applied sciences

Review

A Review of Harmonic Detection, Suppression, Aggregation, and Estimation Techniques

Kamran Daniel [1,*], Lauri Kütt [1], Muhammad Naveed Iqbal [1,2], Noman Shabbir [1,3,*], Hadi Ashraf Raja [1] and Muhammad Usman Sardar [1]

[1] Department of Electrical Power Engineering & Mechatronics, Tallinn University of Technology, 19086 Tallinn, Estonia
[2] Department of Engineering, School of Digital Technology, Innovation & Business, University of Staffordshire, Stoke-on-Trent ST4 2DE, UK
[3] FinEst Centre for Smart Cities, Tallinn University of Technology, 19086 Tallinn, Estonia
* Correspondence: kamran.daniel@taltech.ee (K.D.); noman.shabbir@taltech.ee (N.S.)

Abstract: The rapid growth of power electronics-based devices, such as electric vehicles and renewable energy systems, has introduced nonlinear components into power systems, generating high-frequency harmonics that distort current and voltage waveforms. These distortions pose significant risks to the stability of power grids, potentially leading to equipment malfunctions, reduced efficiency, and even system failures. To address these challenges, advanced harmonic detection, suppression, and estimation techniques are required to ensure the reliable operation of modern power systems. This paper comprehensively reviews the most widely used methods for managing harmonic distortions, focusing on recent harmonic detection, suppression, and estimation advancements. Key techniques, such as Fourier analysis and wavelet transforms, are compared alongside emerging machine learning-based approaches and adaptive filtering methods, which offer enhanced accuracy in real-time and dynamic environments. Additionally, advancements in harmonic suppression technologies, including passive, active, and hybrid filtering, are discussed for their effectiveness in mitigating harmonic impacts. Furthermore, the paper explores harmonic aggregation techniques that assess the cumulative impact of multiple harmonic sources and innovative estimation models that improve harmonic quantification under complex grid conditions. With the growing integration of renewable energy and electric vehicles, this review highlights the importance of advanced harmonic management strategies to ensure the safety, efficiency, and long-term stability of power systems.

Keywords: harmonic detection; harmonic suppression; harmonic sensitivity; estimation models

check for updates

Citation: Daniel, K.; Kütt, L.; Iqbal, M.N.; Shabbir, N.; Raja, H.A.; Sardar, M.U. A Review of Harmonic Detection, Suppression, Aggregation, and Estimation Techniques. *Appl. Sci.* **2024**, *14*, 10966. https://doi.org/10.3390/app142310966

Academic Editor: Alessandro Lo Schiavo

Received: 22 October 2024
Revised: 19 November 2024
Accepted: 22 November 2024
Published: 26 November 2024

1. Introduction

The integration of nonlinear circuits in modern end-user equipment has improved power control management and enhanced utility. However, it has also introduced harmonic pollution into the power system, posing new challenges for engineers [1]. Researchers have responded by developing various techniques for studying the impact of harmonics generated by current and future devices in the power supply network [2]. Harmonic detection, suppression, aggregation, sensitivity analysis, and estimation are critical aspects of understanding and managing the harmonic content in electrical power systems [3–5]. This paper explores these essential techniques and their role in improving the reliability of power systems.

Figure 1 illustrates the methods that deal with harmonic issues to ensure the reliable operation of power systems. Harmonic detection is the process of identifying both the presence and magnitude of harmonic frequencies within an electrical system [6]. While traditional methods such as Fourier transforms have been widely used, recent advancements, including wavelet transforms and machine learning algorithms, provide more accurate real-time detection in non-stationary environments. These modern techniques have made it possible to analyze harmonic content more effectively, allowing for better system monitoring and protection. Harmonic suppression focuses on reducing or eliminating the effects of harmonic distortion. In modern power grids, hybrid filter technologies, which combine passive and active filters, offer a more effective approach [7,8]. Passive filters have long been used for harmonic suppression but have limitations, particularly in their adaptability to changing conditions. Active filters, on the other hand, can adjust dynamically, and when combined with passive filters, they provide more efficient suppression solutions for complex and evolving power systems.

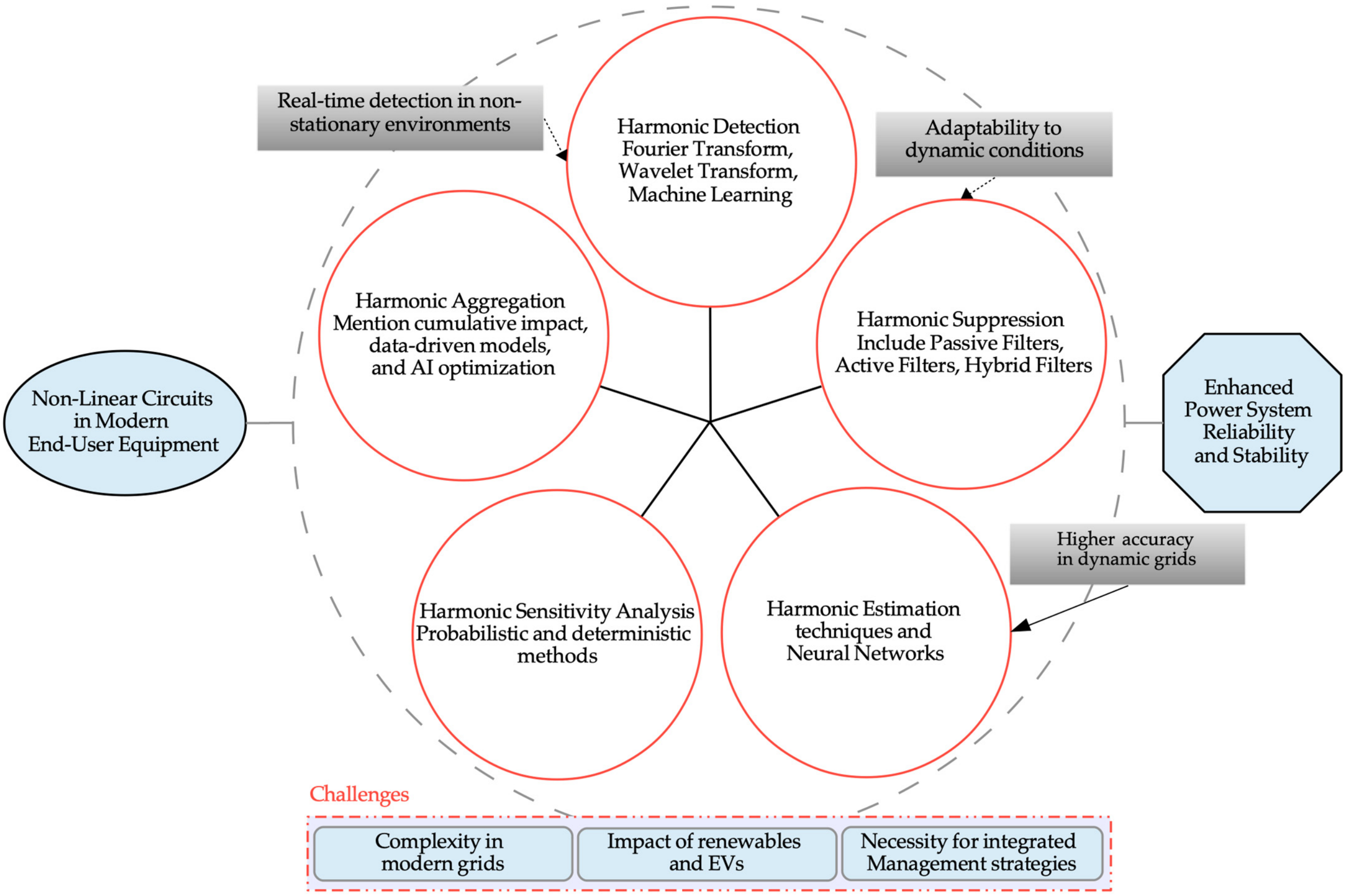

Figure 1. Organization needs and methods for modern power system.

Harmonic aggregation assesses the cumulative impact of multiple harmonic sources. The complexity of modern power systems, with various renewable energy sources and electric vehicles contributing to harmonic distortion, requires more precise prediction tools [9]. Data-driven models and AI-based optimization techniques have improved the ability to predict overall harmonic distortion in these systems, providing engineers with better insight into the performance and stability of power grids. Harmonic sensitivity analysis evaluates a system's response to variations in harmonic content. As power systems grow more interconnected and diverse, this analysis has evolved to incorporate probabilistic methods that account for uncertainties. This is particularly relevant in future smart grids, where unpredictability in energy demand and supply can introduce new harmonic challenges. By considering the probabilistic nature of these variations, engineers can better design systems that are robust and adaptable.

Harmonic estimation, which quantifies the harmonic content, has also advanced significantly. Traditional estimation methods have been supplemented by techniques like Kalman filtering and neural networks, which offer higher accuracy in dynamic grid conditions. These advanced estimation methods allow for more precise forecasting of harmonic behavior, improving system reliability and enabling proactive measures to mitigate harmonic effects before they impact grid stability. Standard detection and mitigation of harmonics are crucial for power system reliability, particularly given the increasing presence of loads like electric vehicles, which can introduce significant harmonic distortion; in addition, due to harmonics in large electrified railway systems, considerable power quality problems are induced [10,11]. This paper reviews existing technologies and measures designed to manage harmonic content, providing a reference point for researchers working in this area. Additionally, the challenges posed by large-scale, complex power networks—similar to the issues faced by large-scale information networks—demand an integrated approach to harmonic management. A comprehensive strategy for harmonic detection, suppression, aggregation, and estimation is vital to maintaining the overall health of modern power systems.

This paper is structured as follows: Section 2 presents an overview of harmonic detection methods, including both traditional and modern approaches. Section 3 discusses harmonic suppression strategies, highlighting passive, active, and hybrid filtering methods. Section 4 focuses on harmonic aggregation, examining the challenges of managing multiple harmonic sources in complex systems. Finally, Section 5 explores harmonic estimation models and their role in predicting harmonic behavior in evolving power grids.

2. Harmonic Detection Principles and Methods

Harmonic detection is the process of identifying and measuring the presence of harmonic frequencies in a signal. Harmonics are multiples of the fundamental frequency of a signal and can be caused by non-linearities in the system generating the signal or by external sources such as power supply interference [9]. The literature [1,12] explains harmonic detection methods, which are used to extract the harmonic components in the power signal or to estimate each harmonic's parameter information. Accurate and fast harmonic detection is significant for subsequent harmonic analysis and control. There are several methods for detecting harmonics in a signal, including the use of Fourier transform, wavelet transform, and harmonic analysis.

Fourier transform is a widely used method for harmonic analysis. It decomposes a signal into its individual frequency components and can be used to identify the presence of harmonic frequencies. However, it is not well suited for signals that have time-varying frequencies or non-stationary signals. Wavelet transform is another popular method for harmonic analysis. It can be used to analyze signals with time-varying frequency and non-stationary signals. It can also provide more detailed information about the harmonic content of a signal than the Fourier transform [13].

2.1. Discrete Fourier Transform

Literature [14] introduced the detection method based on the Discrete Fourier transform. This method has been extensively used in literature for detection due to its convenience and numerous functions. The advantage of the technique is that a number of harmonic eliminations can be selected, and the environment has less influence on the method. However, one of the disadvantages is that the number of calculations is large, the selection of the current value takes considerable time, and the real-time performance of the calculation result is accurate up to a limit [15]. In the sampling process, when the signal frequency and the sampling frequency are inconsistent, the calculated signal parameters will have errors, and the phase will have a significant deviation. This Fourier transform method can be improved using an interpolation and windowing algorithm, a bimodal spectral line correction algorithm, and a sampling frequency synchronization method [14].

2.2. Based on 3-φ Instantaneous Reactive Power

This technique has substantially aggrandized the development of active power filter (APF), as it is used in the detection algorithm in APF [14], initially aimed at three-phase circuits. In recent years, some scholars have developed improved methods based on this theory and extended the application range of this method to single-phase circuits. The technique can also have good detection accuracy for distorted grid voltage, but the asymmetric voltage will affect the detection performance. In general, the harmonic detection algorithm based on instantaneous reactive power has the advantages of simple circuit implementation and good real-time performance. Still, the circuit components greatly influence the algorithm's performance and have specific dependence. The parameter adjustment is more complicated, and the hardware costs more [16,17]. This algorithm can be used to develop reactive power compensation devices and Control harmonics if the limitations are properly addressed.

2.3. Adaptive Detection Method

The techniques described in [18] use voltage as reference input and current as the original input; it uses the adaptive interference cancellation principle of signal processing and reactive current and harmonic information are acquired, as illustrated in Figure 2. This adaptive detection method has little dependence on device characteristics but is almost independent of component parameters. The system has good adaptive ability and can attain higher detection accuracy even when the grid voltage is distorted and the frequency fluctuates.

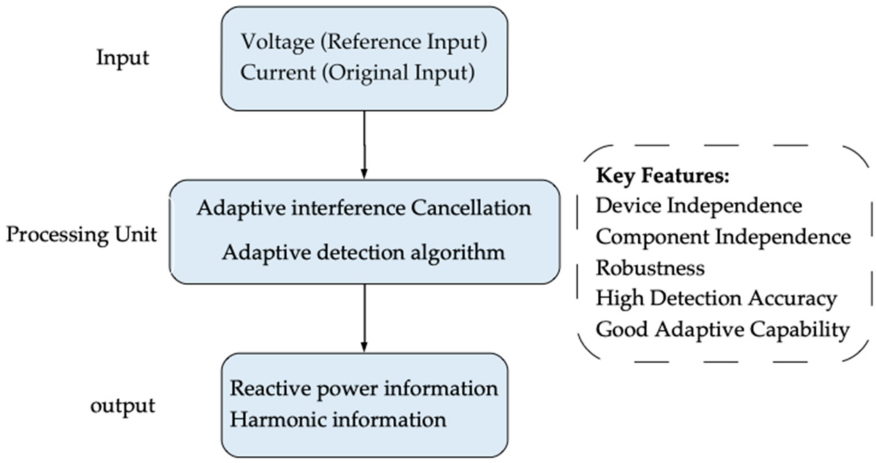

Figure 2. Adaptive detection method.

2.4. Detection Based on Wavelet Analysis

Another common harmonic detection method is the wavelet analysis method [19]; it does not use steady-state waveform signals, but a series of short-term oscillating waveform signals are used as the basis function. The research results show that the wavelet technique has an obvious advantage over the Fourier transform in the harmonic detection of dynamic changes; still, it is not as good as the Fourier transform in the detection of steady-state harmonics. Problems with this method are that, firstly, there is no definite standard for the selection of wavelet bases; secondly, there is the phenomenon of spectrum leakage and band aliasing; and thirdly, the resolution of the conversion process is low, which affects the detection of higher harmonics [13].

2.5. Neural Network (NN) Based Method

With the noticeable growth of research in artificial intelligence, the neural network theory has rapidly developed. The non-linear and adaptive signal processing system composed of many interconnected processing units constitutes the neural network [20]. In recent years, researchers have used various neural network techniques for harmonic detection and harmonic parameter estimation [21–23]. Neural network-based detection methods have their own advantages but also have their own insuperable limitations, so they are combined with other algorithms to compensate for these shortcomings [24]. For example, in [24], a new method for accurate harmonic detection is proposed by combining the Fast Fourier Transform algorithm with the improved artificial neural network. Table 1 presents a comparative analysis of different harmonic detection methods.

Table 1. Harmonic Detection Methods.

Method	Ref.	Advantage	Disadvantage	Applications
Fourier Transform	[13,14]	Widely used, decomposes signals into frequencies	Not suitable for time-varying or non-stationary signals	Power systems with steady-state harmonics
Wavelet Transform	[13,19]	Analyzes non-stationary signals, time-varying frequency	Complex, spectrum leakage, band aliasing	Dynamic systems, transient analysis
Adaptive Detection Method	[16–18]	Independent of component parameters, high accuracy	Complex parameter adjustment, dependent on circuit components	Detection in variable grid voltage
Neural Network-Based Method	[20–24]	Adaptive, can learn from data	Computationally intensive, requires large datasets	Advanced AI-driven detection models

In summary, various harmonic detection methods address specific challenges in identifying harmonic content in electrical signals. The Fourier transform is highly effective for stationary signals but faces limitations with time-varying ones, which wavelet transform can better handle, offering detailed frequency information. Discrete Fourier Transform (DFT) is widely used for its convenience, though it requires improvements like interpolation to enhance accuracy. The reactive power filter methods are advantageous for real-time applications but depend heavily on circuit components, which complicates tuning. Finally, adaptive detection and neural network-based approaches demonstrate robustness under dynamic conditions but are often integrated with other algorithms to compensate for limitations. Hence, various harmonic detection techniques each have their own strengths and weaknesses. These methods enhance their effectiveness by combining the benefits of different theoretical approaches, which greatly improves the overall performance of harmonic detection. The choice of method will depend on the characteristics of the signal being analyzed and the specific information that is desired.

3. Harmonic Suppression Methods

Harmonic suppression, also known as harmonic mitigation, is a technique used to reduce or eliminate harmonic distortion in electrical power systems. Several methods of harmonic suppression can be used, including passive filters, active filters, and harmonic traps. Passive filters are the most common method, and inductors and capacitors are used to filter out harmonic frequencies. Active filters use power electronics and control algorithms to actively cancel out harmonic frequencies. Harmonic traps are specialized passive filters that are designed to trap and filter out specific harmonic frequencies. Figure 3 presents the overview of harmonic mitigation techniques.

The three main measures for harmonic suppression are as follows: First, systems and equipment affected by harmonic interference are improved to enhance their ability to resist it, which indirectly helps suppress harmonic interference. Second, modifications are made to the harmonic generation device to decrease the production of harmonics at the source [25,26]. Third, an external filter is used to eliminate harmonics, preventing them from entering the power system or electrical equipment and thus suppressing harmonics. These measures are called receiving, active, and passive, respectively. The last two techniques need only a slight transformation of the existing equipment/system; these two are relatively low cost as the system/equipment have already been put into use.

Harmonic interference capabilities and functions must be taken into account when designing a reasonable suppression measure or transforming the system/equipment. Passive suppression methods are more feasible and relatively simple to implement, as they can achieve a better suppression effect. Therefore, in the current industrial situation, passive methods are in the mainstream. These methods involve hardware, specifically a filtering device that compensates for harmonics and prevents the harmonics from spreading between the grid and loads. Passive methods include passive power filters, active power filters, and hybrid active power filters.

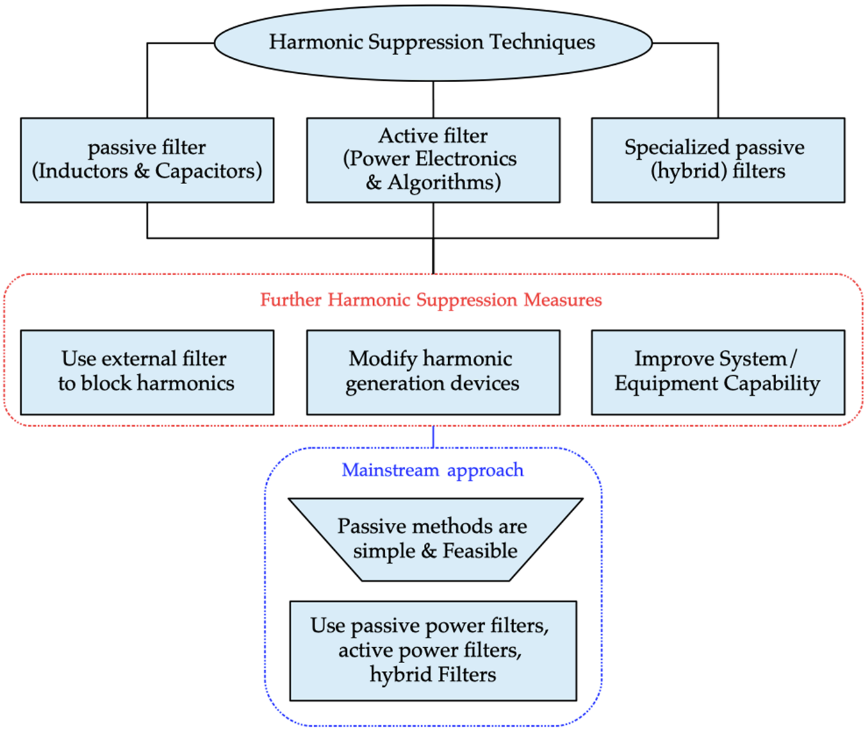

Figure 3. Harmonic suppression methods.

3.1. Passive Power Filter

By the end of the last century, researchers [27] proposed a power filter composed of capacitors and inductors to include harmonics and reactive power compensation; as a result, the power factor of the grid was improved. A passive power filter deploys the principle of resonance to create a low-impedance route for specific frequency components to filter out the harmonics from the power system [28]. The key advantages of the passive power filter are low cost, structural simplicity, and ease of implementation. Passive power filters may need many improvements, such as the parameters of components strongly affecting the filter performance of the source power filter. When the power signal's frequency is changed, over-resonance occurs, and filtering performance will decrease eventually [29,30]. Due to over-resonance, harmonic signals are amplified. In addition, the capacity of PPF is limited when the harmonic signals are too large; it may overload and damage the filter.

3.2. Active Power Filter

Active power filters (APF) are designed to overcome the performance defects of passive power filters. Most active filters try to suppress dynamic harmonics and track the varying harmonic signals. Active filters can compensate for reactive power, suppress dynamic harmonics, avoid overload, and avoid over-resonance in case of a change in power signal frequency [31]. In addition, APF has considerable safety and working stability. The suppression method using APF is a mainstream research topic in harmonic control now.

This APF method of suppression consists of mainly two portions; the first is the detection of harmonic signals, and the second is the compensation of harmonics [32]. In [33], APF techniques first detect, compensate the harmonic, and then transmit it to the grid system through a control strategy so that the original harmonic signal can be canceled out. Doing so results in high performance in suppression and accurate harmonics detection, as harmonic detection is the critical link in the suppression process.

Research on APF is further divided into different methods: topology, DC voltage control, harmonic detection technique, control of current tracking, and PWM methods. Active power filters have various classifications; depending on the application, they are divided into AC and DC [34,35], as presented in Figure 4. APF inverter circuits can be classified as voltage-type (part a) or current-type (part b) filter devices depending on the energy sting element used [36].

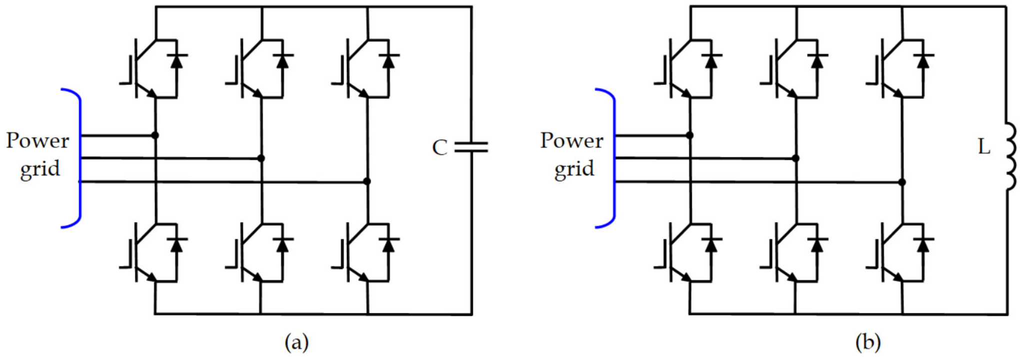

Figure 4. APF inverter circuit structure (**a**) voltage type (**b**) current type.

Active power filters can be connected to the grid in various arrangements, in series, parallel, or hybrid schemes. The above Figure 5 shows the possible schematics of the APF with the grid used in the literature [37–39]. Figures 5a and 5b shows the in-parallel and in-series connections to the grid, respectively. As passive power filters are low-cost, they can be used along with active power filters to create hybrid schemes. The hybrid APF schemes slightly affect the device's capacity but improve the economics [36]. Figure 5c shows the schematic to improve the filtering characteristics of a passive filter when introducing in series a small capacity APF. Figure 5e is referred to as a parallel hybrid active power filter, where the device is in series with a passive filter; this schematic has good performance and a reasonable cost, so it is most common. Figure 5f represents the uniform power quality regulator [39], which combines a passive filter and a series active power filter; this can eliminate power distortion by non-linear loads through adjusting the load terminal voltage and suppressing the harmonic system distortion. Figure 5g,h are LC series and parallel resonant circuits, respectively; this structure can compensate for harmonic currents as it prohibits the oscillation of harmonics between the grid and loads.

A harmonic suppression method based on fractional lower order statistics (FLOC) has been proposed in [40] to deal with the impulse noise in the power system, as the impulsive noise seriously degrades the harmonic suppression performance of the power system. It is an Active Power Filter (APF) method based on the principle of self-sensing actuators, illustrated in Figure 6. The key advantage of this model is that it has a tracking ability for changing harmonics while suppressing impulsive noise activity.

Another method to suppress harmonics is using a "Dynamic Voltage Restorer (DVR)" [41,42]. It is a device that can be used to mitigate voltage sags, swell, and harmonic distortion in power systems. The DVR works by injecting a voltage that is in phase with the system voltage, but with a higher or lower amplitude, depending on the situation. Table 2 presents the comparative analysis of harmonic suppression methods.

In summary, Passive filters, often using inductors and capacitors, offer a cost-effective solution for static harmonic reduction, but they may face performance issues with resonance. Active Power Filters, designed to handle dynamic harmonics, offer better adaptability, stability, and control under varying conditions, making them a research focus. Hybrid APF systems combine passive and active components to enhance performance and cost-efficiency. More advanced methods, such as fractional lower-order statistics and Dynamic Voltage Restorers, address specific disturbances like impulsive noise and voltage sags, adding flexibility to harmonic suppression strategies. In addition to these methods, utilities and power system operators may also use load management techniques to reduce harmonic distortion. This can include adjusting the power factor of large loads, such as industrial motors, to reduce harmonic currents, or installing harmonic measuring devices to monitor and identify sources of harmonic distortion.

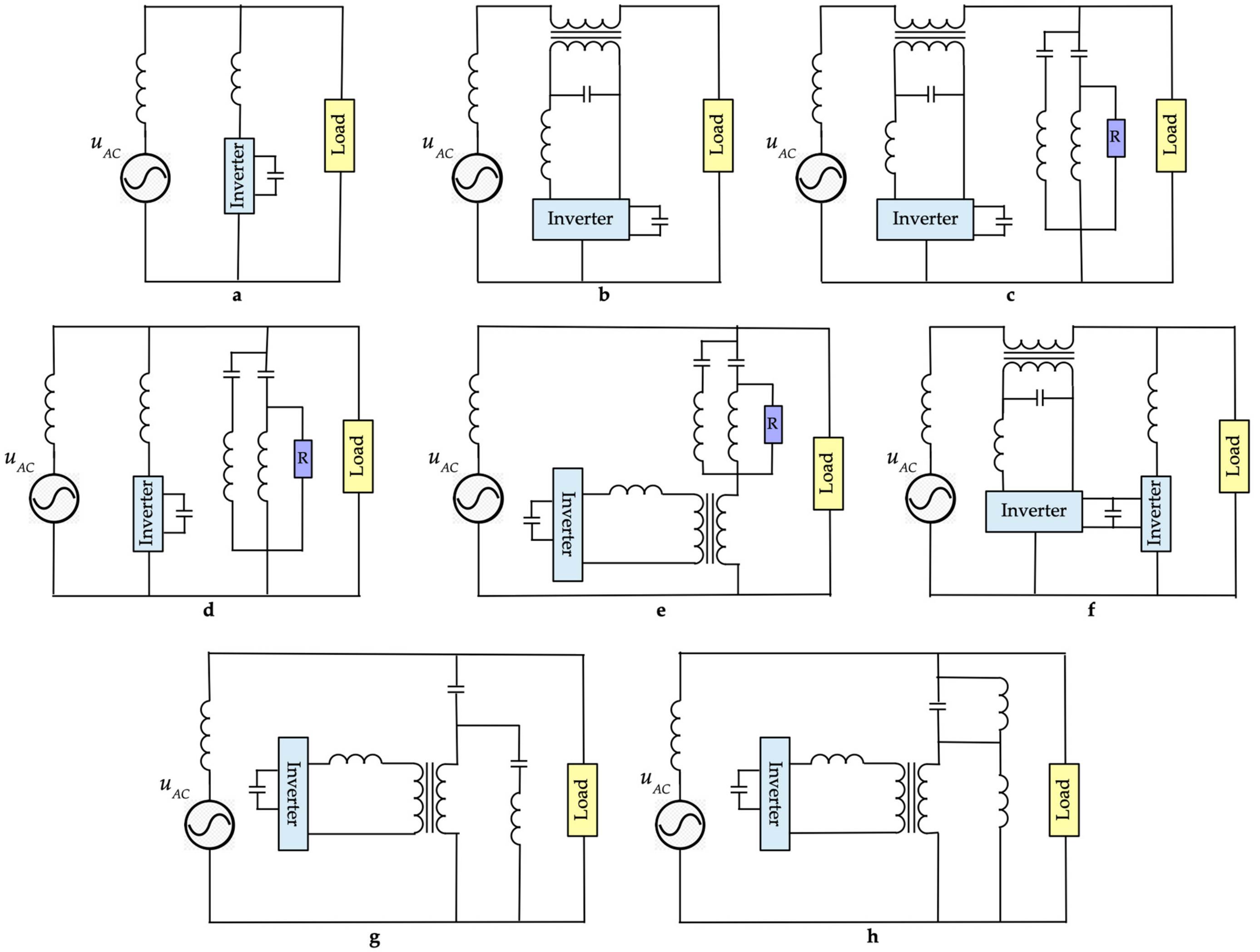

Figure 5. The circuit structure of various derived active power filter (**a**) parallel connection (**b**) series connection (**c**) small APF in series (**d**) parallel hybrid APF (**e**) series hybrid APF (**f**) with uniform power quality regulator (**g**) with series LC resonant circuit (**h**) with parallel LC resonant circuit.

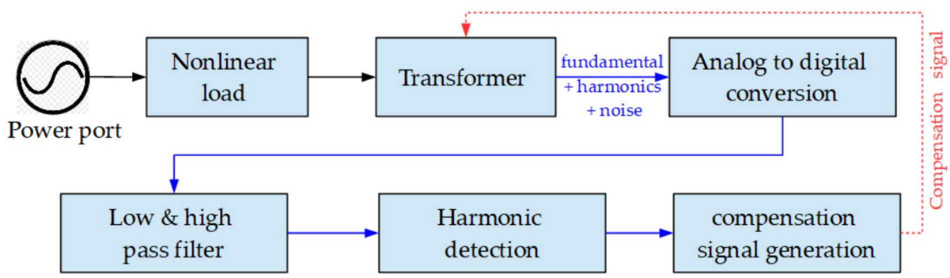

Figure 6. Block diagram of the harmonic suppression method based on self-sensing actuator.

Table 2. Harmonic suppression methods.

Method	Ref.	Advantage	Disadvantage	Applications
Passive Filters	[27–30]	Low-cost, simple implementation	Performance affected by system frequency changes	Common in industrial power systems
Active Power Filters (APF)	[31–35]	Suppresses dynamic harmonics, compensates reactive power	High hardware cost, complex circuit design	High-performance grid systems
Hybrid Filters (Passive + Active PF)	[36–39]	Balances cost and performance	Slight impact on device capacity	Modern power systems with budget constraints
Dynamic Voltage Restorer (DVR)	[41,42]	Compensates for voltage sags/swells, mitigates harmonic distortion	Expensive and complex	Grid systems with voltage fluctuation issues

4. Harmonic Aggregation

Harmonic aggregation is a technique used to combine a signal's harmonic components to estimate the signal's fundamental frequency and overall harmonic content. This technique is widely used in various fields, such as audio signal processing, power system analysis, and communications systems. In recent years, researchers have been developing new methods for harmonic aggregation that are more robust and efficient than traditional methods; Figure 7 presents the overview of harmonic aggregation discussed in this section.

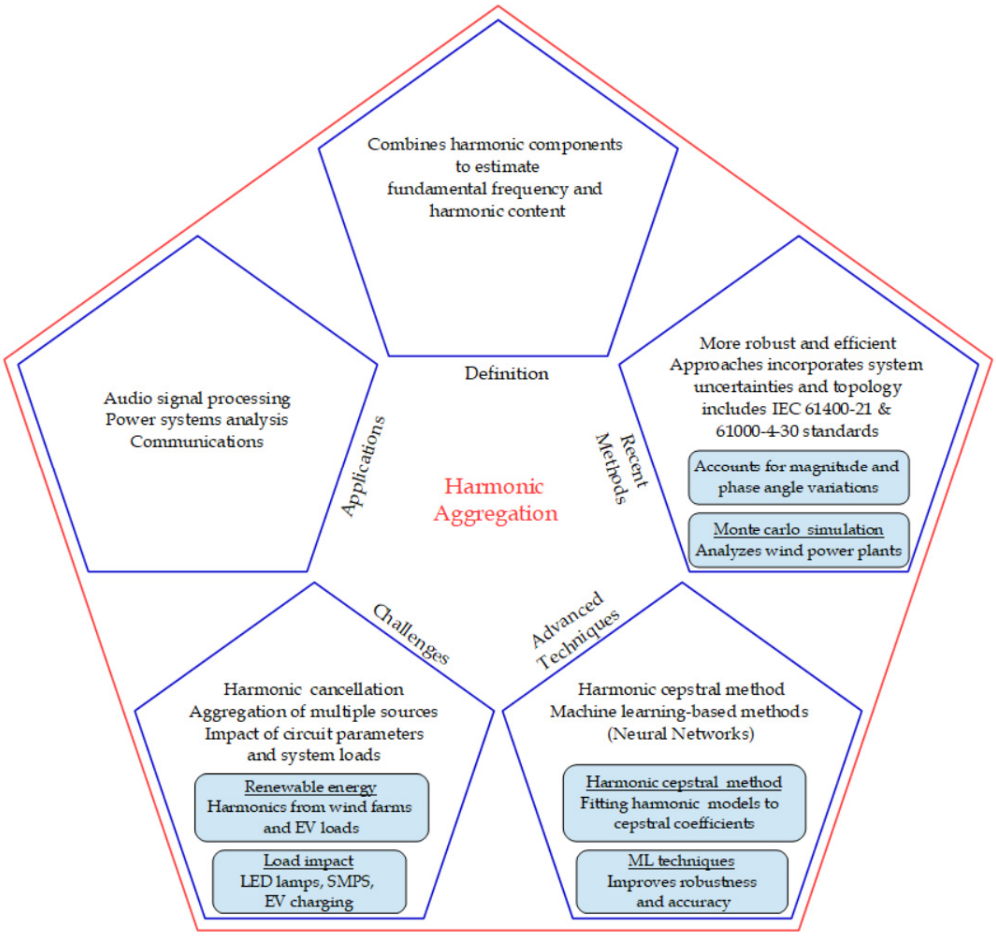

Figure 7. Harmonic aggregation overview.

One part of evaluating the harmonics tolerated by a power system is estimating the total amount of harmonics coming from different sources. The assessment of harmonics is not precise or consistent because there can be unpredictable changes in the system's nonlinear sources and parameters that influence the total. The combination of various harmonic sources usually results in a sum that is less than the arithmetic total of the maximum values due to uncertainties in the magnitude and phase angle. Therefore, accurately estimating the resulting sum is difficult [43].

The accurate assessment of the harmonic combination from several non-linear sources operating at the same time is important because of the uncertainty in the magnitudes and phase angles of the harmonic currents injected into the transmission. The method used in [44] takes into account the system topology of the wind farms and the overall system. The harmonic currents injected for penetration are evaluated, and these alternative values are calculated and compared to the cumulative curves. This study indicates that estimates of harmonic aggregation using the IEC 61400-21-1 [45] methodology may lead to errors in the power system. In [46], the authors provide an overview of the work investigating the aggregation of multiple identical harmonic sources within a single renewable energy generator (REG) plant. REG investors can generate a wide range of harmonics; the magnitude of the error introduced is significant when harmonics from multiple sources are added arithmetically.

The phenomenon of harmonic cancellation happens due to dispersion in harmonic phase angles. Variation of circuit parameters inside switch mode power supply (SMPS) is responsible for harmonic cancellation between same-type and mixed-type SMPS aggregate load [47]. Renewable sources are now a considerable part of modern power generation and distribution systems; due to variable speed turbines, large wind power plants (WPP) are sources of harmonics and inter-harmonics in voltage and current [48]. The model developed in [48] helps meet the challenges of wind power integration; harmonic aggregation and cancellation are some of these challenges. The aggregation of harmonics produced by the wind power plant is independent of the power generated; this is consistent with the findings in [49], which analyzed the accumulation of complex current harmonics and inter-harmonics.

The aggregation factor at low-order harmonics is more significant than that of high-order harmonics; the aggregation factor is high at harmonics while low at inter-harmonics. Figure 8 shows the 10 wind turbine park models used as a case study for the aggregation model presented in [49]. The Monte Carlo simulation is performed for the aggregation of harmonic emission from wind parks; the study found that aggregation was different for low-order, high-order, and inter-harmonics. Aggregating current harmonics in low voltage (LV) networks is one of the critical aspects of harmonic analysis. The characteristics of residential customers' harmonic current emission and propagation depend significantly on the number of users [50]. The aggregation (as well as the summation) is addressed while performing the summation of harmonic currents by taking different combinations of load devices [51]. Energy-efficient LED lamps comprise a considerable portion of the lighting load in modern buildings, and their harmonic profile depends on the internal filtering circuit [49]. These energy-efficient lamps are categorized into four types, depending on the current waveform. Researchers have found that the impedance of cables (connecting the devices to PCC) and the thermal stability of the equipment (loads and measurement devices) affect the harmonic fingerprint of loads [52,53]. The magnitude and phase of current harmonics are small and precise values, so measurement accuracy is critical [15]. In [15], authors have devised an accurate measurement setup that takes into account the uncertainty related to the system and measurement device. Accurate summation can be carried out when the phase angles involve the aggregation procedure and magnitudes [54].

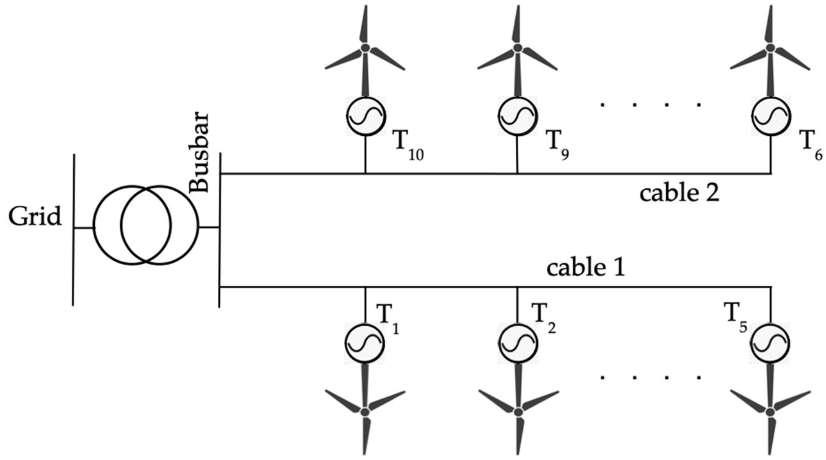

Figure 8. Ten wind-turbine park configurations.

Figure 9 represents the block diagram of the setup used in [54]; the relationship between the harmonic current variation and the number of lamps has been observed for high and low-order harmonics. As the high-order harmonics phasors have more spread on complex plane compared to low-order harmonics, the deviation in aggregated sum and the actual measurement of the high-order harmonic will be more significant than that of low-order harmonics. The reason behind this deviation is the phenomenon of harmonic cancellation. Harmonic cancellation is more visible when several load types are connected simultaneously at the point of common coupling (PCC) and the number of loads is connected. Current harmonics from energy-efficient lamps and electric vehicle (EV) loads are measured individually and combination-wise in [43]. After the accurate aggregation of load harmonics, it was established that the cancellation effect is directly related to the number of loads connected at PCC and is more visible in high-order harmonics.

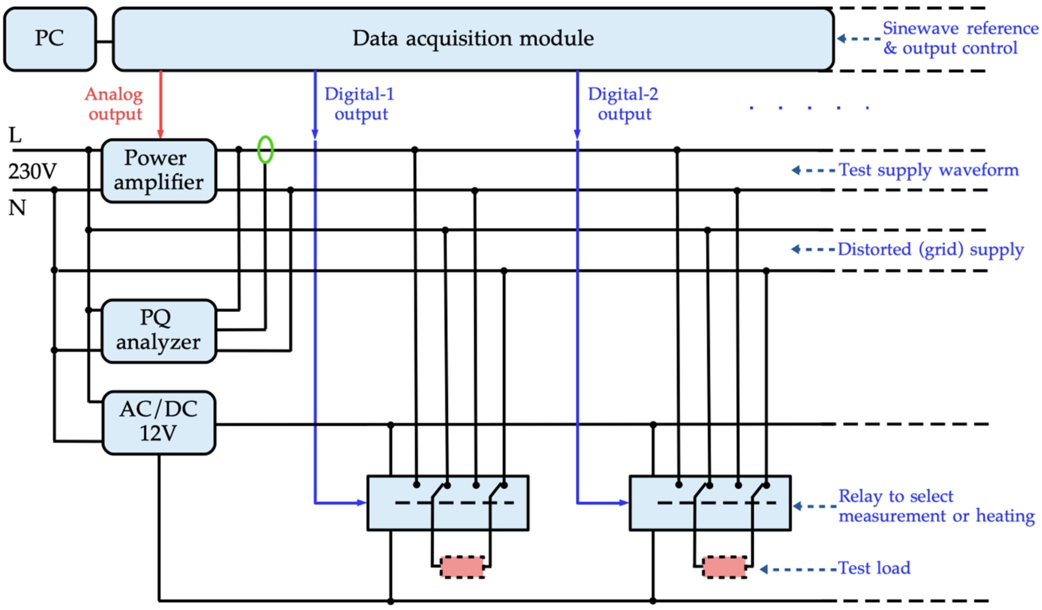

Figure 9. Measurement setup.

The IEC 61000-4-30 [55] standard clarifies harmonic aggregation and synchronization of each measurement interval's start and end time. Data collected during the standard measurement interval is challenging to process as the power system's operation changes continuously due to the integration of renewables, especially EV loads; therefore, ref. [56] presents the method of the reduced data set that aids the continuous assessment and aggregation of harmonics. The large-scale integration of EVs poses new challenges for distribution system operators, so the model proposed in [57] discusses the impact of the aggregation interval; the results indicate that 10 min of aggregation will lead to a significant deviation (>30%) in terms of maximum current harmonic magnitude, as illustrated in Figure 10.

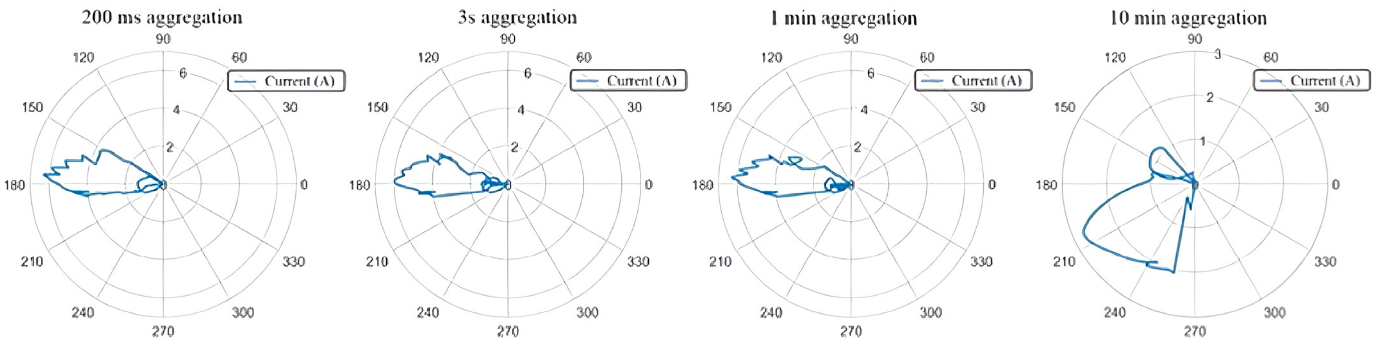

Figure 10. Third current harmonic simulations of aggregated electric vehicle loads for different time aggregation intervals [57].

Because of the impact of current and future loads on the propagation of harmonics in the network, harmonic aggregation models are necessary to accurately assess distortion in the system. In [58], a method for creating a stochastic aggregation model is described. This technique is applied to three low-voltage networks illustrated in Figure 11. The results indicate that it can effectively represent their stochastic behavior while greatly reducing the computational load compared to modeling the downstream network. Another finding from [58] is that resonances occur in a narrower frequency band as the number of customers increases.

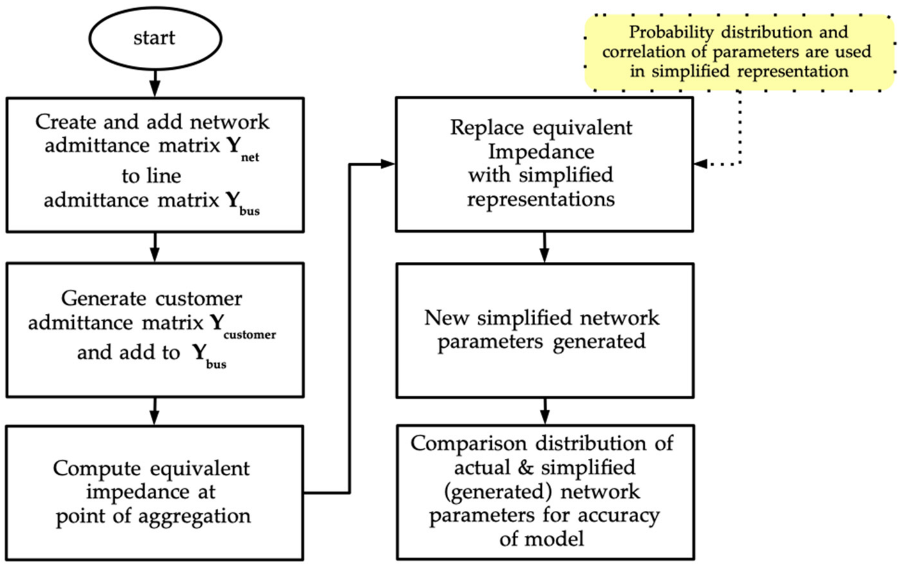

Figure 11. Flowchart of the proposed method for stochastic aggregation model.

The previous standard IEC/TR 63000-3-6 states the general summation law but with a limited number of harmonic sources [59]. Therefore, ref. [59] provides a methodology that uses more sophisticated equipment to allow facility operators to plan accordingly after an accurate harmonic contribution and summation estimate. This new standard aims for a 95% probability of the estimated value not exceeding the actual value.

Another popular method for harmonic aggregation is the harmonic peak picking method [60], which is a non-parametric method that estimates the fundamental frequency of a signal by selecting the peak harmonic frequency of the signal. This method is also simple to implement and computationally efficient, but it can also be sensitive to noise and other distortions. A more recent method for harmonic aggregation is the harmonic cepstral method [61], which is a parametric method that estimates the fundamental frequency of a signal by fitting a harmonic model to the cepstral coefficients of the signal. This method is more computationally intensive than peak picking methods. However, it can provide more accurate estimates of the fundamental frequency of a signal in the presence of noise and other distortions. In addition, recent research has also used machine learning-based approaches, like neural networks, to improve the robustness and accuracy of harmonic aggregation [62,63]. A comparative analysis of harmonic aggregation models is presented in Table 3.

Table 3. Harmonic aggregation models.

Method	Ref.	Advantage	Disadvantage	Applications
Arithmetic Summation	[54]	Simple to implement	Does not account for phase variations	Harmonic assessment in simple systems
Monte Carlo Simulation	[50]	Accounts for randomness and variability	Computationally intensive	Large-scale harmonic studies, renewable energy integration
IEC 61400-Series Methodology	[55–59]	Widely adopted standard	Induces errors in summation	Wind farms and renewable energy grid integration
Machine Learning Approaches	[62,63]	High accuracy, can adapt to complex systems	Requires training, computationally intensive	Advanced grid systems with variable sources

In conclusion, traditional methods face challenges due to variations in non-linear sources and unpredictable system parameters, which impact precision. Techniques mentioned in IEC 61400-21 show limitations with renewable energy generators, where aggregation errors arise due to phase angle dispersion and harmonic cancellation. More recent approaches include advanced modeling, such as stochastic models for load variation, harmonic peak picking, and cepstral methods for improved accuracy. Machine learning models further enhance robustness and accuracy, addressing complex system dynamics and noise.

5. Harmonic Estimation Models

Current harmonic estimation models typically use techniques from signal processing, such as Fourier transforms and harmonic analysis, to estimate the harmonic content of a signal. This can include both the amplitude and phase of each harmonic component, as well as the fundamental frequency of the signal. Harmonic estimation is crucial in various fields, such as audio signal processing, power system analysis, and communications systems. In these applications, it is essential to accurately estimate the harmonic content of a signal to understand its underlying structure and to perform further signal processing tasks.

In recent times, the parameters of power systems have been highly distorted, due to the increased application of non-linear loads. Monitoring harmonic and inter-harmonic distortion is an essential issue for delivering high-quality power. Modern power systems' devices generate a broad spectrum of harmonic components, especially vast converter systems that propagate non-characteristic harmonics and inter-harmonics. Many algorithms have been proposed to address harmonic estimation that eventually improve power quality performance, but to date, an accurate estimate is challenging. Researchers have developed different probabilistic and deterministic techniques, that vary in accuracy and complexity.

Pisarenko's approach of separating the output waveform into signal and noise subspaces is used to perform an estimation of the harmonics from the industrial converter in [64]; two estimation techniques, prony and min-norm, show better accuracy than the Fourier algorithm in most cases. Ref. [65] presents an adaptive Kalman filter method for dynamic harmonic state estimation and harmonic injection tracking. Figure 12 shows the flow chart of the adaptive filtering technique used. In this technique, the noise covariance matrix is not fixed but dynamic, as the adaptive filter is measurement-dependent.

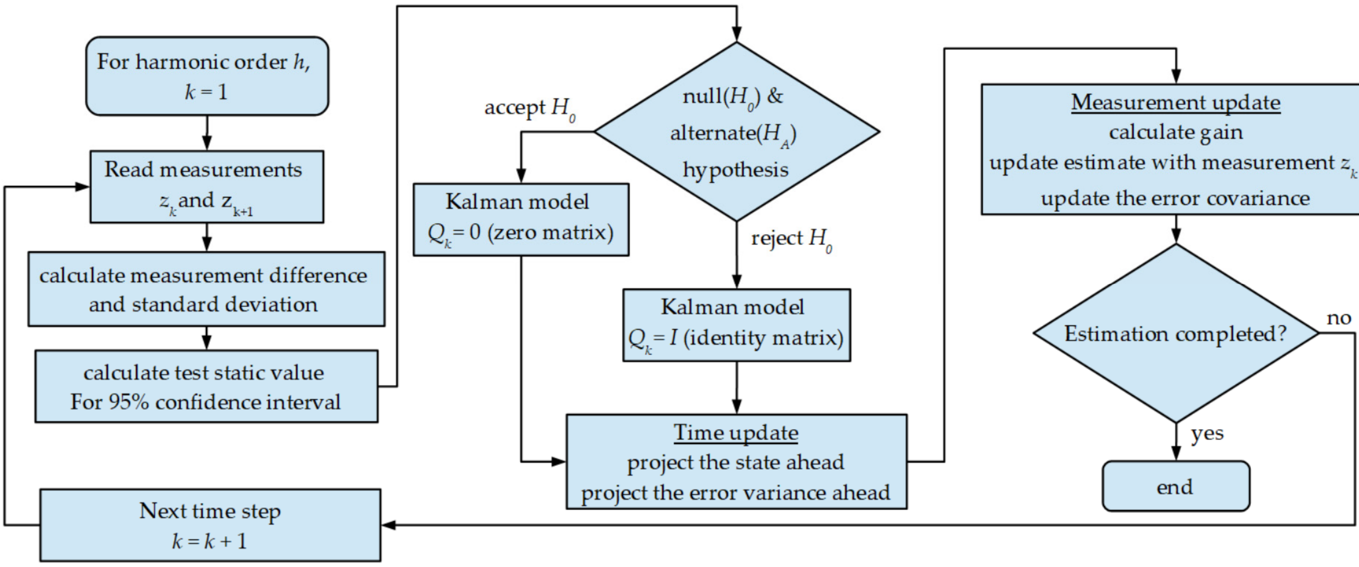

Figure 12. Flow chart of adaptive Kalman filter.

The authors in [66] propose an algorithm for estimating dynamic frequency and amplitude in unbalanced three-phase power systems with harmonics. This algorithm can accurately estimate an unbalanced power system's frequency and amplitude by using a non-linear power system voltage model that includes harmonic content, employing an unscented Kalman filter (UKF). Evaluation of this algorithm's performance, conducted using the Monte Carlo simulation, shows that it is able to track the grid voltage waveform accurately and rapidly when frequency and amplitude change, but only a limited number of harmonics can be estimated.

The number of electric vehicles (EVs) is rising, leading to an increasing demand for EV charging stations, which in turn is causing a rapid rise in harmonic pollution from EV chargers. Ref. [67] proposes a harmonic analytical model to estimate the equivalent circuit parameters of chargers based on measured voltage and current data at the AC side and the circuit constraints during the charging process. This model is created by grouping similar types of chargers. Figure 13 shows the equivalent circuit used to develop the analytical model, the circuit charger uncontrolled converter. A key advantage of this method is that the parameters can be estimated from measurements taken under different voltage conditions.

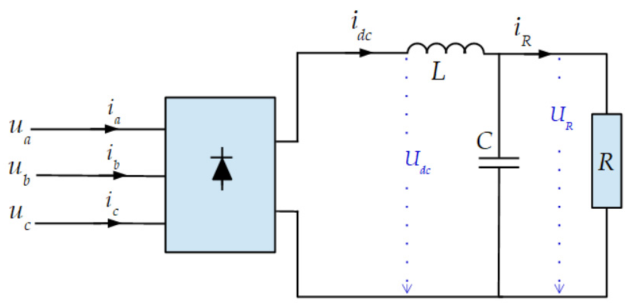

Figure 13. Equivalent charging circuit.

A mathematical signal model is developed in [68] with a factor increase in all harmonics except the fundamental frequency component. A new Taylor–Kalman–Fourier (TKF) filter is proposed to estimate dynamic phasor and time-varying harmonic components while reducing total harmonic distortion (THD) in power systems. In [69], a state-estimation-based model is presented that determines the harmonic contribution at the point of common coupling (PCC) from iron and steel plants, where non-linear characteristics are modeled as current sources and the harmonic fingerprint of the loads are separated from the upstream. The flowchart of this state-based algorithm is presented in Figure 14. The main benefit of this model is that it removes the need for expensive and cumbersome resistive-capacitive voltage transformers (RCVTs) for continuous measurements to accurately measure harmonic voltages. State-estimation-based corrections are applied to harmonic voltage measurements obtained from conventional voltage transformers (CVTs).

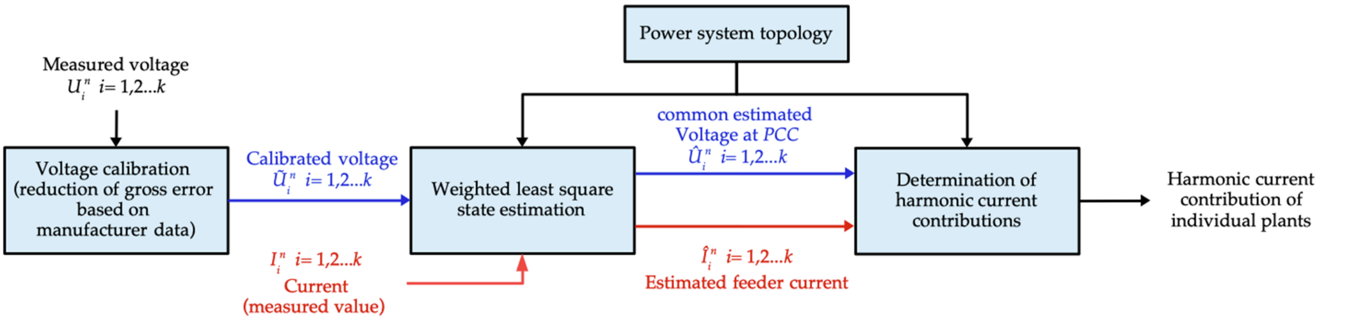

Figure 14. Flow diagram of state-estimation-based harmonic current contribution determination method.

In [70], an adaptive observer-based, closed-loop feedback approach is introduced for estimating single-phase grid voltage parameters that include harmonics. This proposed estimation method is robust against harmonic voltage disturbances due to its closed-loop feedback design. It ensures zero steady errors even when the grid's fundamental frequency changes significantly from its nominal value. The adaptive observer method is further extended in [71] to provide an asymptotic estimate of three-phase grid voltage parameters, including amplitude, frequencies, and phase angles under unbalanced grid faults and harmonic voltage disturbances. Nodes and devices in electric distribution networks are often nonlinear and unbalanced, making precise measurement devices and methods necessary to monitor harmonic propagation and power quality (PQ) phenomena. A complete or redundant monitoring system may not be feasible for estimating the harmonic status of the entire grid due to technical and economic factors. In [72], the authors present an efficient compressive sensing harmonic detector (CSHD) for identifying and estimating the main sources of pollution.

In [73], a noninvasive and multiparametric estimation algorithm is proposed for grid-connected voltage-source converter systems, based on time-domain models of voltage-source converters. This proposed method performs harmonic estimation using the steady-state extended harmonic domain (EHD) model in combination with the nonlinear least squares (NLSQ) fitting algorithm; the flowchart is presented in Figure 15**.** The EHD model reduces the necessity of synchronized measurements, which eventually enhances the performance and robustness of the NLSQ model. This proposed system is a flexible, less complex, and reliable algorithm under measurement uncertainties that can identify grid equivalent, ac filter, and switching and conduction parameters from a reduced number of non-synchronized measurements.

An estimation of the harmonic synchro phasor is proposed in [72], utilizing the flat-top (FT) finite-impulse-response (FIR) filter. Analysis under both dynamic and steady-state conditions was conducted to determine the properties of the proposed algorithm, which is based on convolution and can be implemented in common embedded systems. Harmonic distortion, intermodulation, and noise affect the overall linearity of electronic circuits [74]. Consequently, the authors in [75] present a time-domain harmonic distortion estimation method that offers a compact and systematic approach to modeling complementary metal oxide semiconductor (CMOS) transistor stages, estimating the harmonic contribution at each node in CMOS circuits with any number of stages.

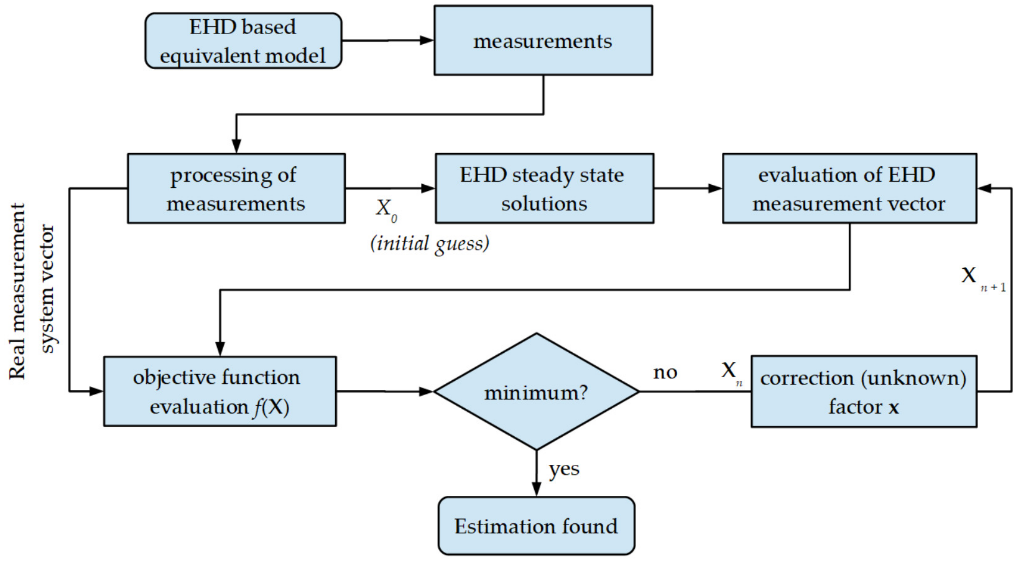

Figure 15. Harmonic estimation using extended harmonic domain algorithm.

Finite impulse response (FIR) harmonic estimators based on the Taylor signal model have gained attention for their ability to accurately estimate harmonic phasors in dynamic power systems [76]. However, these filters can introduce significant errors when the frequency deviates from the nominal value. A proposed solution in [77] involves the online calculation of Taylor weighted least squares (TWLS) to determine FIR filter bank coefficients and suggests a dynamic harmonic estimation algorithm by extending the symmetric TWLS algorithm to harmonic symmetric TWLS (HSTWLS). This algorithm aims to improve measurement accuracy at both nominal and off-nominal frequencies while reducing computational complexity. Based on the frequency-domain sampling theorem, a novel harmonic phasor estimator (HPE) is proposed in [77]. This HPE is compared with the Sinc interpolation function-based estimator (SIFE) [78] in terms of frequency response, model parameter selection scheme, and simulation tests. The proposed HPE has three advantages: a more manageable model parameter selection scheme, zero-error results under nominal frequency conditions, and higher accuracy under harmonic frequency deviations and modulation conditions.

Harmonic distortion in residential distribution systems is a growing concern for utility companies, but understanding the extent of the distortion is challenging due to a lack of monitoring infrastructure. To address this, ref. [79] proposes a solution for estimating harmonic distortions in residential distribution systems by introducing a probabilistic harmonic load flow (HLF) algorithm. This algorithm uses the network model provided by the utility and incorporates available harmonic measurements to reduce estimation uncertainty. Measurements are taken at several representative service transformers, and a unified harmonic model is developed for the secondary residential system. The layout of the residential network is shown in Figure 16 and a flowchart for the proposed harmonic model is shown in Figure 17.

The authors in [80] introduce an advanced frequency estimation algorithm that effectively compensates for the interference of harmonics using a new "harmonics interference decomposition model". In this model, the interference effect of harmonics is represented as the sum of two separate components: a deviation bias and an oscillatory disturbance. The deviation bias component includes only the uncoupled amplitude parameter terms, while the oscillatory disturbance component includes only the phase parameter coupled terms and represents the location of the power spectral peak. Adjustable speed drives (ASD), negatively impacting power quality in distribution networks by introducing harmonic distortions [81,82]. Ref. [83] presents a new mathematical model for determining the current harmonics that flow through the DC-link in ASD; conventional and slim dc link filter equivalent circuits are shown in Figure 18. The model takes into account precise voltage ripple measurements across the DC-link to calculate current harmonics on the load side of the ASD, and uses mathematical calculations to determine the current harmonics passing through the DC-link based on the load side currents.

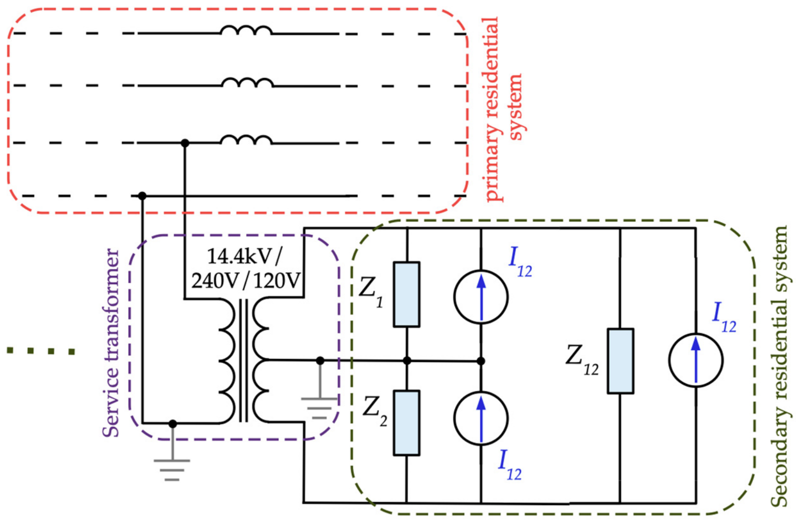

Figure 16. Secondary Residential System layout.

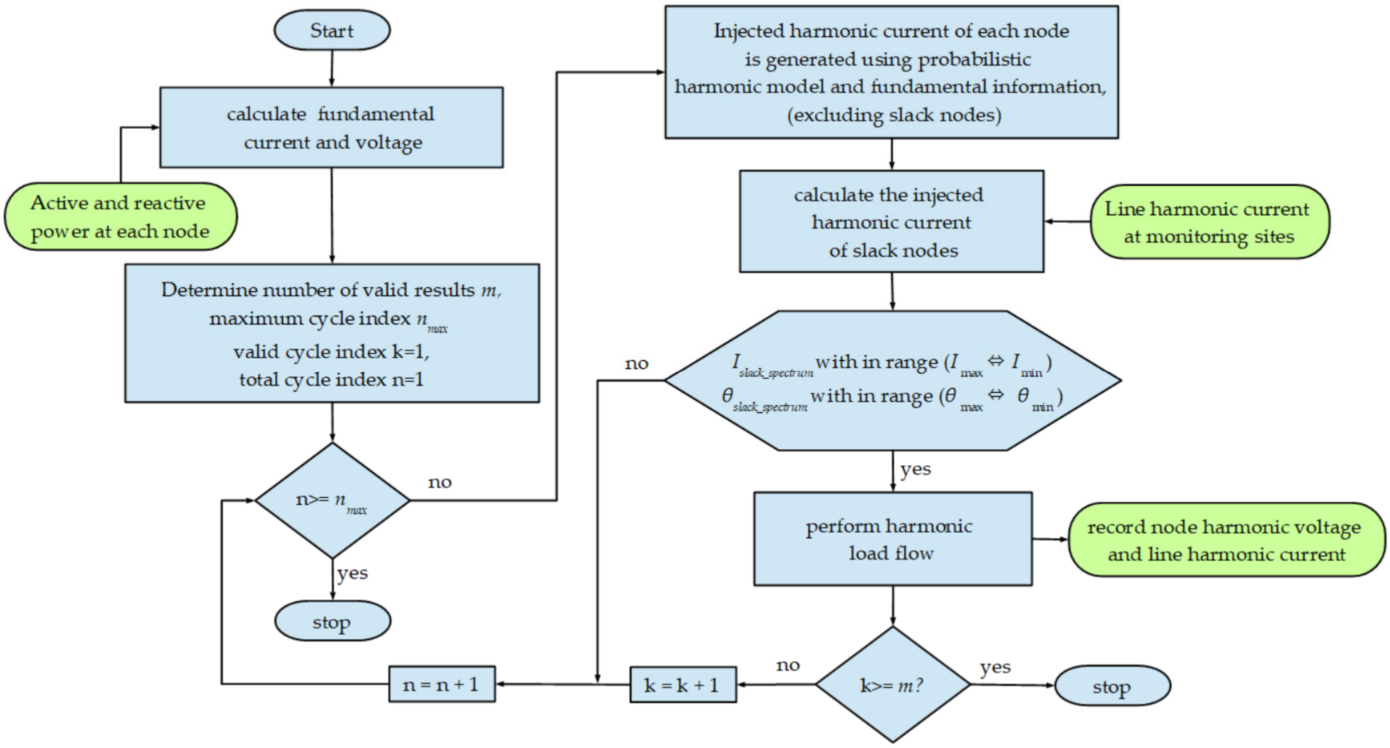

Figure 17. Proposed probabilistic harmonic flow using a single harmonic monitor.

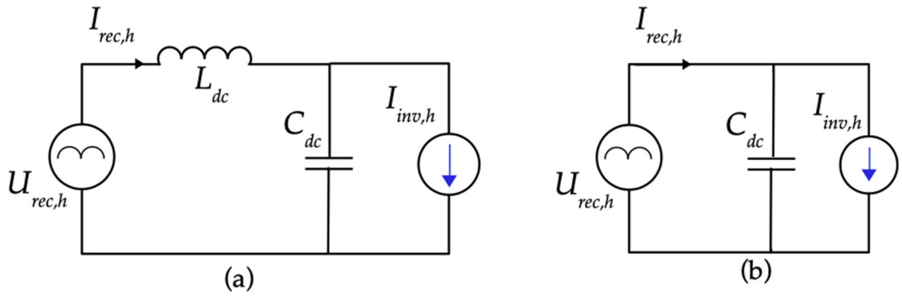

Figure 18. Simplified circuit of adjustable speed derive DC link when (**a**) conventional type (**b**) Slim DC-link capacitor (SDLC) type filter is employed.

The electric power grid is experiencing a growing presence of power converters, which can generate harmonic currents and voltages that negatively impact power quality and protection devices. One of the effective techniques for modeling converter harmonics is the frequency coupling matrix (FCM) [84], which can be obtained through experimental characterization or direct calculation using a converter's internal parameters. This study presents a new method for estimating FCMs and harmonic line admittances from network measurements. The researchers also introduce a novel harmonic reduction theorem that can calculate equivalent virtual FCMs for unobservable portions of a network [85]. The study [86] examines how grid impedance affects the FCM approach to model the harmonic generated by a three-phase variable frequency drive. It suggests a method to identify FCM elements when grid impedance is present. In FCM, with the increase in voltage harmonics orders increased admittance coefficients in the admittance matrix are increased in multiples. The FCM-based model uses a form of

$$I^*_{xFCM} = I^*_{x,Base} + U^*_y \, Y^*_{xy}$$

where x is the current harmonic order, y is the voltage harmonic order, and $I_{x,Base}$ is the response of fundamental harmonic in supply voltage; the total load current is the cumulative-sum of all harmonic currents, i.e., same-order and cross-order. Figure 19 shows the basic diagram of the based Harmonic load reaction model.

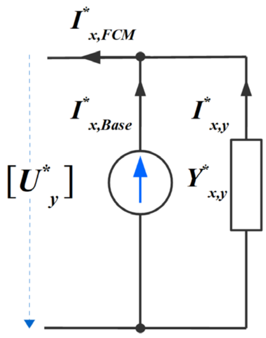

Figure 19. Harmonic load reaction FCM model.

Ref. [87] presents an experimental non-linear load assessment of the sensitivity of current harmonics to supply voltage harmonics. The proposed waveform variation definition model (WVDM) provides an in-depth coordination of actual load physical operation when the inter-order coupling between the supply voltage and the variations in the current harmonics occurs. The proposed model, shown in Figure 20, specifies how to implement the non-impedance relationship and the separate phase and size response components in the empirical results of the voltage-to-current harmonic variation relationship. Furthermore, the proposed model can provide a precise estimate of the cumulative influence of different power supply harmonics, including the most likely power supply harmonics in the residential network and the low-order strange harmonics. This model provides an excellent correlation of the harmonic voltage influence estimates on the harmonic levels of the measured load current, including phase and magnitude values.

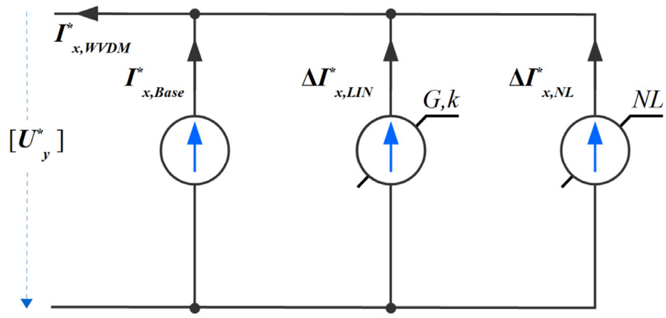

Figure 20. Schematic description of waveform variation defined model.

Recent research in harmonic estimation has focused on developing efficient and robust algorithms that can accurately estimate the harmonic content of a signal in the presence of noise and other distortions. Some popular harmonic estimation algorithms that have been widely used in recent research include the harmonic product spectrum (HPS) [88], the harmonic sum spectrum (HSS), and the iterative adaptive harmonic estimation (IAHE) algorithm [89,90]. The harmonic product spectrum (HPS) algorithm is a non-parametric method that estimates the harmonic content of a signal by multiplying the magnitude of the Fourier transform of the signal at different harmonic frequencies. The HPS method is relatively simple to implement and computationally efficient, but it can be sensitive to noise and other distortions.

The harmonic sum spectrum (HSS) algorithm is another non-parametric method that estimates the harmonic content of a signal by adding the magnitude of the Fourier transform of the signal at different harmonic frequencies. The HSS method is also relatively simple to implement and computationally efficient, but it can also be sensitive to noise and other distortions. The iterative adaptive harmonic estimation (IAHE) algorithm is a parametric method that estimates the harmonic content of a signal by fitting a harmonic model to the signal using an iterative optimization process. The IAHE algorithm is more computationally intensive than the HPS and HSS methods, but it can provide more accurate estimates of the harmonic content of a signal in the presence of noise and other distortions. The comparison of harmonic estimation methods is given in Table 4.

Table 4. Harmonic Estimation Methods.

Method	Ref.	Advantage	Disadvantage	Applications
Prony Method	[64]	Accurate in estimating harmonic parameters, effective in noisy environments	Requires high computational resources, not efficient for real-time use	Harmonic estimation in industrial converters
Min-Norm Method	[64]	Provides better accuracy than Fourier in some cases	Limited by its dependence on frequency precision	Harmonic detection in systems with precise frequency requirements
Adaptive Kalman Filter (AKF)	[65]	Adaptive, handles dynamic harmonic states, noise covariance is dynamic	Complex, high computational cost, can estimate limited harmonics	Dynamic systems with fluctuating grid voltage and harmonic distortion
Unscented Kalman Filter (UKF)	[66]	High accuracy in tracking grid waveform changes, handles frequency and amplitude variations.	Limited harmonic estimation capacity, computationally expensive	Unbalanced three-phase power systems with dynamic harmonic content

Table 4. *Cont.*

Method	Ref.	Advantage	Disadvantage	Applications
State-Estimation-Based Method	[69]	Eliminates need for expensive equipment, accurate even without synchronized measurements	May struggle with high-frequency harmonics, complex model tuning	Large-scale industrial power systems like iron and steel plants
Compressive Sensing Harmonics Detector (CSHD)	[72]	Efficient, reduces the number of necessary measurements	May be less effective in high variability environments	Identifying and estimating principal pollution sources in distribution grids
Taylor–Kalman–Fourier (TKF) Filter	[68]	Reduces total harmonic distortion (THD), accurate with dynamic components	Complexity in implementation, sensitive to tuning parameters	Estimating dynamic harmonic content in power systems
Flat-Top FIR Filter (Harmonic Phasor Estimation)	[76]	Accurate under nominal frequency conditions, computationally efficient	May produce errors under frequency deviations	Embedded systems with fixed harmonic frequencies
Time-Domain Harmonic Distortion Estimation	[75]	Compact modeling of harmonic distortion in circuits	Limited to specific circuit types	Estimating harmonic distortion in CMOS circuits
Dynamic Harmonic Phasor Estimation (HPE)	[81]	High accuracy with harmonic modulation, zero-error under nominal conditions	Complex mathematical modeling, limited flexibility	Systems with variable harmonic frequencies, improving estimation accuracy
Norton Coupled Model	[91]	Effective for estimating harmonics in nonlinear loads	Requires detailed component-level data	Nonlinear loads in distribution networks
Frequency Coupling Matrix (FCM) Model	[84–86]	Can estimate harmonic currents and voltages in complex systems, includes harmonic interactions	Sensitive to variations in grid impedance, complex parameter tuning	Harmonic analysis in AC/DC converters and multi-frequency grid systems
Fourier-based Estimation	[92]	Widely used, fast computations	Inaccurate for non-stationary signals	Stationary power systems with constant harmonics
Waveform Variation Defined Model (WVDM)	[87]	Models cross-order supply voltage harmonics influence, precise with low-order harmonics	Complex to implement, requires empirical validation	Estimating harmonic current emissions in residential systems
Harmonic Product Spectrum (HPS), Harmonic Sum Spectrum (HSS)	[88,89]	Simple to implement, computationally efficient	Sensitive to noise and distortions	Used in signal processing where speed is prioritized
Iterative Adaptive Harmonic Estimation (IAHE)	[89,90]	More accurate in noisy/distorted environments, robust in challenging conditions	Computationally intensive, more complex to implement	Suitable for accurate harmonic estimation in noisy conditions

Recent research has also focused on developing adaptive and robust harmonic estimation algorithms that can handle non-stationary and non-linear signals. In addition, other techniques, like time-frequency-based approaches and machine-learning-based approaches like neural networks, have also been used in recent research to improve the robustness and accuracy of harmonic estimation. In conclusion, harmonic estimation is a crucial task in power system fields, and recent research has focused on developing efficient and robust algorithms that can accurately estimate the harmonic content of a signal in the presence of noise and other distortions; it has also focused on developing an adaptive and robust model to improve the robustness and accuracy of harmonic estimation.

6. Conclusions

Harmonic detection, suppression, aggregation, and estimation are essential for managing harmonic content in modern power systems. The rise of non-linear devices, like electric vehicles and renewable energy sources, has significantly increased the risk of harmonic distortions, making advanced and adaptable methods necessary. Traditional techniques, such as Fourier and wavelet transforms, are foundational in harmonic detection, but newer methods like machine learning models and adaptive filters offer enhanced accuracy and flexibility, especially in handling dynamic and non-stationary conditions.

As power systems become more complex with the increased integration of renewable energy, the ability to control and suppress harmonics will be crucial for maintaining system reliability and efficiency. Hybrid filters, combining passive and active components, are an effective solution for mitigating the negative impacts of harmonics. These filters, along with real-time harmonic estimation techniques, are vital for adapting to the evolving grid conditions. In particular, active and adaptive filters are more flexible than passive filters, as they can adjust to changing harmonic conditions, making them more suitable for modern power grids.

Harmonic aggregation refers to the process of combining harmonic signals to represent the overall harmonic content in a system, often through techniques like the harmonic mean, geometric mean, or root mean square. Additionally, harmonic sensitivity—how a system responds to harmonic distortions—must be considered during power system design, as high distortion levels can damage equipment and reduce performance. Estimation techniques that are tailored to signal characteristics play a critical role in determining harmonic content.

Future efforts to manage harmonic content in low-voltage distribution networks must contend with the increasing complexity introduced by high-power, non-linear loads and distributed energy storage. This review emphasizes, the tools/techniques of harmonic assessment that can provide bases to enhance harmonic models by incorporating data from photovoltaic systems and battery storage, thus improving the network's adaptability to near-zero energy buildings and electric vehicle charging. Expanding harmonic estimation to include network impedance measurements across multiple frequencies would provide valuable insights into the effects of harmonics on system parameters. As the hosting capacity of power/distribution networks for renewable sources is a topic under extensive research presently, this harmonic review can offer a crucial basis for assessing policies and technology integration. Addressing harmonic sensitivity remains essential in managing increasingly complex grid conditions.

All in all, traditional and innovative techniques for harmonic detection, suppression, aggregation, sensitivity analysis, and estimation will continue to evolve, playing a central role in ensuring the stability and efficiency of power systems as they integrate more renewable energy sources. Future research should focus on refining these methods and their application in large-scale grids with diverse energy sources.

Author Contributions: Conceptualization, K.D. and M.N.I.; methodology, H.A.R. and N.S.; software, M.U.S. and M.N.I.; validation, K.D., M.N.I. and N.S.; formal analysis, K.D. and H.A.R.; investigation, N.S. and M.U.S.; resources, L.K. and K.D.; data curation, H.A.R. and M.N.I.; writing—original draft preparation, M.N.I. and K.D.; writing—review and editing, K.D. and N.S.; visualization, M.U.S. and H.A.R.; supervision, L.K. and N.S.; project administration, L.K. and M.N.I.; funding acquisition, L.K. and N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Estonian Research Council grant PRG2055, PSG142 and EU Commission through H2020 project FinEST Twins grant No. 856602.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Li, C.S.; Bai, Z.X.; Xiao, X.Y.; Liu, Y.M.; Zhang, Y. Research of Harmonic Distortion Power for Harmonic Source Detection. In Proceedings of the 2016 17th International Conference on Harmonics and Quality of Power (ICHQP), Belo Horizonte, Brazil, 16–19 October 2016; pp. 126–129. [CrossRef]
2. Iqbal, M.N.; Kütt, L.; Asad, B.; Shabbir, N.; Rasheed, I. Time-Dependent Variations in Current Harmonic Emission by LED Lamps in the Low-Voltage Network. *Electr. Eng.* **2021**, *103*, 1525–1539. [CrossRef]
3. Rakpenthai, C.; Uatrongjit, S.; Watson, N.R.; Premrudeepreechacharn, S. On Harmonic State Estimation of Power System with Uncertain Network Parameters. *IEEE Trans. Power Syst.* **2013**, *28*, 4829–4838. [CrossRef]
4. Yang, J.Z.; Yu, C.S.; Liu, C.W. A New Method for Power Signal Harmonic Analysis. *IEEE Trans. Power Deliv.* **2005**, *20*, 1235–1239. [CrossRef]
5. Frigo, G.; Derviskadic, A.; Pegoraro, P.A.; Muscas, C.; Paolone, M. Harmonic Phasor Measurements in Real-World PMU-Based Acquisitions. In Proceedings of the 2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Auckland, New Zealand, 20–23 May 2019. [CrossRef]
6. Wright, P.S.; Christensen, A.E.; Davis, P.N.; Lippert, T. Multiple-Site Amplitude and Phase Measurements of Harmonics for Analysis of Harmonic Propagation on Bornholm Island. *IEEE Trans. Instrum. Meas.* **2017**, *66*, 1176–1183. [CrossRef]
7. Sardar, M.U.; Vaimann, T.; Kutt, L.; Kallaste, A.; Asad, B.; Kudelina, K.; Akbar, S. Analysis of Common Mode and Rapidly Varying Voltage Profile on Stator Current Harmonics of an Inverter-Fed Induction Motor. In Proceedings of the 2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Online, 9–11 October 2023. [CrossRef]
8. Sardar, M.U.; Kütt, L.; Kudelina, K. Characterization of High-Frequency Impedance- Based Models for Transient Terminal Overvoltage Estimation in Cable-Fed Motor Drive Systems. In Proceedings of the 2024 International Conference on Electrical Machines (ICEM), Torino, Italy, 1–4 September 2024; pp. 1–7. [CrossRef]
9. Shabbir, N.; Kütt, L.; Jarkovoi, M.; Iqbal, M.N.; Rassõlkin, A.; Daniel, K. An Overview of Measurement Standards for Power Quality. *Agron. Res.* **2021**, *19*, 944–960. [CrossRef]
10. An, B.; Li, Y.; Liu, F.; Xie, B.; Hu, S.; Wang, P.; Zhang, Z.; Luo, L.; Cao, Y. An Asymmetrical Connection Balance Transformer-Based Hybrid Railway Power Conditioning System with Cost-Function Optimization. *IEEE Trans. Transp. Electrif.* **2018**, *4*, 577–590. [CrossRef]
11. Chen, J.; Hu, H.; Ge, Y.; Wang, K.; He, Z.Y. Techno-Economic Model-Based Capacity Design Approach for Railway Power Conditioner-Based Energy Storage System. *IEEE Trans. Ind. Electron.* **2022**, *69*, 4730–4741. [CrossRef]
12. Davis, E.J.; Emanuel, A.E.; Pileggi, D.J. Closure to Discussion of "Harmonic Pollution Metering: Theoretical Considerations". *IEEE Trans. Power Deliv.* **2000**, *15*, 1353–1354. [CrossRef]
13. Shabbir, N.; Kütt, L.; Asad, B.; Jawad, M.; Iqbal, M.N.; Daniel, K. Spectrum Analysis for Condition Monitoring and Fault Diagnosis of Ventilation Motor: A Case Study. *Energies* **2021**, *14*, 2001. [CrossRef]
14. Duffey, C.K.; Stratford, R.P. Update of Harmonic Standard IEEE-519—IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. *IEEE Ind. Appl. Soc.* **1989**, *25*, 1618–1624. [CrossRef]
15. Iqbal, M.N.; Kütt, L.; Daniel, K.; Shabbir, N.; Amjad, A.; Awan, A.W.; Ali, M. Inaccuracies and Uncertainties for Harmonic Estimation in Distribution Networks. *Sustainability* **2024**, *16*, 6523. [CrossRef]
16. Soares, V.; Verdelho, P.; Marques, G.D. An Instantaneous Active and Reactive Current Component Method for Active Filters. *IEEE Trans. Power Electron.* **2000**, *15*, 660–669. [CrossRef]
17. Baccarelli, P.; Burghignoli, P.; Frezza, F.; Galli, A.; Lampariello, P.; Lovat, G.; Paulotto, S.; Member, S.S.; Galli, A.; Lampariello, P.; et al. Fundamental Modal Properties of Surface Waves on Metamaterial Grounded Slabs. *IEEE Trans. Microw. Theory Tech.* **2005**, *53*, 1431–1441. [CrossRef]
18. Moeini, A.; Zhao, H.; Wang, S. A Current-Reference-Based Selective Harmonic Current Mitigation PWM Technique to Improve the Performance of Cascaded H-Bridge Multilevel Active Rectifiers. *IEEE Trans. Ind. Electron.* **2018**, *65*, 727–737. [CrossRef]
19. Wilkinson, W.A.; Cox, M.D. Discrete Wavelet Analysis of Power System Transients. *IEEE Trans. Power Syst.* **1996**, *11*, 2038–2044. [CrossRef]
20. Shabbir, N.; Kutt, L.; Jawad, M.; Iqbal, M.N.; Ghahfarokhi, P.S. Forecasting of Energy Consumption and Production Using Recurrent Neural Networks. *Adv. Electr. Electron. Eng.* **2020**, *18*, 190–197. [CrossRef]
21. Cichocki, A. Artificial Neural Networks for Real-Time Estimation of Basic Waveforms of Voltages and Currents. *IEEE Trans. Power Syst.* **1994**, *9*, 612–618. [CrossRef]
22. Hu, Y.; Zhu, Z.-Q.; Liu, K. Current Control for Dual Three-Phase Permanent Magnet Synchronous Motors Accounting for Current Unbalance and Harmonics. *IEEE J. Emerg. Sel. Top. Power Electron.* **2014**, *2*, 272–284. [CrossRef]
23. Gao, X.; Liao, L.-Z. A New One-Layer Neural Network for Linear and Quadratic Programming. *IEEE Trans. Neural Netw.* **2010**, *21*, 918–929. [CrossRef]
24. Zhu, X.; Shen, C.; Ren, X. Harmonic Detection Method Using APFFT and Neural Network. In Proceedings of the 2013 5th International Conference on Intelligent Human-Machine Systems and Cybernetics, Hangzhou, China, 26–27 August 2013. [CrossRef]

25. Hu, Y.; Shao, Y.; Yang, R.; Chen, G. Current Harmonic Suppression for Grid-Connected VSG Based on Virtual Harmonic Impedance. In Proceedings of the 2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019—ECCE Asia), Busan, Republic of Korea, 27–30 May 2019; Volume 3, pp. 2022–2026. [CrossRef]
26. Rong, S.; Xu, M.; Chen, X.; Liu, Z.; Su, H.; Li, H. Research on Optimal Virtual Impedance Harmonic Suppression Method for Grid-Connected Inverter. In Proceedings of the 2023 8th Asia Conference on Power and Electrical Engineering (ACPEE), Tianjin, China, 14–16 April 2023; pp. 585–591. [CrossRef]
27. Beres, R.N.; Wang, X.; Liserre, M.; Blaabjerg, F.; Bak, C.L. A Review of Passive Power Filters for Three-Phase Grid-Connected Voltage-Source Converters. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 54–69. [CrossRef]
28. Dekka, A.R.; Beig, A.R.; Poshtan, M. Comparison of Passive and Active Power Filters in Oil Drilling Rigs. In Proceedings of the 11th International Conference on Electrical Power Quality and Utilisation, Lisbon, Portugal, 17–19 October 2011; pp. 470–475. [CrossRef]
29. Shakeri, S.; Esmaeili, S.; Hossein, M.; Koochi, R. Passive Harmonic Filter Design Considering Voltage Sag Performance-Applicable to Large Industries. *IEEE Trans. Power Deliv.* **2022**, *37*, 1714–1722. [CrossRef]
30. Rizk, G.; Salameh, S.; Kanaan, H.Y.; Rachid, E.A. Design of Passive Power Filters for a Three-Phase Semi-Controlled Rectifier with Typical Loads. In Proceedings of the 2014 9th IEEE Conference on Industrial Electronics and Applications, Hangzhou, China, 9–11 June 2014; pp. 590–595. [CrossRef]
31. Kedra, B. Comparison of an Active and Hybrid Power Filter Devices. In Proceedings of the 2014 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest, Romania, 25–28 May 2014; pp. 556–560. [CrossRef]
32. Alhuwaishel, F.M.; Morsy, A.S.; Enjeti, P.N. A New Active Output Filter (AOF) for Variable Speed Constant Frequency (VSCF) Power System in Aerospace Applications. *IEEE Trans. Power Electron.* **2018**, *33*, 1087–1093. [CrossRef]
33. Wang, L.; Lam, C.S.; Wong, M.C. Unbalanced Control Strategy for a Thyristor-Controlled LC-Coupling Hybrid Active Power Filter in Three-Phase Three-Wire Systems. *IEEE Trans. Power Electron.* **2017**, *32*, 1056–1069. [CrossRef]
34. Grady, W.M.; Samotyj, M.J.; Noyola, A.H. Survey of Active Power Line Conditioning Mehtodologies. *IEEE Trans. Power Deliv.* **1990**, *5*, 1536–1542. [CrossRef]
35. El-Habrouk, M.; Darwish, M.K.; Mehta, P. Active Power Filters: A Review. *IEEE Proc. Electric Power Appl.* **2000**, *147*, 403–413. [CrossRef]
36. Xie, N.; Xu, Q.; Zeng, J.; Liu, X.; Zhang, W.; Zhang, C. Noval Hybrid Control Method for APF Based on PI and FRC. *J. Eng.* **2019**, *2019*, 3002–3006. [CrossRef]
37. Kim, S.; Enjeti, P.N. A New Hybrid Active Power Filter (APF) Topology. *IEEE Trans. Power Electron.* **2002**, *17*, 48–54. [CrossRef]
38. Chen, Z.; Blaabjerg, F.; Pedersen, J.K. A Hybrid Compensation System with an Active Filter and Distributed Passive Filters in Power Systems with Dispersed Generation. In Proceedings of the IEEE 34th Annual Conference on Power Electronics Specialist, Acapulco, Mexico, 15–19 June 2003; Volume 2, pp. 767–772. [CrossRef]
39. Peng, F.Z.; Akagi, H.; Nabae, A. A New Approach to Harmonic Compensation in Power Systems A Combined System of Shunt Passive and Series Active Filters. *IEEE Trans. Ind. Appl.* **1990**, *26*, 983–989. [CrossRef]
40. Chen, Z.; Geng, X.; Yin, F. A Harmonic Suppression Method Based on Fractional Lower Order Statistics for Power System. *IEEE Trans. Ind. Electron.* **2016**, *63*, 3745–3755. [CrossRef]
41. Chan, K. Technical and Performance Aspects of a Dynamic Voltage Restorer. In Proceedings of the IEE Half Day Colloquium on Dynamic Voltage Restorers—Replacing Those Missing Cycles (Digest No. 1998/189), Glasgow, UK, 11 February 1998. [CrossRef]
42. Tu, C.; Guo, Q.; Jiang, F.; Chen, C.; Li, X.; Xiao, F.; Gao, J. Dynamic Voltage Restorer With an Improved Strategy to Voltage Sag Compensation and Energy Self-Recovery. *CPSS Trans. Power Electron. Appl.* **2019**, *4*, 219–229. [CrossRef]
43. Daniel, K.; Kütt, L.; Iqbal, M.N.; Shabbir, N.; Ur Rehman, A.; Shafiq, M.; Hamam, H. Current Harmonic Aggregation Cases for Contemporary Loads. *Energies* **2022**, *15*, 437. [CrossRef]
44. Medeiros, F.; Brasil, D.C.; Marques, C.A.G.; Duque, C.A.; Ribeiro, P.F. Considerations on the Aggregation of Harmonics Produced by Large Wind Farms. In Proceedings of the 2012 IEEE 15th International Conference on Harmonics and Quality of Power, Hong Kong, China, 17–20 June 2012; pp. 364–369. [CrossRef]
45. *IEC 61400-21-1:2019*; Wind Energy Generation Systems: Measurement & Electrical Characteristics—Wind Turbines. IEC International Electrotechnical Commission: Geneva, Switzerland, 2019.
46. David, J.; Robinson, D.; Elphick, S. Aggregation of Multiple Inverter-Based Harmonic Sources within a Renewable Energy Generation Plant. In Proceedings of the 2022 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 29 May–1 June 2022; pp. 1–6. [CrossRef]
47. Collin, A.J.; Cresswell, C.E.; Djokić, S.Ž. Harmonic Cancellation of Modern Switch-Mode Power Supply Load. In Proceedings of the 14th International Conference on Harmonics and Quality of Power—ICHQP 2010, Bergamo, Italy, 26–29 September 2010. [CrossRef]
48. Larose, C.; Gagnon, R.; Prud'Homme, P.; Fecteau, M.; Asmine, M. Type-III Wind Power Plant Harmonic Emissions: Field Measurements and Aggregation Guidelines for Adequate Representation of Harmonics. *IEEE Trans. Sustain. Energy* **2013**, *4*, 797–804. [CrossRef]
49. Yang, K.; Bollen, M.H.J.; Larsson, E.O.A. Wind Power Harmonic Aggregation of Multiple Turbines in Power Bins. In Proceedings of the 2014 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest, Romania, 25–28 May 2014; pp. 723–727. [CrossRef]

50. Blanco, A.M.; Meyer, J.; Schegner, P. Aggregation Characteristic of Low-Order Harmonic Currents in Residential Low-Voltage Networks. In Proceedings of the 2017 IEEE Manchester PowerTech, Powertech, Manchester, UK, 18–22 June 2017; pp. 1–6. [CrossRef]
51. Blanco, A.M.; Yanchenko, S.; Meyer, J.; Schegner, P. The Impact of Supply Voltage Distortion on the Harmonic Current Emission of Non-Linear Loads. *DYNA* **2015**, *82*, 150–159. [CrossRef]
52. Iqbal, M.N.N.; Lauri, K.; Kütt, L.; Asad, B.; Shabbir, N. Impact of Cable Impedance on the Harmonic Emission of LED Lamps. In Proceedings of the 2020 21st International Scientific Conference on Electric Power Engineering (EPE), Prague, Czech Republic, 19–21 October 2020; pp. 1–6. [CrossRef]
53. Naveed Iqbal, M.; Jarkovoi, M.; Kutt, L.; Shabbir, N. Impact of LED Thermal Stability to Household Lighting Harmonic Load Current Modeling. In Proceedings of the 2019 Electric Power Quality and Supply Reliability Conference (PQ) & 2019 Symposium on Electrical Engineering and Mechatronics (SEEM), Kärdla, Estonia, 12–15 June 2019. [CrossRef]
54. Jarkovoi, M.; Naveed Iqbal, M.; Kutt, L. Analysis of Harmonic Current Stability and Summation of LED Lamps. In Proceedings of the 2019 Electric Power Quality and Supply Reliability Conference (PQ) & 2019 Symposium on Electrical Engineering and Mechatronics (SEEM), Kärdla, Estonia, 12–15 June 2019; pp. 1–8. [CrossRef]
55. *IEC 61000-4-30*; 2003 Electromagnetic Compatibility (EMC) Part 4-30: Testing and Measurement Techniques Power Quality Measurement Methods. IEC International Electrotechnical Commission: Geneva, Switzerland, 2003.
56. Peterson, B.; Blanco, A.M.; Rens, J.; Meyer, J.; Botha, G.; Desmet, J. Impact of Aggregation Interval on Harmonic Phase Angle Measurements. In Proceedings of the 2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS), Bologna, Italy, 26–28 September 2018; pp. 1–6. [CrossRef]
57. Foskolos, G.; Lundengard, K. The Impact of Aggregation Interval on Current Harmonic Simulation of Aggregated Electric Vehicle Loads. In Proceedings of the 2020 19th International Conference on Harmonics and Quality of Power (ICHQP), Dubai, United Arab Emirates, 6–7 July 2020. [CrossRef]
58. Lennerhag, O.; Bollen, M.H.J. A Stochastic Aggregate Harmonic Load Model. *IEEE Trans. Power Deliv.* **2020**, *35*, 2127–2135. [CrossRef]
59. Trelles-Molina, D.; Rosado-Romero, R.A.; Ortuno-Gonzalez, D.A.; Fernandez, E. Extension on IEC 61000-3-6's General Summation Law to Estimate Harmonic Current at PCC Based on Probability Distribution. *IEEE Lett. Electromagn. Compat. Pract. Appl.* **2022**, *4*, 36–39. [CrossRef]
60. Morfi, V.; Degottex, G.; Mouchtaris, A. A Computationally Efficient Refinement of the Fundamental Frequency Estimate for the Adaptive Harmonic Model. In Proceedings of the 2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Florence, Italy, 4–9 May 2014; pp. 1478–1482. [CrossRef]
61. Olga, P.; Alexey, P.; Natalia, S. Application of Parametric DFT in Cepstral Method for Scales Bases Identification. In Proceedings of the 2020 22th International Conference on Digital Signal Processing and its Applications (DSPA), Moscow, Russia, 25–27 March 2020. [CrossRef]
62. Taghvaie, A.; Warnakulasuriya, T.; Kumar, D.; Zare, F.; Sharma, R.; Vilathgamuwa, D.M. A Comprehensive Review of Harmonic Issues and Estimation Techniques in Power System Networks Based on Traditional and Artificial Intelligence/Machine Learning. *IEEE Access* **2023**, *11*, 31417–31442. [CrossRef]
63. de Oliveira, R.A.; Bollen, M.H.J. Deep Learning for Power Quality. *Electr. Power Syst. Res.* **2023**, *214*, 108887. [CrossRef]
64. Lobos, T.; Leonowicz, Z.; Rezmer, J. Harmonics and Interharmonics Estimation Using Advanced Signal Processing Methods. In Proceedings of the Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441), Orlando, FL, USA, 1–4 October 2000; Volume 1, pp. 335–340. [CrossRef]
65. Yu, K.K.C.; Watson, N.R.; Arrillaga, J. An Adaptive Kalman Filter for Dynamic Harmonic State Estimation and Harmonic Injection Tracking. *IEEE Trans. Power Deliv.* **2005**, *20*, 1577–1584. [CrossRef]
66. Wu, C.; Magaña, M.E.; Cotilla-Sánchez, E. Dynamic Frequency and Amplitude Estimation for Three-Phase Unbalanced Power Systems Using the Unscented Kalman Filter. *IEEE Trans. Instrum. Meas.* **2019**, *68*, 3387–3395. [CrossRef]
67. Zhou, N.; Wang, J.; Wang, Q.; Wei, N. Measurement-Based Harmonic Modeling of an Electric Vehicle Charging Station Using a Three-Phase Uncontrolled Rectifier. *IEEE Trans. Smart Grid* **2015**, *6*, 1332–1340. [CrossRef]
68. Rodriguez Maldonado, J. Total Harmonic Distortion Estimation, Minimization Inter Harmonic Amplitude and Expanding Bands Rejection in TKF Filters. *IEEE Lat. Am. Trans.* **2016**, *14*, 652–656. [CrossRef]
69. Sezgin, E.; Göl, M.; Salor, Ö. State-Estimation-Based Determination of Harmonic Current Contributions of Iron and Steel Plants Supplied from PCC. *IEEE Trans. Ind. Appl.* **2016**, *52*, 2654–2663. [CrossRef]
70. Dai, Z.; Lin, W.; Lin, H. Estimation of Single-Phase Grid Voltage Parameters with Zero Steady-State Error. *IEEE Trans. Power Electron.* **2016**, *31*, 3867–3879. [CrossRef]
71. Dai, Z.; Lin, W. Adaptive Estimation of Three-Phase Grid Voltage Parameters under Unbalanced Faults and Harmonic Disturbances. *IEEE Trans. Power Electron.* **2017**, *32*, 5613–5627. [CrossRef]
72. Carta, D.; Muscas, C.; Pegoraro, P.A.; Sulis, S. Identification and Estimation of Harmonic Sources Based on Compressive Sensing. *IEEE Trans. Instrum. Meas.* **2019**, *68*, 95–104. [CrossRef]
73. Esparza, M.; Segundo, J.; Gurrola-Corral, C.; Visairo-Cruz, N.; Barcenas, E.; Barocio, E. Parameter Estimation of a Grid-Connected VSC Using the Extended Harmonic Domain. *IEEE Trans. Ind. Electron.* **2019**, *66*, 6044–6054. [CrossRef]

74. Dobrovolný, P.; Vandersteen, G.; Wambacq, P.; Donnay, S. Analysis and Compact Behavioral Modeling of Nonlinear Distortion in Analog Communication Circuits. *IEEE Trans. Comput. Des. Integr. Circuits Syst.* **2003**, *22*, 1215–1227. [CrossRef]
75. Baxevanakis, D.; Sotiriadis, P.P. A General Time-Domain Method for Harmonic Distortion Estimation in CMOS Circuits. *IEEE Trans. Comput. Des. Integr. Circuits Syst.* **2021**, *40*, 157–170. [CrossRef]
76. Platas-Garza, M.A.; De La O Serna, J.A. Dynamic Phasor and Frequency Estimates through Maximally Flat Differentiators. *IEEE Trans. Instrum. Meas.* **2010**, *59*, 1803–1811. [CrossRef]
77. Zecevic, Z.; Krstajic, B. Dynamic Harmonic Phasor Estimation by Adaptive Taylor-Based Bandpass Filter. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 6500509. [CrossRef]
78. Chen, L.; Zhao, W.; Wang, Q.; Wang, F.; Huang, S. Dynamic Harmonic Synchrophasor Estimator Based on Sinc Interpolation Functions. *IEEE Trans. Instrum. Meas.* **2019**, *68*, 3054–3065. [CrossRef]
79. Xiao, X.; Li, Z.; Wang, Y.; Zhou, Y. A Practical Approach to Estimate Harmonic Distortions in Residential Distribution System. *IEEE Trans. Power Deliv.* **2021**, *36*, 1418–1427. [CrossRef]
80. Son, K.J.; An, G.S.; Nam, K.D.; Chang, T.G. An Advanced Frequency Estimation Algorithm Based on Analytic Compensation of Effects of Dominant Harmonic in Power Systems. *IEEE Access* **2021**, *9*, 146568–146577. [CrossRef]
81. Yaghoobi, J.; Zare, F.; Rehman, T.; Rathnayake, H. Analysis of High Frequency Harmonics in Distribution Networks: 9-150 KHz. In Proceedings of the 2019 IEEE International Conference on Industrial Technology (ICIT), Melbourne, VIC, Australia, 13–15 February 2019; pp. 1229–1234. [CrossRef]
82. Rathnayake, H.; Khajeh, K.G.; Zare, F.; Sharma, R. Harmonic Analysis of Grid-Tied Active Front End Inverters for the Frequency Range of 0-9 Khz in Distribution Networks: Addressing Future Regulations. In Proceedings of the 2019 IEEE International Conference on Industrial Technology (ICIT), Melbourne, VIC, Australia, 13–15 February 2019; pp. 446–451. [CrossRef]
83. Moradi, A.; Yaghoobi, J.; Zare, F. A Precise Model of DC-Link Current in Adjustable Speed Drives for the Harmonic Analysis of Electrical Networks. *IEEE Access* **2022**, *10*, 45663–45676. [CrossRef]
84. Sun, Y.; Zhang, G.; Xu, W.; Mayordomo, J.G. A Harmonically Coupled Admittance Matrix Model for AC/DC Converters. *IEEE Trans. Power Syst.* **2007**, *22*, 1574–1582. [CrossRef]
85. Savoor, R.; Meier-Hellstern, K. Estimating the Frequency Coupling Matrix From Network Measurements. *IEEE Trans. Control Netw. Syst.* **2020**, *7*, 353–388. [CrossRef]
86. Yadav, J.; Vasudevan, K.; Meyer, J.; Kumar, D. Frequency Coupling Matrix Model of a Three-Phase Variable Frequency Drive. *IEEE Trans. Ind. Appl.* **2022**, *58*, 3652–3663. [CrossRef]
87. Daniel, K.; Kütt, L.; Iqbal, M.N.; Shabbir, N.; Parker, M.; Jarkovoi, M. Waveform Variation Defined Model for Harmonic Current Emissions Including Cross-Order Supply Voltage Harmonics Influence. *IEEE Access* **2023**, *11*, 42276–42289. [CrossRef]
88. Yi, C.; Wang, H.; Zhou, Q.; Hu, Q.; Zhou, P.; Lin, J. An Adaptive Harmonic Product Spectrum for Rotating Machinery Fault Diagnosis. *IEEE Trans. Instrum. Meas.* **2023**, *72*, 3500612.
89. Bi, G.; Zhang, G.; Wang, G.; Wang, Q.; Hu, Y.; Xu, D. Adaptive Iterative Learning Control-Based Rotor Position Harmonic Error Suppression Method for Sensorless PMSM Drives. *IEEE Trans. Ind. Electron.* **2022**, *69*, 10870–10881. [CrossRef]
90. Sun, W.; So, H.C.; Chen, Y.; Huang, L.T.; Huang, L. Approximate Subspace-Based Iterative Adaptive Approach for Fast Two-Dimensional Spectral Estimation. *IEEE Trans. Signal Process.* **2014**, *62*, 3220–3231. [CrossRef]
91. Iqbal, M.N.; Kütt, L.; Daniel, K.; Jarkovoi, M.; Asad, B.; Shabbir, N. Bivariate Stochastic Model of Current Harmonic Analysis in the Low Voltage Distribution Grid. *Proc. Est. Acad. Sci.* **2021**, *70*, 190–206. [CrossRef]
92. Iqbal, M.N.; Kutt, L.; Shabbir, N.; Asad, B. Comparison of Current Harmonic Emission by Different Lighting Technologies. In Proceedings of the 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 5–7 November 2020; pp. 1–5. [CrossRef]