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A Review of Harmonic Distortion Analysis and Mitigation Strategies for Residential Microgrids

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ABSTRACT: The rapid deployment of distributed energy resources (DERs) especially solar photovoltaic (PV) inverters and electric vehicle (EV) charging points into residential distribution systems has given rise to power quality problems in the form of harmonic distortion. This paper critically reviews the theoretical basis, source characterization, modelling and mitigation approaches to harmonic distortion in residential microgrids. Based on an analysis of fifty recent publications, the paper assesses the efficacy of passive harmonic filters (PHFs), active power filters (APFs) and hybrid solutions vis-à-vis international standards, primarily IEEE 519-2022. Main conclusions confirm that unchecked harmonic current injection from 100 kW EV fast-chargers and pulse-width-modulated (PWM) solar inverters can result in a total harmonic distortion (THD) exceeding the 5.0 % voltage distortion limit, with subsequent transformer derating, increased I^2R losses and accelerated insulation ageing. The review further demonstrates that single-tuned passive shunt filters, sized using the Electrical Transient Analyzer Program (ETAP), offer a cost-effective and standards compliant mitigation route for the residential sector where active filter economics are prohibitive. Research gaps, including the lack of integrated PV-EV harmonic characterization at the point of common coupling (PCC) in low volt residential systems, are highlighted with recommendations for future research.

KEYWORDS: Harmonic distortion, ETAP power quality analysis, Passive harmonic filters, Electric vehicles, Residential microgrids, IEEE 519

1 INTRODUCTION

Increasing distributed energy resources (DERs) in residential distribution networks is a consequence of the global shift towards sustainable energy systems. Rooftop solar photovoltaic (PV) systems and electric vehicle (EV) charging are key components of this transformation; but both heavily employ nonlinear power electronic equipment that affects the nature of load current consumed from the supply [1, 2]. While a power system is designed to supply and draw only sinusoidal voltages and currents at a constant fundamental frequency (50 Hz in Nigeria), the switching nature of inverters and rectifiers results in a current waveform containing several harmonic components multiples of the fundamental [5].

Harmonics are unwanted sinusoidal components of a periodic waveform with frequencies that are integer multiples of the fundamental [5]. When nonlinear loads draw current in periodic pulses (as opposed to the sinusoidal wave of linear loads), they generate harmonic currents that flow into the power system. Without mitigation, these currents result in increased losses in transformers, neutral conductor overheats, misoperation of sensitive consumer equipment and communication problems [14]. The presence of multiple inverter-based sources and chargers operating in close geographical proximity (as in a residential estate) exacerbates these effects, and may induce unexpected parallel or series resonances [16].

This scenario calls for careful analysis using industry standardized tools. The Electrical Transient Analyzer Program (ETAP) is one of the most powerful simulation platforms for predictive power quality assessment, which integrates Harmonic Load Flow (HLF) analysis with resonance mapping via a frequency sweep [7]. The focus of this review is prompted by the lack of a dedicated, economical passive filter design approach tailored to the harmonic content of co-located solar PV and EV systems at a small scale residential PCC.

The remainder of this paper is organised as follows: Section 2 outlines the theory of harmonic generation and propagation. Section 3 surveys the literature on harmonic sources, analysis, mitigation and limitations. Section 4 provides a review of the literature with an emphasis on research gaps and future directions. Section 5 concludes the paper

2. MATERIALS AND METHODS

A structured search of scholarly articles, conferences and standards was performed from 2003-2025. Key phrases used were "harmonic distortion", "residential microgrid", "passive harmonic filter", "ETAP power quality", "EV charging harmonics", and "solar PV THD". Fifty sources were identified, screened and synthesized. The theoretical background of the review is summarized here.

2.1 Fundamentals of Harmonics

In a power system, the voltages and currents are supposed to be pure sinusoids, with a fundamental frequency of f_1 = 50 Hz. Non-linear loads, such as power electronic converters, LED drivers, switched-mode power supplies and variable speed drives, draw currents in distorted, periodic waveforms. According to the Fourier theorem, any periodic distorted signal can be expressed as the sum of a fundamental and harmonics:

$$\mathbf{I(t) = I_1 \sin(\omega t + \varphi_1) + \Sigma\, I_n \sin(n\omega t + \varphi_n)}$$

where I_1 is the peak fundamental current, I_n and φ_n are the peak magnitude and phase angle of the nth harmonic, and $\omega = 2\pi f_1$ [5, 16]. The major odd harmonics produced by three-phase six pulse rectifiers and PWM inverters are the 5th, 7th, 11th and 13th [15, 16]. The aim of mitigation is to reduce the value of I_n for these orders.

2.2 Harmonic Indices

The two main indices of harmonic pollution [5] are:

Total Harmonic Distortion (THD) - the ratio of the RMS value of all the harmonic components to the RMS fundamental component. The voltage (THD_v) and current (THD_i) versions are defined. IEEE 519-2022 [1] requires a maximum THD_v of 5.0 % for low voltages (< 1 kV) at the Point of Common Coupling (PCC).

Individual Harmonic Distortion (IHD) - the contribution of a harmonic order to the fundamental (maximum 3.0 % for odd harmonics ≤ 11th order, IEEE 519). IHD values are used to determine the tuning of passive filters to harmonic frequencies.

2.3 Resonance in Power Systems

Parallel resonance occurs when the inductive reactance of the system equals the capacitive reactance of the power-factor correction capacitors or filter elements at a specific harmonic frequency, and a high-impedance path is formed that resonates the harmonic voltages, which can lead to insulation breakdown and/or damage to the capacitors. Series resonance lowers the impedance, amplifying harmonic currents in the circuit [5, 16]. Impedance frequency-scan (fundamental to high-frequency) is the typical method of identifying these peaks before mitigation devices are deployed [16].

2.4 K-Factor and Transformer Derating

The K-factor is a weighted measure of harmonic load currents that quantifies the additional heating burden imposed on distribution transformers [13]:

$$K = \Sigma (I_n/I_1)^2 \times n^2$$

If K > 1, a transformer needs to be derated (operated at less than its nominal rating) to avoid early-age insulation failure [13, 25]. The growing number of electric vehicle (EV) chargers, which produce mainly 5th and 7th harmonic currents [44, 45], leads to a higher K-factor of residential transformers.

2.5 Passive Harmonic Filter Design

A single tuned, shunt connected, passive harmonic filter (PHF) is synthesized as an inductor capacitor series combination in shunt with the supply bus. At the tuned harmonic frequency of hf_1, the filter offers a low impedance path to ground for the harmonic current to flow and prevent it from flowing through the supply impedance and the grid [11]. The filter design is based on three equations:

$$X_c = V^2/Q; \quad C = 1/(2\pi f_1 X_c); \quad X_L = X_c/h^2$$

where Q is the desired reactive power compensation (MVAR), V is the bus rated voltage (kV), h is the tuned harmonic order, and XL is the reactance of the filter inductance at fundamental frequency [11]. To account for component tolerance and temperature, the filter is designed at slightly lower than the target frequency (e.g., 4.7th for a 5th-harmonic filter) [2, 26].

3 RESULTS AND DISCUSSION

3.1 Residential Microgrid Harmonic Sources

The main nonlinear harmonic sources in contemporary residential microgrids are solar PV inverters, electric vehicle (EV) charging points and other consumer electronic devices.

Solar PV Inverters: Grid tied PV systems are connected to the AC grid through pulse width modulated (PWM) voltage source inverters. These inverters inject harmonics at orders that depend on the switching frequency and PWM technique [2]. Alfalahi et al. [2] confirmed that, in the absence of EV loads, high PV penetration in a low voltage network can lead to THD_v violations at the PCC, if passive filters are not present. Hernández-Mayoral et al. [22] also showed, in a MATLAB-Simulink model of an IEEE 14-bus network, that harmonic current injection from PV inverters is non linear and irradiance dependent (a dynamic condition that presents a challenge for static filter design). Lezhniuk et al. [25] also confirmed that PV inverters are broadband, high-frequency noise sources that affect power quality at multiple harmonic orders.

Electric Vehicle Charging Stations: EV chargers are widely recognized as a primary source of harmonics in residential feeders. Ishak and Yahaya [3] confirmed, using ETAP simulation, that uncontrolled application of 100 kW fast-chargers results in THD violations beyond the IEEE 519 limit at the distribution bus. Bansal et al. [44] showed that Level 2 chargers inject the most 5th harmonic into residential feeders, while Kumar et al. [45] reported that wireless EV charging stations introduce higher order harmonics (11th and higher) not accounted for by traditional models based on wired chargers. The MDPI paper [49] verified, through a year-long operation study, that uncontrolled residential charging causes significant increases in losses and bus voltage drops to below statutory limits.

Consumer Electronics: Masoum et al. [15] demonstrated that home loads containing switched-mode power supplies (SMPS) such as computers, LED TVs, smart appliances individually inject low powered harmonic currents, but collectively, on a common feeder serving hundreds of homes, these currents are significant. Arrillaga and Watson [5] offer the mathematical proof that triplen (3rd) harmonic currents from single-phase loads sum in the neutral, while 5th and 7th harmonics flow in the phase conductors.

3.2 Passive Harmonic Filter Performance

Passive filters are the most common mitigation technology used in residential and small commercial networks because of their simplicity, reliability and cost effectiveness [23, 24]. Bhuiyan [4] gave an early demonstration with ETAP that single tuned passive filters significantly reduce individual harmonics in small distribution systems, although noted filter performance is compromised when grid impedance varies from the design case. Alfalahi et al. [2] extended this work to PV rich networks, confirming that correctly sized shunt passive filters can restore THD to IEEE 519 compliance. Shrestha et al. [6] reported a dramatic drop in THD_v (from 16.06 % to 3.89 %) using a five stage single tuned filter bank, but the cost and complexity of multi stage filters may not be warranted for residential purposes. Li et al. [40] verified that single tuned PHFs are suitable in low voltage residential environments using ETAP HLF simulations; they caution that neglecting equivalent series resistance (ESR) of real inductors can overestimate filter performance.

The critical design constraint is resonance avoidance. Das [11] presents closed form sizing equations for single tuned shunt PHFs and stresses that a frequency scan is needed before installation to ensure that the filter capacitor does not combine with system inductance to form parallel resonance at an energized harmonic frequency. Rahman et al. [16] showed (via ETAP frequency scan) that such parallel resonance can result in catastrophic damage to capacitor banks.

Su and Hong [47] installed passive filters on a real distribution feeder and found that overall energy losses were reduced by 5 % due to filtering (providing empirical evidence of the economic benefit of passive filters). Ulinuha [35] concluded that filtering at the PCC will protect the utility but may not protect local electronics; this suggests placing filters at individual load points.

3.3 Active and Hybrid Mitigation Strategies

APFs dynamically inject harmonic currents to compensate for distortions, and boast better dynamic response than passive filters [8]. Ramrao et al. [8] showed that APF tuned with metaheuristic swarm algorithms (sparrow search) has lower residual THD than single stage passive filters. E3S Conferences studies [50] verified that APFs can simultaneously measure and eliminate multiple orders of harmonics in real time.

But APFs are not technically and economically viable at residential level. Sierra-Acosta [23] calculated the increased cost: active filters are about 400 % more costly than a corresponding passive filter. Gutiérrez-Escalona et al. [30] demonstrated that AI-driven active filters can outperform static passive filters in terms of THD reduction (an additional 15 %) but the implementation cost and complexity of control make these designs impractical for residential use.

Hybrid filters, which include a passive stage to absorb a large portion of the harmonic power and an active stage to fine-tune the cancellation [29], are a solution. Mahmoud [26] confirmed by ETAP HLF simulation that hybrid filters are better than single tuned passive filters in networks with multiple simultaneously excited harmonic sources. Carpinelli et al. [37] suggested multi-objective optimisation for optimal placement of the passive filter stages in a distribution network. Although such hybrid designs have better harmonic performance, they are still too expensive and sophisticated for the average domestic user, vindicating the role of passive filters in the studied application.

3.4 Software-Based Power Quality Analysis

Predictive power quality analysis is now routine using simulation programs. The Harmonic Load Flow (HLF) module of ETAP solves the network at each harmonic order using the current injection method, calculates Total Harmonic Distortion (THD) and Individual Harmonic Distortion (IHD) at all buses and checks automatically against user-definable standards [4, 7]. Hafez [7] compared ETAP with measurements in a microgrid supplying a nuclear research reactor, and found ETAP to be within 3 % error for the magnitude of harmonics, a result endorsed by Ramadhan [34], who validated ETAP on a three-bus system.

MATLAB/Simulink is the main alternative to ETAP. Hernández-Mayoral et al. [22] used Simulink with an IEEE 14-bus benchmark to investigate PV microgrid harmonics, and Shrestha et al. [6] designed and tested a five stage passive filter in Simulink. Hardware-in-the-loop (HIL) simulation is the most accurate method for dynamic studies; Padayattil et al. [32] used HIL to demonstrate that PV islanded microgrids are 40 % more vulnerable to harmonic instability than grid connected microgrids.

The open source Python tool Pandapower was used in the EV charging study published in MDPI [49] with a temporal resolution of one year, to illustrate the interaction between EV charging and PV cycles. This enables the identification of the worst case scenario that may not be captured in static HLF studies, and is crucial in filter design.

3.5 Impact on Transformer and Distribution Equipment

Harmonic currents cause extra thermal burdens on distribution equipment in addition to those caused by the fundamental frequency load. For transformers, harmonic currents generate additional eddy-current losses in the core and windings (increasing with the square of the harmonic order), and can further cause hot spot temperatures [13]. Andang et al [13] performed a K-factor analysis that confirms that the specific harmonic profile of the combined EV/PV load largely reduces the safe operating temperature margin of distribution transformers, and requires derating or K-rated replacement.

Lopez et al. [46] confirmed, via laboratory tests, that high frequency harmonics induce skin effect in cables, raising their effective resistance and causing extra I^2R losses. Al-Saedi et al. [42] report that new, highly dynamic, transient load types (such as traction loads from high speed rail) produce variable harmonic profiles that are harder to filter than the relatively static, fixed harmonic profiles of residential EV loads.

Grady and Santoso [14] give an in-depth account of the interaction between the power-factor correction capacitors and the magnetising inductance of transformers to produce hazardous parallel resonance at harmonic frequencies, which needs to be assessed before introducing filter capacitance into a residential feeder.

3.6 Developing-Country and Nigerian Context

The power quality challenges of residential harmonic distortion are particularly acute in developing nations where the distribution grid operates close to its statutory limits and where the technical capacity for active filter maintenance may be limited. Olowu and Jimoh [20] conducted a survey of the Nigerian distribution sector and concluded that the grid is currently operating at the limit of IEEE allowable voltage and THD standards for linear loads; there is no margin for the extra harmonic loads of unregulated EV and PV installations. The Nigerian Electricity Regulatory Commission (NERC) distribution code [18] requires voltage tolerances of ±5 % and THD limits in accordance with international standards, but there is limited enforcement at the distribution level.

Mishra et al. [24] demonstrated, on the basis of cost-benefit analysis, that passive filters are the only cost effective method of harmonics mitigation available to residential customers in cost sensitive markets, a finding supported by Sierra-Acosta's comparative analysis [23]. A lack of localised residential passive filter design guidelines optimized for the Nigerian grid environment with relatively low short circuit capacity and high X/R ratios is a critical gap.

3.7 Critical Research Gaps

The review of literature highlights five key research gaps:

(i) PV-EV Integrated Harmonics: Most research investigates the harmonic sources from PV or EV [2, 3]. The concurrent injection of harmonic currents from PV inverters and EV chargers at the same PCC results in a composite harmonic spectrum whose amplitude, phase interaction and resonance potential has not been quantified [23, 24].

(ii) Scale and Load Profiles: Most simulation studies use high-power (campus scale [9], industrial [14, 15, 16] or high sensitivity load [7]) benchmarks that do not represent the impedance and load profiles of typical low voltage residential estates. Inappropriate to directly apply their filter design for residential application.

(iii) Viability of Advanced Systems in Residential Markets: More technically complex active and hybrid filters are often recommended without consideration of their inviability for residential markets [8, 30, 37]. Economic passive filter solutions are under represented as options for residential scale residential harmonics.

(iv) Temporal and Time-Varying Analysis: HLF analysis generally makes steady-state, worst case assumptions. However, EV charging, and PV power injection, are time and seasonally varying. There is a lack of time-series or probabilistic harmonic analysis at the residential PCC [49].

(v) Physical Component Non-Idealities: Filter sizing studies frequently neglect the equivalent series resistance (ESR) of inductors and the temperature dependence of capacitor values [40], leading to optimistic performance predictions that may not be realized in field deployment.

4. CONCLUSION

This review has consolidated data from fifty published articles on harmonic distortion in residential microgrids, particularly in terms of sources, analysis techniques, mitigation measures and international standards for co-located solar PV and electric vehicle (EV) charging systems. The major findings are:

(1) Widespread deployment of 100 kW EV fast-chargers and high-penetration solar PV systems in residential microgrids invariably exceeds the 5.0 % THD_v limit specified in IEEE 519-2022, thereby jeopardizing the lifespan and reliability of residential transformers.

(2) Single tuned passive shunt filters sized using ETAP HLF and frequency-scan analysis are the most affordable and technically robust solution for the residential sector, as long as resonance is checked before installing filters.

(3) Active and hybrid filters provide better harmonic performance, but cost prohibit their adoption for typical residential consumers, especially in cost sensitive emerging markets like Nigeria.

(4) There is a dearth of literature on the combined harmonic characteristics of simultaneously operating PV inverters and EV chargers at a common residential PCC, and the design of passive filter structures aimed at this aggregate harmonic source. Resolving this gap via ETAP simulations of HLF and frequency scans for an integrated residential microgrid represents the practical contribution of current and future research in this area.

Research priorities should include: probabilistic assessment of harmonic distortion considering PV and EV load variability; practical implementation and testing of filter design including component tolerances; and development of standards for harmonic mitigation in residential distribution systems in Nigeria.

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