

Harmonic Distortion in Renewable Integrated Power Systems: Impacts, Standards, and Control Approaches

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ABSTRACT

The integration of renewable energy sources (RES) including solar photovoltaic, wind energy, and small hydro systems into modern power networks offers compelling environmental and economic benefits. However, this transition also introduces significant power quality challenges, particularly in the form of harmonic distortions. Unlike conventional synchronous generators, RES interfaced through power electronic converters exhibit nonlinear and switching behavior, altering the harmonic landscape of the grid. This review provides a comprehensive evaluation of harmonic generation, propagation, and mitigation in RES-dominated power systems. It systematically classifies the harmonic contributions of different RES technologies, analyzes their interaction with grid impedance, and examines advanced inverter control strategies that influence harmonic behavior. Additionally, it explores global standards and grid code requirements such as IEEE 519-2014 and assesses emerging harmonic mitigation techniques. To support analysis, this study includes simplified measurement setups, mitigation frameworks, comparative tables, and illustrative figures. This work aims to guide engineers, researchers, and policymakers in achieving harmonic compliance and maintaining power quality in the evolving landscape of converter-dominated grids.

Keywords: Grid code compliance, IEEE 519-2014, Inverter harmonics, Power electronics, Renewable energy sources, Smart grid.

1. INTRODUCTION

The incorporation of renewable energy sources (RES) into contemporary power networks has increased due to the rising need for clean and sustainable energy on a worldwide scale. The advantages of switching to RES for the environment, energy security, and long-term cost effectiveness have been emphasized in a number of studies [1-3]. In order to battle climate change and reduce greenhouse gas emissions, nations all over the world are implementing more ambitious renewable energy regulations. Consequently, during the past 20 years, the proportion of RES in the generation of power worldwide has grown dramatically. Understanding and researching the existing RES technologies such as solar, hydel, wind, bio, geothermal, and hydrogen energy is the goal of a review presented in [4]. To increase the overall effectiveness of RES in producing power, a number of hybrid RES technologies have been investigated and contrasted in this study. A thorough analysis of the incorporation of RES into EV charging infrastructure is provided in a study [5], which tackles the pressing issues of lowering carbon emissions and lowering reliance on fossil fuels in the transportation industry. In terms of renewable resources and technology, [6] reviews and summarizes solar energy,

heating and cooling, wind and wave power resource evaluation, renewable energy fuels, and integrated energy systems. In order to maximize availability utilizing RES and minimize operating costs and pollution emissions, a new energy optimization model is proposed in [7] to maximize the performance of the smart micro grid (MG). The study presented in [8] focuses on electricity consumption and aims to present the current energy mix, the status of RES, and a scenario-based projection of energy consumption across all energy types in Slovenia up to 2050. It also evaluates energy demand in key sectors like industry, transportation, residential, and services under various development scenarios, while highlighting the potential impact of RES deployment. It is anticipated that energy consumption in the industrial sector would continue to rise. The study presented in [9] discusses the economic benefits and environmental impacts of RES, highlighting their role in sustainable development and strategies to optimize their use. Ocean thermal, solar photovoltaic, wind, biomass, geothermal, hydro-power, tidal, ocean current, oceanic wave, ocean thermal, and osmotic effects are all taken into consideration in this research [10], which analyzes the environmental implications of RES based power plants. A successful energy transition is greatly aided by green hydrogen, or hydrogen produced from RES, as discussed in [11]. For steady operation and control of the power system integrated with RES under random minor load disturbances, a sophisticated, intelligent, and reliable automated generation control scheme is necessary, as explained in [12]. Presenting Poland's RES sector's current state against the backdrop of global development trends is the primary goal of the study suggested in [13].

Maintaining power quality has become a top priority for utilities and grid operators as the use of renewable energy grows. Due to their ability to alter voltage and current waveform, which can result in equipment failures and higher system losses, harmonics

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are one of the most important power quality problems [14-15]. Nonlinear loads and power electronic converters, which are widely utilized in renewable energy systems, are the primary sources of harmonics. A key consideration in analyzing the adverse effects of harmonic currents is the variation in harmonic content caused by the summation and cancellation effects in the total current drawn from the grid by nonlinear loads. The experimental tests in [16] demonstrate that the harmonic currents generated by various nonlinear load types tend to reduce the current total harmonic distortion (THD) factor. Due to the extensive usage of nonlinear loads, power quality is a significant challenge for practical MG applications. It is illustrated by the inherent trade-off between harmonic current sharing across distributed generators and voltage quality in the MG nodes [17]. To reduce harmonics and enhance power quality, the study in [18] employs a distribution static compensator. Its effectiveness in a solar-powered grid is evaluated by comparing it with other methods reported in the literature. To reduce the third harmonic component in the input current of the power factor corrector circuit in electric car charging systems, a study presented in [19] introduces a unique active compensation-based harmonic reduction approach. Through an in-depth harmonic study of the impacts of voltage harmonics and voltage unbalance in three 0.75-kW electric motor classes (IE2, IE3, and IE4), the study presented in [20] compares energy efficiency improvement with the associated power quality loss. The findings indicate that in the higher efficiency electric motors sample under analysis, other harmonics also increase as the percentage of a particular harmonic distortion increases. Similar responses are noted for high percentages of voltage unbalance, primarily in the line-start permanent magnet motor class IE4. The issue of appropriate power quality measures for DC grids is addressed in a study presented in [21]. Low and medium voltage applications include electric automobiles, distributed generation and MG's, all electric ships and airplanes, electric transporters, and contemporary data centers. The interval type-II fuzzy logic controlled distribution static compensator, a novel method for improving power quality in sensitive local distribution grids, outperforms type I fuzzy logic controllers and conventional PI controllers in terms of harmonic mitigation is presented in [22]. A study presented in [23] uses the optimization capabilities of the Cuckoo search algorithm based on swarm intelligence to examine parameter estimation of the power system harmonics. A detailed performance evaluation is carried out for various signal to noise ratios, particle sizes, and generations. The study presented in [24] proposes an objective function for joint amplitude and phase estimation of inter- and sub-harmonics to improve harmonic mitigation and reduce their adverse effects on power electronics and grid-connected equipment.

Renewable energy systems, in particular inverter-based technologies, have been found to be significant contributors to harmonic distortion in power networks. These systems frequently use power electronic converters, which cause nonlinear behaviors in the grid due to their high frequency switching. Complex resonance condition can arise from the interplay between these harmonics and grid impedance, particularly in weak or islanded networks. As a result, the stability, compliance, and power quality of RES dominated systems have become seriously questioned. In order to estimate and measure the harmonic emissions from the RES components, an analytical method is presented in [25]. The analysis of the harmonics produced by RES intermittent integration of wind and solar power systems in the MG distribution power network is the main goal of a study presented in [26]. In the form of an AC/DC hybrid micro grid (HMG), distributed energy is being rapidly linked to the grid due to advances on both the power supply and

load sides, as well as breakthroughs in power electronics devices. The development will lead to new design challenges for the micro-grid control unit, new needs for the simulation testing laboratory, and a significant change in the network architecture. For HMG to maintain power balance and voltage stability between the AC and DC grids, a bidirectional AC DC converter is required according to a study presented in [27]. The integration of RES with the grid causes power quality problems, which are covered in a study presented in [28]. These problems affect the grid by causing voltage swell, sag, and harmonic distortion, which affects consumers. For voltage regulation and neutral current compensation, a study in [29] presents an analytical method for reactive power control and fair active power restriction. Each photovoltaic (PV) inverter phase is separately controlled to maintain the required power quality. Inverter-based wind turbines, due to their low inertia and reliance on communication networks, pose challenges for frequency stability, which are mitigated in [30] by a virtual damping method that significantly improves frequency deviation up to 67% and a 62% improvement in damping speed compared to conventional approaches. By combining the advantages of multilevel converters (MLC) with Internet of Things (IoT) technologies, this study in [31] suggests a way to address harmonics issues. Using IoT device data sharing capabilities, the suggested space vector modulation control approach enhances MLC performance and monitoring, resulting in more accurate control and simpler problem discovery. Furthermore, remote monitoring, control, and diagnostics are made possible via the IoT platform, which enhances the functionality of RES. The primary concept of [32] is to use a combined technique of analysis based on a lucrative divide and conquer strategy to enhance the performance of existing methods; the approach ensures the optimal compromise between accuracy and processing effort. Study presented in [33] suggests an efficient grey wolf optimization based scheme for maximizing the power quality of grid connected hybrid power systems that combine wind and solar photovoltaic electricity under various fault and unbalanced conditions.

Primary objectives of the proposed study are:

- To examine and classify the harmonic sources that different RES bring into power networks.
- To examine how power electronic converters contribute to harmonic distortion while integrating RES.
- To look at how grid characteristics and harmonics interact, particularly in weak or islanded power systems.
- To examine how various RES technologies affect power quality indicators, such as THD.
- To investigate the suitability of current harmonic mitigation strategies for RES integrated grids.
- To list important research gaps and suggest future lines of inquiry for harmonic management in power networks with a lot of renewable energy.

The survey's main points are graphically summarized in Figure 1, which also shows how different RES like solar, wind, and small hydro contribute to power system harmonics via power electronic interfaces. It gives a succinct summary of the survey's future directions and subject organization while also illuminating the relationship between mitigation techniques and grid impedance.

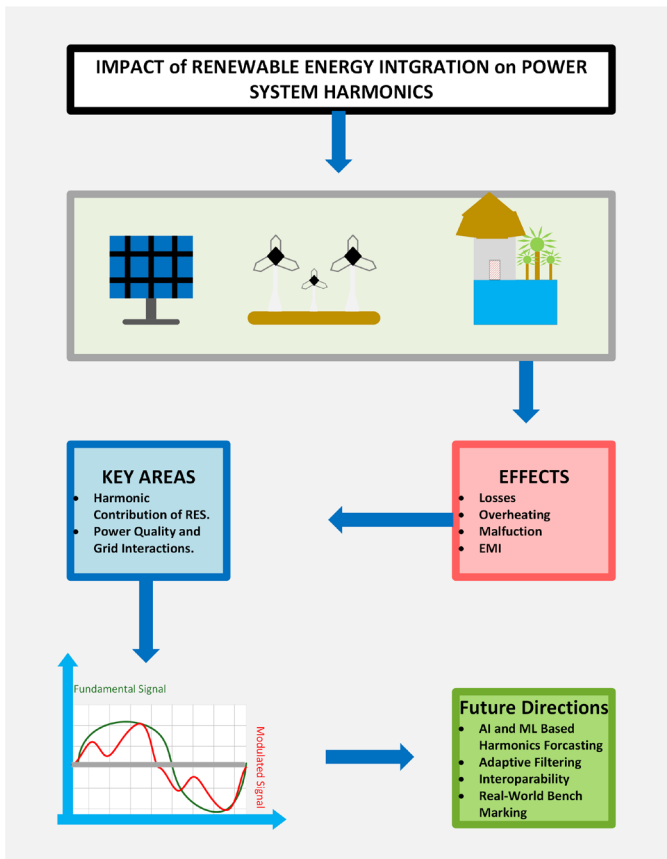


Fig. 1 Graphical Abstract of Proposed Study.

Section 2 presents in-depth description of power system harmonics. Section 3 discusses the contribution of RES to harmonics. Section 4 addresses the interaction with the grid and system impedance. Section 5 covers the measurement, monitoring, and analysis techniques. Section 6 outlines the standards and grid codes for harmonic control. Section 7 presents harmonic mitigation techniques in RES. Section 8 discusses case studies and real world impacts. Section 9 concludes the proposed study, and section 10 highlights future directions.

2. POWER SYSTEM HARMONICS

In power systems, waveform of voltage or current that diverge from the basic sinusoidal frequency because of the existence of integer multiples of fundamental frequency are referred to as harmonics. Nonlinear loads and switching devices, which introduce higher frequency components into the network, are usually the source of these distortions. Analyzing harmonics effects on power quality and system stability requires an understanding of their origin and behavior.

Waveform distortions that depart from the ideal sinusoidal shape are known as harmonics, and they are usually caused by the superposition of many frequency components. The basic waveform, its modulated version, and a few chosen harmonic components the third, fifth, and seventh orders are shown graphically in Figure 2. This pictorial representation shows how each harmonic affects waveform distortion, a major issue in power quality analysis for renewable integrated systems.

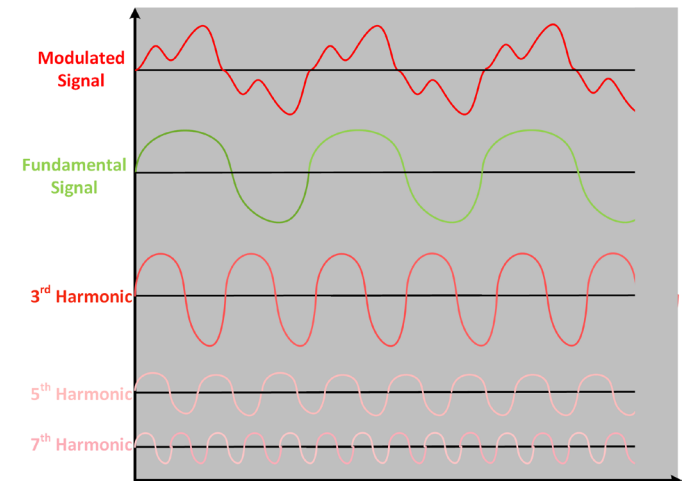


Fig. 2 Harmonic in of an AC Signal with Modulated and Fundamental Components

2.1 Fundamentals of Power System Harmonics

A periodic waveform’s harmonics are sinusoidal elements that appear at integer or non-integer multiples of the fundamental frequency. Non-linear loads and power electronic devices in the system are the main causes of harmonics. According to their sequence and behavior, harmonics can be roughly divided into a number of categories.

Following the types of harmonics;

- Odd harmonics: third, fifth, seventh, and so forth.
- Even harmonics (second, fourth, etc.; often uncommon).
- Triplen harmonics, or multiples of three, are especially troublesome in three-phase systems.
- Inter-harmonics, are non-integer multiples and these are often caused by frequency converters.
- Sub-harmonics are less common but crucial; they are frequencies lower than the fundamental.

Based on their origin and frequency order, the different kinds of harmonics may be divided into several categories mentioned above. Regarding waveform distortion, heating, and stability problems, each kind has a distinct impact on the power system. A brief description of the harmonics that are frequently found in power systems, as well as their usual origins and related effects, is given in Table 1.

Table 1 Classification of Harmonics in Power Systems

Harmonic Type	Order	Example Source	Impact on System
Odd harmonics	3rd, 5th, 7th, so on	Inverters, Nonlinear loads	Heating, Waveform distortion
Even harmonics	2nd, 4th, etc.	Asymmetrical loads	Voltage waveform shift
Triplen harmonics	3rd, 9th, 15th, etc.	Single-phase nonlinear loads in 3-phase	Neutral conductor overloading
Inter-harmonics	Non-integer multiples	Frequency converters, Cycloconverters	Flicker, Control malfunction
Subharmonics	< Fundamental	Motor drives, Arc furnaces	Oscillations, Resonance

2.2 Sources of harmonics in traditional and RES based systems

In conventional power systems, nonlinear loads including variable frequency motors, rectifiers, and arc furnaces are the main source of harmonics. Other harmonic sources have surfaced as RES integration has increased, especially from inverter based systems like wind turbines and solar photovoltaics. Power electronic converters, whose fast switching processes provide intricate harmonic profiles to the grid, are a major component of these systems.

Traditional power systems and those that incorporate RES, have different harmonic generating methods. While RES based systems generate harmonics through power electronic interfaces like inverters and converters, conventional systems mainly produce harmonics through nonlinear industrial loads, as seen in Figure 3.

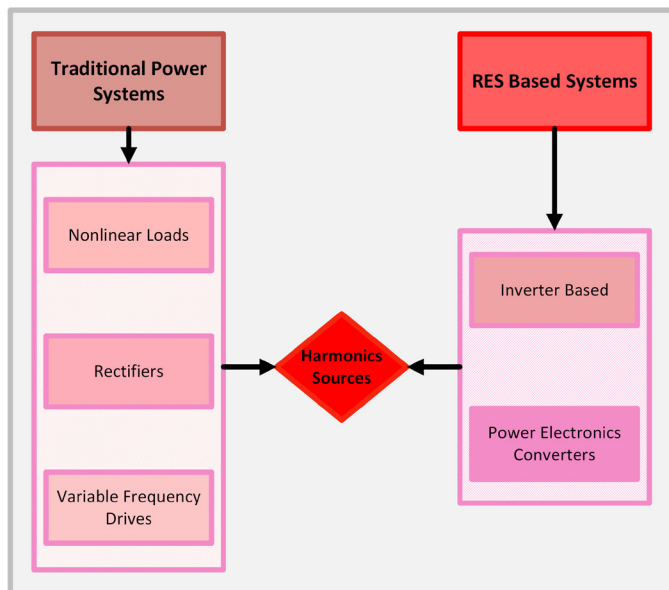


Fig. 3 Sources of Harmonics in Traditional and Renewable Energy Based Power Systems

2.3 Effects of Harmonics on Power Systems

Power systems are negatively impacted by harmonics in a number of ways, including higher copper and core losses in motors and transformers, which can cause overheating and shorten equipment lifespan. Distorted waveforms can cause sensitive equipment to malfunction or failure, and high harmonic currents can annoy protection relays by tripping them. Furthermore, communication cables and adjacent electronic equipment are impacted by electromagnetic interference, which is a result of harmonics.

3. RENEWABLE ENERGY SOURCES AND HARMONIC CONTRIBUTIONS

Because power electronic converters are used for energy conversion and grid interface, the growing integration of RES into contemporary power systems presents special harmonic problems. In contrast to conventional synchronous machines, switching based power electronics, which are significant causes of harmonic distortion, power RES units including solar PV, wind turbines, small hydro, and biomass generators. The harmonic behavior of various RES types is explained in detail in this section.

3.1 Solar PV Systems

In contemporary power networks, solar PV systems are one of the most extensively used renewable energy technologies. In order to integrate with the grid, these systems convert sunlight into DC power, which is subsequently converted into AC using inverters. The main causes of harmonic production in PV based systems are the dynamic nature of maximum Power point tracking (MPPT) algorithms and the usage of high frequency switching in inverters [34-37].

3.1.1 Role of Inverters

Inverters are essential components of PV systems because they transform the DC electricity produced by solar panels into AC power that is compatible with the utility grid. High switching frequencies and pulse width modulation (PWM) techniques are common operating methods for these inverters, which can lead to harmonic generation.

3.1.2 Harmonics due to MPPT and Switching

The inverter's switching behavior may fluctuate due to MPPT algorithms, which guarantee optimal power extraction under changing irradiance. High frequency harmonics are introduced into the grid by these switching transients, particularly in cases where isolation transformers or low-pass filters are not properly built.

3.2 Wind Energy Systems

Due to the existence of power electronic converters, wind energy technologies greatly increase harmonic distortion in contemporary power systems. The kind and intensity of harmonics differ depending on whether the generator is a permanent magnet synchronous generator (PMSG) or a double fed induction generator (DFIG). PMSG and DFIG are the two primary generator topologies used in wind turbines. PMSGs are combined with full-scale converters, whereas DFIG systems use partial scale converters. For grid synchronization and control, both topologies rely on converters, which employ high frequency switching and cause non-linearities in the waveforms of voltage and current [38-41].

3.2.1 Converter Based Harmonic Injection

For frequency and voltage management, both DFIG and PMSG systems rely on voltage source converters. Depending on the grid circumstances, control technique, and switching frequency, these converters generate harmonics. Harmonic routes are emphasized in Figure 2, which depicts typical wind and solar topologies.

3.3 Small Hydro and Biomass Generators

Harmonic distortion is also caused by the growing use of small scale hydro and biomass generator based systems in rural and microgrid environments. Depending on scale and application, these systems frequently employ synchronous machines with rectifiers and inverters or asynchronous generators. Low order harmonics may originate from the nonlinear behavior of mechanical control systems and, in certain situations, uncontrolled electrical connections [42-43].

Table 2 Typical Harmonic Orders Introduced by Different RES

RES Type	Harmonic source	Typical harmonic orders	Notes
Solar PV	Switching of inverters	3rd, 5th, 7th, 11th	Rises with MPPT mode and load variations
Wind (DFIG)	Rotor-side converter	5th, 7th, 11th	The majority of the contribution comes from partial converters
Wind (PMSG)	Full-scale converter	5th to 25th (odd orders)	Depending on the switching approach
Small hydro	Nonlinear loads/inverter	3rd, 9th	Less pronounced but still present
Biomass	Power electronics	3rd, 5th, 7th	Load-dependent harmonics

4. INTERACTION WITH GRID AND SYSTEM IMPEDANCE

The relationship between grid impedance and power systems is drastically changed by the incorporation of RES. Grid stability, equipment safety, and adherence to power quality regulations all depend on an understanding of how these relationships affect harmonic behavior.

4.1 Grid Strength and Its Effect on Harmonic Propagation

One important factor in determining a system’s capacity to absorb or suppress harmonic distortion is grid strength, which is often quantified by the Short circuit ratio. Harmonic currents can be effectively dampened by a strong grid, characterized by low source impedance and high short-circuit fault levels. On the other hand, even mild harmonic injection can increase voltage distortion in a weak grid with a high source impedance. Impedance at the Point of Common Coupling (PCC) becomes more crucial and changeable when additional power electronics based RES, like wind inverters or solar PV’s, are included into the grid.

Because strong grids have superior current sink capabilities, harmonic voltages are reduced; with weak grids, however, the same amount of harmonic current can cause much more voltage distortion. In order to prevent power quality degradation, grid impedance characteristics must be taken into account while evaluating and planning RES integration.

The different behavior of harmonic propagation under weak and strong grid conditions is shown in Figure 4. The reduced impedance efficiently reduces harmonic currents in robust grids, hence reducing voltage distortion. Weak grids, on the other hand, have higher impedance, which can magnify harmonic components, especially at resonant frequencies. This increases THD and raises the possibility of equipment failure or malfunction.

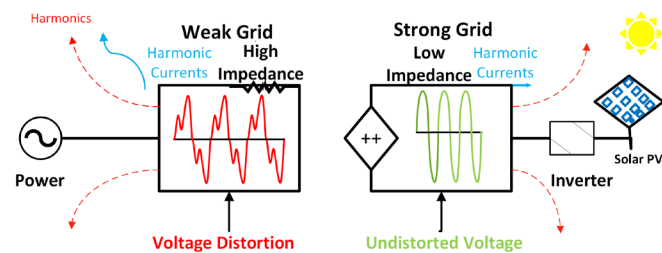


Fig. 4 Harmonic Propagation in Weak vs. Strong Grids

4.2 Resonance Issues and Impedance Mismatch

Parallel or series resonance events are frequently the result of interactions between RES inverters and the grid. Usually, these resonances happens at particular harmonic frequencies where the combined impedance of the linked equipment and the grid reaches a minimum or a peak, respectively. Parallel resonance amplifies voltage harmonics by creating a high impedance channel at specific frequencies. Series resonance, on the other hand, creates a low impedance route that results in high harmonic currents.

Unpredictable harmonic behavior is caused by an impedance mismatch between the network impedance, grid tie transformers, and RES output filters. These discrepancies may worsen local distortion and potentially result in overvoltage or protective system triggering. For secure operation, it becomes essential to identify resonance frequencies using harmonic impedance scanning and impedance modeling.

4.3 Impact on Weak vs. Strong Grids

The effects of harmonic integration on strong and weak grids are very different. The prevalence of inverter based sources with low rotational inertia makes weak grids more susceptible to harmonics distortion. Furthermore, weak grids are more vulnerable to harmonic instability and voltage waveform distortion due to their poor damping and filtering capabilities as shown in Figure 4. In remote or rural networks, even small scale RES can seriously disrupt operations.

Strong grids, on the other hand, are better able to tolerate the effects of nonlinear loads or generation and maintain more stable voltage profiles. Localized weak areas, however, could appear as RES penetration grows even in robust grids, necessitating the use of more specialized mitigation techniques like active compensation or harmonic filters.

To avoid detrimental interactions and maintain power quality in RES integrated systems, a system aware strategy that takes into account grid impedance, resonance behavior, and the unique strength of the grid is required. Weak grids are more susceptible to voltage distortion and instability caused by resonance because they have substantially greater impedance at almost all harmonic orders, as Table 3 [44-46] illustrates.

Table 3 Impedance Characteristics at Different Harmonic Orders

Harmonic order	Typical frequency (Hz)	Strong grid impedance (Ω)	Weak grid impedance (Ω)	Remarks
3 rd	150	0.05 – 0.1	0.3 – 0.6	Predominant in unbalanced loads; transformer windings frequently reduce triplen harmonics
5 th	250	0.1 – 0.2	0.6 – 1.0	Inverter based systems frequently
7 th	350	0.15 – 0.3	0.8 – 1.2	Influenced by resonance and line inductance
11 th	550	0.2 – 0.4	1.0 – 2.0	Resonance is vulnerable in weak grids
13 th	650	0.25 – 0.5	1.5 – 2.5	Harmonics at high frequencies caused by switching operations
17 th	>850	0.3 – 0.6	2.0 – 3.5	Increased in systems with insufficient filtering or dampening

5. MEASUREMENT, MONITORING, AND ANALYSIS TECHNIQUES

Maintaining power quality and grid stability requires precise and real time harmonic monitoring as power systems change due to the growing integration of RES. In order to determine the causes of distortion, assess grid code compliance, and create mitigation plans, converter based RES harmonic emissions require advanced measuring and analysis methods.

5.1 Harmonic measurement equipment and placement

Selecting the right measuring equipment and placing it strategically are the first steps towards effective harmonic monitoring. In contemporary substations and distributed generation configurations, devices like Phasor Measurement Units (PMUs), digital fault recorders, power quality analyzers, and harmonic analyzers are frequently utilized. These devices accurately record waveforms of harmonic voltage and current at different levels.

Harmonic evaluation relies heavily on placement. Typical monitoring locations consist of:

- Utility grid and RES PCC
- Terminals for inverter outputs
- Feeders for substations
- Transformers for distribution

Accurate harmonic source localization and propagation impact evaluation are ensured by proper placement of PMU's. A simplified schematic of a RES integrated system's harmonic measuring setup is shown in Figure 5, emphasizing key parts such as the solar PV array, inverter, and monitoring unit. In such settings, it serves to show the general flow and measurement locations.

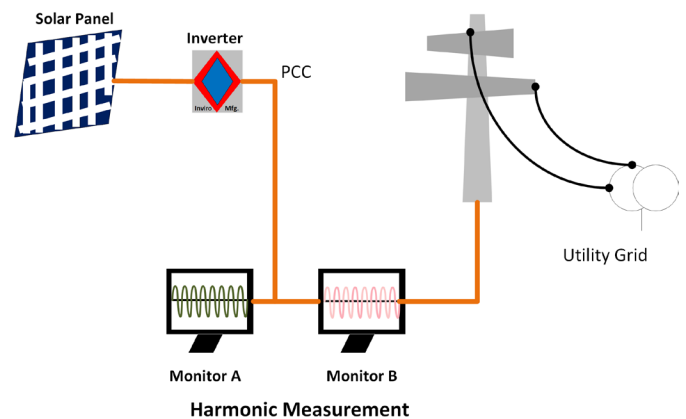


Fig. 5 Harmonic Measurement Setup for RES Integrated Systems

5.2 Time Domain vs. Frequency Domain Analysis

There are two primary methods for harmonic analysis:

- Time domain analysis:

Time domain analysis use numerical techniques or transformations to identify distortion after directly capturing voltage/current waveforms. Despite offering a time perspective on harmonic dynamics, it can be computationally costly.

- Frequency domain analysis:

In frequency domain analysis, signals are broken down into harmonic components using methods such as the Fourier Transform, Fast Fourier Transform (FFT), and Wavelet Transform. This technique works well for detecting amplitude changes and steady state harmonic ordering. Because of their computational effectiveness and interoperability with digital signal processors in inverter controllers, FFT-based solutions are recommended in RES applications.

5.3 Real Time Harmonic Tracking with PMUs and FFT Based Tools

Harmonic monitoring has been transformed by the incorporation of PMUs with real time signal processing capabilities. PMUs provide time synchronized harmonic phasor measurements throughout the grid, allowing for:

Finding patterns of harmonic propagation
 Grid control center coordination
 Finding the harmonic modes that oscillate
 FFT based algorithms built into digital relays and microcon-

trollers are also used by real time harmonic monitoring systems to continually monitor grid conditions and sound an alert when thresholds are crossed.

Table 4 Overview of Methods for Harmonic Analysis

Method	Domain	Application	Advantages	Limitations
Time domain sampling	Time	Transient harmonic analysis	High resolution	Requires a high rate of sampling
FFT	Frequency	Steady state harmonic order detection	Fast and efficient	Restricted ability to resolve non-stationary signals
Wavelet transform	Time & Frequency	Detection of non stationary harmonics	Good localization of time and frequency	Complex implementation
PMU based monitoring	Frequency/Phasor	Grid wide synchronized harmonic tracking	Real time and scalable	Expense and infrastructure needs

6. STANDARDS AND GRID CODES FOR HARMONIC CONTROL

Maintaining harmonic boundaries has grown more important as RES are progressively integrated into contemporary electricity networks. National grid codes and power quality standards are created to manage harmonics and guarantee dependable grid operation. Permissible limitations for current and voltage harmonics generated by power equipment, such as RES inverters and converters, are established by these regulatory frameworks [47-48].

6.1 IEEE 519-2014

One of the most well known standards for harmonic control in power systems is IEEE 519-2014. It establishes the permissible harmonic values of voltage and current at the PCC. The standard uses Total Demand Distortion (TDD) and system voltage levels to classify harmonic limits. For example, compared to high voltage systems, it establishes more stringent current distortion restrictions for low voltage systems.

IEEE 519-2014 highlights that the consumer, not the utility, is responsible for harmonic distortions. Additionally, it offers compliance techniques based on frequency domains and aggressively promotes end user side harmonic filtering or mitigation devices like active and passive filters.

6.2 IEC 61000 Standards

Another set of important standards, known as IEC 61000, are provided by the International Electrotechnical Commission (IEC) and explicitly address electromagnetic compatibility (EMC) and harmonics. Especially noteworthy:

- IEC 61000-3-2: Limits individual harmonic currents and is applicable to equipment with a maximum current of 16 A per phase.
- Similar specifications are extended for equipment rated between 16 A and 75 A in IEC 61000-3-12.
- IEC 61000-4-7: Offers broad recommendations for FFT-based harmonic measuring methods.
- Power quality monitoring techniques and instrumentation requirements are defined in IEC 61000-4-30.

With stringent testing procedures before being approved

for sale, these standards provide a greater emphasis on end-user equipment, particularly industrial and commercial inverters.

6.3 National Grid Codes

Numerous nations have included IEEE and IEC frameworks into their national grid codes, frequently with adjustments made in response to historical distortion levels, frequency stability, and local grid strength.

- India: Grid connected RES must adhere to IEEE 519 and IEC 61000, according to the Central Electricity Authority (CEA). Limits on harmonic distortion of voltage and current are specified for each voltage class.
- Pakistan: Although National Transmission and Dispatch Company (NTDC) and the National Electric Power Regulatory Authority (NEPRA) have released rules that roughly adhere to IEEE 519, enforcement is still relax, especially in rural regions.
- Germany: Leading the way in the implementation of RES, Germany’s grid code (VDE-AR-N 4105) mandates regular compliance testing for distributed energy resources and lays out specific harmonic emission restrictions.

6.4 Comparison and Limitations of Existing Frameworks

Despite offering strong foundations for handling harmonics, these standards have a number of drawbacks.

- Dynamic circumstances: While RES introduces dynamic operating circumstances, standards frequently assume static grid impedance and constant loads.
- Monitoring Gaps: In developing nations, inadequate instrumentation and monitoring facilities frequently result in a lack of real time compliance enforcement.
- Lack of Harmonization: There are notable disparities among nations, which cause irregularities in equipment manufacture and global connectivity.
- Emphasis on Equipment: The majority of standards govern the performance of equipment rather than the grid’s overall harmonic impact.

Key harmonic standards and national grid codes from several nations are compared side by side in Table 5.

Table 5 Comparative Overview of Harmonic Standards

Standard / Code	Emphasis region	Applicability	Key bounds defined	Limitations
IEEE 519-2014	Grid connected systems	Global (esp. North America)	THD, TDD by voltage class	No real time enforcement mechanism
IEC 61000-3-2/12	End user devices	EU and others	Individual harmonic current limits	Limited to equipment ≤ 75 A
India CEA grid code	National grid operation	India	Voltage/current THD	Grid strength assumptions not dynamic
Pakistan NEPRA/NTDC	National grid guidelines	Pakistan	General IEEE 519 compliance	Weak monitoring and enforcement
Germany VDE-AR-N 4105	Distributed RES systems	Germany and EU	Harmonic voltage & current emissions	Strict compliance, costly for small players

7. HARMONIC MITIGATION TECHNIQUES IN RES

Harmonic distortion has increased as a result of the growing usage of power electronic converters in power systems for RES. Effective harmonic mitigation strategies are necessary to guarantee grid compatibility and electricity quality. The most popular harmonic mitigation techniques for RES integrated systems are covered in this section.

7.1 Passive Filters

The most conventional method of suppressing harmonics is through passive filters, which are made up of tuned LC (inductor-capacitor) circuits that absorb particular harmonic frequencies. In general, these filters are easy to use, reasonably priced, and appropriate for mitigating fixed-frequency harmonics. However, they are less flexible in dynamic grid situations.

7.2 Active Power Filters (APFs)

APFs dynamically inject compensatory currents to eliminate harmonic distortions using power electronics. Because they can handle a variety of harmonic orders and adjust to shifting harmonic spectra, APFs are more adaptable than passive filters. They work

well with inverter-based RES systems and non linear loads. APFs provide accurate compensation and enhanced performance in contemporary grids, although being more costly and sophisticated.

7.3 Hybrid Filtering Techniques

To get the best results, hybrid filters blend passive and active filtering techniques. While active portions adjust for high frequency harmonics and dynamic distortions, passive components manage bulk power and low order harmonics. This method preserves a larger compensatory bandwidth while improving system cost effectiveness and dependability.

7.4 Harmonic Compensation through Inverter Control

By using sophisticated control methods, contemporary RES inverters provide integrated harmonic mitigation. Inverters can lower the harmonic content at the PCC by refining control loops, such as Phase Locked Loop (PLL) tuning, enhanced current controllers, and PWM techniques. To reduce THD, solar and wind inverters frequently use Space Vector PWM and selective harmonic removal approaches. To help system designers choose appropriate solutions, Table 6 lists the benefits and drawbacks of each mitigation strategy.

Table 6 Pros and Cons of Harmonic Mitigation Techniques

Mitigation technique	Advantages	Limitations
Passive filters	<ul style="list-style-type: none"> ●Design simplicity ●Low cost ●Reliable for fixed loads 	<ul style="list-style-type: none"> ●Not adaptive to varying harmonic profiles ●Risk of resonance ●Massive
Active power filters (APFs)	<ul style="list-style-type: none"> ●Wide band harmonic compensation ●Adaptive and precise ●Real time control 	<ul style="list-style-type: none"> ●Higher cost ●Complex design and maintenance ●Needs fast switching devices
Hybrid filters	<ul style="list-style-type: none"> ●Combines strengths of passive and active filtering ●Effective for broad frequency ranges 	<ul style="list-style-type: none"> ●Moderate complexity ●Needs coordination between passive and active parts
Inverter-based control (PLL tuning, PWM)	<ul style="list-style-type: none"> ●No extra hardware ●Integrates with existing inverter controls ●Efficient and compact 	<ul style="list-style-type: none"> ●Limited compensation capacity ●Depends on control strategy quality and system dynamics

8. CASE STUDIES AND REAL WORLD IMPACTS

Different nations and areas have encountered significant har-

monic related issues as the use of renewable energy continues to increase, and they have put mitigating measures in place [49-52]. Selected real world case studies that illustrate the harmonic impact of RES and the strategies employed to mitigate them are presented

in this section.

8.1 Harmonic Issues in Solar Dominated Grids

Grid operators in California, one of the biggest solar PV system users in the world, have observed higher harmonic distortion as a result of the extensive use of rooftop solar inverters and massive PV farms. The inverters have demonstrated high frequency harmonic injections, particularly when functioning in partially shaded or suboptimal MPPT settings. According to grid studies, during peak solar generating hours, THD at several substations exceeded IEEE 519 standards. The implementation of selective passive filters at distribution transformers and required inverter compliance with IEEE 1547 and UL 1741 SA standards were among the corrective measures.

With measured THD levels reaching 6-8% in isolated areas, Gujarat, India’s “Solar Rooftop Program”, which encourages the fast adoption of solar power, has resulted in an increase in harmonic distortions in weak distribution feeders. In response, utilities installed smart meters to monitor waveform distortions and issued recommendations for inverter connectivity. They then used hybrid filters in certain locations in regions that were deemed sensitive.

8.2 Wind Farm Integration: The Danish Example

Denmark, a forerunner in wind energy worldwide, encoun-

tered problems with harmonic stability while connecting huge offshore wind farms that included full converter PMSG’s and DFIG’s. One well known example was the Horns Rev offshore wind farm, where switching harmonics from back to back converters and resonance from grid impedance mismatch caused voltage distortion in the 11th and 13th harmonic orders. The problem was effectively reduced and grid compliance was restored by integrating wide band active filters with impedance reshaping techniques employing series reactors.

8.3 Smart Grids and Harmonic Control Using AI

The development of smart grids has led to the application of Machine Learning (ML) and Artificial Intelligence (AI) algorithms for harmonic monitoring and mitigation. Neural networks and adaptive FFT were used by a utility to develop an AI based real time harmonic monitoring system in a research conducted in South Korea. With the use of distributed PV and real time APF parameter adjustments, the system was able to forecast harmonic production patterns with accuracy. Even in the presence of variable solar circumstances, the results demonstrated a 35-40% improvement in harmonic suppression. The increasing significance of intelligent harmonic control in dynamic, high penetration RES situations are demonstrated by this example.

Table 7 Case Study Summary of Harmonic Events and Solutions

Location	RES type	Harmonic issue	Mitigation applied	Outcome
California, USA	Solar PV	High inverter induced THD at substations	Inverter standards enforcement + passive filters	Reduced THD to <5%
Gujarat, India	Solar PV	Harmonic distortion on weak feeders (6-8% THD)	Smart metering + hybrid filters	Improved waveform quality
Horns Rev, Denmark	Wind	Resonance and harmonic injection from offshore converters	Impedance reshaping + wide-band APFs	Elimination of 11th and 13th order distortions
South Korea	Solar PV	Dynamic harmonics in smart grid	AI-based harmonic prediction and adaptive APF tuning	40% improvement in harmonic suppression

9. CONCLUSION

The increased usage of power electronic converters in RES is the main driver of the growing impact of RES on power system harmonics, which was examined in this investigation. The study emphasized how these technologies lead to harmonic distortion, especially in weak grids, and how both conventional and cutting edge filtering techniques are developing to address the issue. The study highlights the need for harmonic mitigation to be a crucial component of future smart grid design and operation by looking at monitoring methods, global standards, and real world case studies. Intelligent control methods, standard harmonization, and cooperative research are necessary to ensure power quality in renewable dominated systems.

Following are the key points that can be concluded from this survey;

- The main source of system harmonics in RES is the power converter, particularly at higher switching frequencies.

- Weak grids need impedance aware integration techniques because they are more susceptible to harmonic resonance.
- Real time harmonic tracking under dynamic grid settings requires monitoring instruments like as FFT analyzers and PMUs.
- Although baseline compliance frameworks are provided by standards like as IEEE 519 and IEC 61000, changes are required to meet new RES issues.
- Inverter based compensation methods and passive, active, and hybrid filters are examples of mitigation strategies.
- Case examples, such as wind integration in Denmark and solar farms in California, demonstrate the difficulties and efficacy of mitigating techniques in practical settings.

10. FUTURE DIRECTIONS

Research and engineering efforts will continue to focus on comprehending and reducing the harmonic consequences of re-

newable energy systems as they continue to spread around the world. Although the present level of knowledge, instruments, and standards has been brought to light by this assessment, there are still a number of open problems and exciting new research directions. These include the use of intelligent grid elements, adaptive filtering in real-time, and improved simulation models that can evaluate harmonic behavior under various operating conditions.

The proliferation of prosumer networks and the increasing complexity of inverter based systems highlight the need for intelligent control and dynamic harmonic monitoring. Furthermore, there is a lot of room for data driven harmonic prediction and mitigation as AI and ML should be used more and more in smart grids.

The following crucial areas are suggested for further research in order to progress the field:

- AI and ML Based Harmonic Forecasting: In dynamically changing RES situations, use AI and ML techniques for early harmonic prediction, categorization, and real time mitigation.
- Adaptive Filtering Strategies: Create active or hybrid filters that adjust to variations in load profiles, inverter switching patterns, or grid strength.
- Wide Area Harmonic Monitoring Networks: For grid wide harmonic evaluation and coordinated mitigation methods, put in place PMU based wide area harmonic measuring infrastructures.
- Harmonic Aware RES Planning Tools: To guarantee harmonic compliance from the design phase, incorporate harmonic estimating capabilities into RES size, placement, and grid interconnection tools.
- Interoperability Standards: Make efforts for improvements to IEEE and IEC standards that particularly address harmonics brought about by contemporary RES systems, such as multi inverter topologies and flexible distributed generation.
- Harmonics in Prosumers and Car to Grid (V2G): Examine how bidirectional energy flows behave harmonically in new systems such as MG's based on prosumers and electric car charging.
- Real World Benchmarking: To promote best practices and benchmarking, support utility sponsored case studies that release harmonic performance data after RES integration.

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