could simulate converter and network behavior to allow for prediction of potentially damaging resonance and supraharmonic conditions prior to their occurrence.

In addition, intelligent controllers may use reinforcement learning and adaptive optimization to decide on mitigation actions based on changing grid conditions. These controllers could dynamically change the switching strategy of the inverter, the compensation of the active filter or other control parameters.

With the growth of the number of electric vehicle chargers, battery storage systems, photovoltaic systems and other distributed converters, coordinated mitigation will gain in significance. It is important to note that the next step should look from the device level of mitigation to the system level of coordination between multiple converters

12. Conclusions

The study concludes that supraharmonics are an emerging power-quality issue that must be taken into account as the share of renewable energy and converter-based technologies grows. Traditional power-quality evaluation methods that typically measure low-frequency harmonics do not always provide adequate information to detect and quantify high-frequency emissions. Therefore, adequate measurement bandwidth, sampling rates, signal-processing methods, and monitoring strategies are needed to perform the assessment of supraharmonics. The review also confirms that PV inverters, wind energy converters, battery energy storage systems, EV chargers, industrial drives, and electronic loads are significant sources of supraharmonic emissions. These devices can emit complex patterns of interactions with the network impedance, which sometimes cannot be easily explained by a single converter. Multi-converter interactions should be taken into account as well as individual converter emissions for supraharmonic analysis.

Another key finding is that traditional passive filters are not suitable in the dynamic smart grid environment. The effectiveness of the filter can be affected by changes in grid impedance, operating conditions, renewable generation and converter switching frequencies, which can create undesirable resonance conditions. Active and hybrid filtering techniques are more flexible since the compensation characteristics are adjustable depending on the changing conditions of the grid. The study also concludes that the intelligent techniques offer substantial possibilities for improving the detection, classification, prediction and mitigation of supraharmonics. Advanced techniques such as machine learning and AI-based algorithms can detect intricate structures in measured signals and may be able to differentiate various supraharmonic sources. Adaptive intelligent controllers can also adjust compensation parameters according to the varying operating conditions. They are, however, highly reliant on the availability of quality measurement data and suitable training datasets, and on computational resources and comprehensive validation.

Moreover, the review shows that smart inverter control is one of the most crucial mitigation pathways. The control algorithms of the existing digital control system of the renewable energy converter can be optimized to meet the active power and reactive power control requirements while minimizing the high-frequency emissions. A coordinated approach to supraharmonic mitigation may be possible through the integration of intelligent control with active filters and inverter-based compensation. Lastly, the paper suggests a shift from the traditional, fixed approach to mitigation to an adaptive, data-driven and coordinated strategy for managing supraharmonic systems in the context of the dynamic nature of smart grids with renewable energy.

Authors' Contribution

All authors contributed to the interpretation of the reviewed literature, critically revised the paper, authorized the version to be published 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, Quillbot and ChatGPT were used 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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