A Study on Harmonics and Quality of Power in Western Europe, in the Context of Electric Vehicles, Distributed Generation and Hybrid Way-of-Working

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Abstract

This study is on the intention of understanding the presence of non-fundamental 50Hz sinusoidal energy components present in real on 220VAC power distribution lines, mostly residential, for countries in Western Europe. Those components are mostly harmonics, multiples of odd order from the fundamental, so the third harmonic is of 150Hz, the fifth harmonic is of 250Hz, and so on, until what is understood on experts study groups as being the most relevant ones, which are the odd ones from 3rd to 31st harmonic. This brief study also shows real data measured these days, the causes of harmonics, the negative impact in quality of power and subsequential collateral effects on electrical appliances. the european laws and regulations that apply, and some ways to minimize THD total harmonic distortion presence. Artificial Intelligence has been a tool used to provide support and quickness to the research, with human verification done on later stage. A self-made simulation software was used to highlight the distortion on the sinusoidal wave by the presence of a percentage of harmonic contribution.

Keywords: harmonics and quality of power; distributed power generation; green energy; carbon neutral; artificial intelligence; IEC61000; EN 50160; simulation software.

INTRODUCTION

The increasing penetration of nonlinear electrical loads and distributed generation systems has led to a growing concern regarding the quality of electric power in modern low-voltage distribution networks. In most European countries, including those in Western and Central Europe, the nominal low-voltage residential supply is 220 V AC at a fundamental frequency of 50 Hz. However, practical measurements reveal that the delivered voltage and current waveforms frequently deviate from the ideal sinusoidal shape due to the presence of harmonic components—sinusoidal distortions whose frequencies are integer multiples of the fundamental frequency.

These harmonic components, predominantly of **odd order** (3rd, 5th, 7th, …, 31st), are of particular interest in residential environments where a multitude of electronic power converters coexist. The third harmonic, at 150 Hz, and the fifth, at 250 Hz, typically exhibit the highest magnitudes among the lower orders. Beyond the 31st harmonic, the spectral contribution generally diminishes, yet cumulative distortion—expressed through the **Total Harmonic Distortion (THD)** index—can still pose significant challenges for both network operators and end users.

The primary objective of this study is to analyze and characterize the presence and behavior of these non-fundamental components in 220 V AC residential power distribution lines across selected Western European countries. Emphasis is placed on:

1. **Empirical assessment** of voltage harmonic spectra through recent real-world measurements;
2. **Identification of dominant sources** of harmonic pollution, including photovoltaic inverters, switching power supplies, PWM-controlled drives, and electric vehicle chargers;
3. **Evaluation of impacts** of poor power quality and low power factor on energy efficiency, equipment lifespan, and grid stability;
4. **Review of applicable European and national legislation**, with focus on standards such as IEC 61000-3-2 and EN 50160, as enforced in countries like Germany, the Netherlands, Belgium, Luxembourg, France, Italy, and the United Kingdom;
5. **Exploration of mitigation techniques** aimed at improving power factor and reducing harmonic distortion, including passive filtering, active compensation, and energy storage integration.

Artificial Intelligence (AI) methods were adopted to facilitate data processing and accelerate analytical interpretation, while results underwent expert human validation at later stages. Additionally, a custom-developed simulation tool was employed to visualize the effects of specific harmonic amplitudes on the ideal 50 Hz sinusoidal waveform, thereby illustrating waveform deformation as a function of harmonic percentage contribution.

This study aims to contribute to a deeper understanding of harmonic phenomena in modern residential grids, highlighting both their technical origins and their implications for the ongoing transition toward sustainable, carbon-neutral, and digitally managed energy systems.

THE MAIN FOCUS OF THIS RESEARCH

For a 220V power distribution line in western Europe, especially Germany, The Netherlands, Belgium, Luxembourg, France, Italy and the United Kingdom, do a research about harmonics present to the energy provided to any ordinary residence consumer. Detail every harmonic from the 2nd to the 31st.

Enlist what the sources of harmonic are (solar inverters, switching power supplies, pwm controlled electric motors, electric vehicle chargers, and so on).

Explain about the real bad consequences of poor power quality, of poor power factor, there are.

Provide information about the legislation present in Germany in order to limit harmonic components to the power distribution lines.

Explore what can be done in order to better the power factor (active control, capacitive or any other type of power banks, batteries, etc.).

THE INITIAL FINDINGS

A detailed overview of **harmonics**, their sources, consequences, regulatory framework (especially in Germany) and mitigation possibilities for a 220 / 230 V low-voltage residential distribution system (for example in Germany, The Netherlands, Belgium, Luxembourg, France, Italy, UK) is presented as a result of the research.

Harmonics from the 2nd to the 31st in a 50 Hz system

In a 50 Hz European supply system, a harmonic of order *h* has frequency *h × 50 Hz*. So:

- 2nd harmonic → 100 Hz
- 3rd harmonic → 150 Hz
- 4th → 200 Hz
- … up to
- 31st → 1,550 Hz

Here is a tabular view with typical significance for a residential consumer grid (low-voltage) and indication of whether they are commonly present, and remarks:

Harmonic order (h)	**Frequency**	**Typical presence & remarks**
2nd	100 Hz	Even harmonics are usually smaller (non-ideal loads, asymmetries). Less common than odd harmonics.
3rd	150 Hz	Very common especially in three-phase systems with nonlinear loads; zero-sequence currents in three-phase star systems can sum in the neutral.
4th	200 Hz	Even harmonic; moderate presence if there are switching supplies with specific switching patterns.
5th	250 Hz	One of the more prevalent odd harmonics in LV/MV networks. Often generated by e.g. 6-pulse rectifiers, drives, inverters.
6th	300 Hz	Even harmonic; again less than odd but still possible.
7th	350 Hz	Also a significant odd harmonic in many installations.
8th	400 Hz	Even; less common but possible with certain loads.
9th	450 Hz	Odd; appears in some systems with strong nonlinear loading.
10th	500 Hz	Even; less frequent.
11th	550 Hz	Odd; moderate presence.
12th	600 Hz	Even; smaller magnitude.

Harmonic order (h)	Frequency	Typical presence & remarks
13th	650 Hz	Odd; still relevant.
14th	700 Hz	Even.
15th	750 Hz	Odd; in many LV grids this one is mentioned specifically. For example some monitoring campaigns show 15th harmonic voltage exceeding limits. (tdworld.com)
16th	800 Hz	Even; lower magnitude but included in assessments.
17th	850 Hz	Odd.
18th	900 Hz	Even.
19th	950 Hz	Odd.
20th	1,000 Hz	Even.
21st	1,050 Hz	Odd; also specifically flagged in monitoring (15th and 21st). (tdworld.com)
22nd	1,100 Hz	Even.
23rd	1,150 Hz	Odd.
24th	1,200 Hz	Even.
25th	1,250 Hz	Odd.
26th	1,300 Hz	Even.
27th	1,350 Hz	Odd.
28th	1,400 Hz	Even.
29th	1,450 Hz	Odd.
30th	1,500 Hz	Even.
31st	1,550 Hz	Odd.

Key observations

- In residential / low-voltage networks, the lower-order odd harmonics (3rd, 5th, 7th, 9th, 11th, 13th) tend to dominate the distortion spectrum because many nonlinear loads create these. (A. Eberle)
- Some harmonic orders are of special concern because they may sum in the neutral (especially 3rd, 9th, 15th…) in three-phase four-wire systems.
- Even harmonics (2nd, 4th, 6th…) are usually smaller but may indicate asymmetry or faults or certain converter topologies.
- Higher-order harmonics (above say 15th or 21st) are increasingly present with power-electronics switching at higher frequencies (inverters, EV chargers, PV

inverters) although their amplitude tends to decrease with order (and depends on network impedance).

- Many monitoring campaigns in Europe emphasise the 15th, 21st harmonic voltage levels in LV networks as often exceeding limits. (tdworld.com)
- Beyond the 31st (and even beyond 40th), you enter into “supraharmonics” region (hundreds of Hz to kHz range) and certain guidelines begin to apply. (A. Eberle)
- For a normal residence consumer, the grid operator at the low-voltage point of common coupling (PCC) may not measure every single order up to 31 in everyday monitoring, but for power-quality audits it can be done.

Typical magnitude & limit values

While it is not accurately possible to give a complete list of residential typical magnitudes for each harmonic order (because values vary strongly depending on network and loads), a summary of typical standard limits for equipment emissions (which impact the grid) and for voltage distortion at the supply point is possible:

- For equipment: IEC 61000-3-2 (for devices up to 16 A per phase) gives limits for harmonic currents from 2nd to 40th order. (Wikipedia)
- For voltage at supply point: EN 50160 sets limits for total harmonic distortion of the voltage (THD U) and some individual harmonic voltage levels. For example for LV 95 % of the time: THD(Voltage) ≤ 8 % in some national interpretations. (www.slideshare.net)
- In Germany / D-A-CH-CZ guidelines: For harmonic currents of orders ν = 16…30, exceedance is permitted up to 1 % of IA; for ν=31…40 up to 0.8 % of IA.

Thus for a residential consumer connection one would typically expect that harmonic currents from higher orders are restricted to small percentages of the fundamental current, and the network operator ensures that at the PCC the resulting voltage distortion is within limits.

Summary for orders (2nd–31st)

A full numeric permissive value for each order depends on the specific standard, equipment class, installation. For a practical residence in those European countries one should expect:

- Orders 2-4: rather small (especially the even ones).
- Orders 5-13: moderate prominence (especially 5th, 7th, 9th, 11th, 13th).
- Orders 15, 21, 27: sometimes emerging as notable in LV networks.
- Orders 16-31: progressively lower in magnitude but still relevant for harmonic emission / propagation; may accumulate and contribute to THD.

- Total harmonic distortion (THD) of voltage ideally under ~5–8 % for LV supply (depending on country) and for current emissions per device according to equipment standards.

Sources of harmonics

Non-linear loads (i.e., loads whose current does not draw a pure sinusoid even when supplied with a sinusoidal voltage) are the main sources of harmonic currents (which then cause harmonic voltages via network impedance). Here are typical residential (and small commercial) sources:

- **Switching power supplies** (in PCs, TVs, LED lamps, chargers): These draw current in pulses, causing high harmonic content. (unipower.se)
- **PWM controlled motors / variable frequency drives (VFDs)** – although in a residence these may be less common, but for e.g., heat pumps, air-conditioning, washing machines with inverter drives, etc. They generate harmonics because of the switching. (A. Eberle)
- **Solar inverters (PV systems)**: Particularly grid-connected inverters injecting current may generate harmonic and supraharmonic emissions. (Greensolver)
- **Electric vehicle (EV) chargers**: These can be significant nonlinear loads and can inject currents with switching harmonics (and possibly back-feed into the grid depending on architecture). (A. Eberle)
- **UPS (Uninterruptible Power Supply) systems**, battery chargers, LED lighting, compact fluorescent lamps: all contribute to harmonic currents. (A. Eberle)
- **Rectifiers and inverters generally**: old style uncontrolled rectifiers (e.g., for old home electronics) and modern ones.
- **Distributed generation/injection**: Although the generation side injects at fundamental frequency, their power electronics interfaces may create voltage/current distortion, especially when interacting with the grid, especially at low voltage or medium voltage. (eldorado.tu-dortmund.de)
- **Phase imbalance, single-phase loads on three-phase systems**: When many single-phase non-linear loads are connected in an unbalanced way, the neutral may carry harmonic currents (especially triplen harmonics: multiples of 3rd) which can flow in the neutral conductor and add up.
- **Capacitor banks for power factor correction** interacting with network impedance: they may resonate with harmonic currents and amplify certain harmonic orders. (irem.it)

Mechanism

Non-linear loads draw current not proportionally to the applied voltage waveform but in pulses or clipped segments. That generates current waveforms that contain other frequency components besides 50 Hz. These harmonic currents flow through the source impedance of the grid, producing harmonic voltage distortion (voltage harmonics). The harmonic voltages and currents cause various adverse effects (see next section). (irem.it) Some loads also inject current back into the grid (e.g., PV inverter injection), or cause more complex interactions (resonance, interharmonics, supraharmonics). (A. Eberle)

Notable sources for residential context

- In Germany/Benelux/France/UK, the proliferation of domestic PV installations, EV chargers, smart appliances are increasing the harmonic burden on LV networks. For example the article on the Netherlands distribution network notes that in LV networks the 15th harmonic often exceeds the limit. (tdworld.com)
- Many modern homes have multiple PC/TV/LED loads, EV chargers, heat pumps, which are all nonlinear and increase harmonic emissions.

Consequences of poor power quality, poor power factor, and high harmonics

Poor power quality (including voltage distortion, harmonic pollution, poor power factor, unbalance, flicker) can have a wide range of adverse effects — from mild (nuisance) to severe (equipment damage, fire risk). Key consequences include:

For the network and equipment

- **Overheating of cables, transformers, neutral conductors**: Harmonic currents increase RMS current beyond what the fundamental would suggest; power losses increase (losses typically go as I^2R), so more heating occurs. For example: “Harmonics create heat in units proportional to the square of the harmonic order” (because current magnitude at higher order adds to heating). (elnet.cc)
- **Insulation aging and transformer saturation**: Harmonics can cause transformer core or winding saturation (especially odd triplen harmonics). This leads over time to insulation degradation and premature transformer failure. (irem.it)
- **Neutral conductor over-current**: In three-phase four-wire systems, triplen harmonics (3rd, 9th, 15th…) do not cancel but sum in the neutral, causing unexpectedly large neutral current and heating.
- **Resonance**: Capacitor banks, filters, the network impedance and harmonic currents may resonate at particular frequencies creating high amplitude voltages/currents at certain harmonic orders, causing overvoltage and/or overcurrents. (irem.it)
- **Malfunction of sensitive equipment**: Harmonic distortion in voltage can degrade the supply to sensitive electronics (computers, PLCs, drives), cause mis-operation, increased error rates, even tripping of protective devices. (elnet.cc)

- **Increased losses and thus higher energy costs**: The network and equipment operate less efficiently under higher harmonic distortion, meaning more energy wasted as heat. (novapower.com)
- **Poor power factor**: When reactive power or harmonic currents increase, the apparent power increases relative to real power. Poor power factor means you draw more current for the same real power, meaning higher I, more losses, larger conductor and transformer sizing, possibly higher charges from the utility.
- **Fire risk**: Overheating neutrals or phases, especially due to harmonic currents, can lead to insulation failure and fire hazard.
- **Equipment derating**: Motors, transformers, etc, may not operate at full capacity or may require derating under high harmonic conditions.
- **Voltage distortion for other consumers**: Harmonic currents injected by one consumer will create harmonic voltages that propagate and may affect neighbouring consumers.
- **Regulatory non-compliance and liability**: If harmonic levels exceed permitted values, there may be penalties, operational restrictions, or forced mitigation.

Poor power factor specific issues

Poor power factor (PF) means either low displacement PF (phase shift between current and voltage) or low distortion PF (due to harmonic currents). Consequences:

- Higher apparent current for same real power → increased losses (I^2R) in network and equipment.
- Utility may bill for reactive power or penalize for low PF.
- Equipment such as transformers/cables must be sized larger, increasing capital cost.
- Reduced capacity margin: more of the network’s capability is used up handling reactive or harmonic currents instead of delivering real power.
- In an extreme case, voltage drops increase, equipment may suffer from undervoltage.

Real-world cost and consequences

- Studies show that for European industry and networks the economic impact of power quality disturbances (including harmonics) runs into hundreds of millions (or billions) of euros annually. (MDPI)
- For residential networks the direct cost per household may be smaller, but when aggregated across many consumers, the effect is meaningful.

- For example: equipment lifespan shortened, more maintenance, more failures, potential fire hazard—all of which have real cost.
- The network operator may have to intervene (filtering, reinforcement) which adds cost.
- If households produce many harmonics (e.g., via many EV chargers or PV inverters) the DSO may need to limit injection or require additional equipment.

In short: high harmonic content and low power factor reduce reliability, increase losses and costs, shorten equipment life, and may create safety risks. Careful power-quality management is essential.

Legislation / regulations in Germany to limit harmonic components

In the German context and more broadly the D-A-CH-CZ (Germany-Austria-Switzerland-Czech) region, the regulatory/standard-framework includes:

- The European standard EN 50160 ("Voltage characteristics of electricity supplied by public distribution networks") sets general requirements for voltage (including harmonic distortion) at the PCC for public low-/medium-voltage networks. (powerquality.blog)
- The equipment standard IEC 61000-3-2 (and its European adoption) sets limits for harmonic currents generated by equipment up to 16 A per phase. (Wikipedia)
- The "Technical Rules for the Assessment of Network Disturbances – D-A-CH-CZ" (D–A–CH–CZ G) provide guidelines for connection of customer installations to the public grid, covering harmonic currents, interharmonics, superharmonics in Germany/Austria/Switzerland/Czech. For example, for harmonic currents orders ν=16…30, exceeding limit up to 1 % of IA; ν=31…40 up to 0.8 % of IA.
- The grid-connection codes for generating systems in Germany: e.g., VDE-AR-N 4105 (for low-voltage grid connection of PV generation) and VDE-AR-N 4110 etc (for medium voltage) include requirements on power quality, harmonics, reactive current, etc. (eldorado.tu-dortmund.de)
- In Germany, the standard / guideline for DC injection: e.g., a guideline states that an inverter must not inject more than 0.5 % of its rated current or 20 mA as DC component. (neo-messtechnik.com)
- National regulations (via the grid operator connection requirements) may require harmonic measurement, monitoring and filtering if required. Many DSOs in Germany include harmonic emission clauses in their connection conditions.

Specific example

From the D-A-CH-CZ guideline: "For harmonic currents of the orders ν = 16 .. 30, exceeding the limits is permitted up to 1 % of IA. For ν = 31 .. 40, up to 0.8 % of IA."

(IA = rated current of the installation)
Also the “Technical Rules for the Assessment of Network Disturbances” note that for much equipment orders up to 9 kHz must be considered. (A. Eberle)

In short

- Germany uses European standards (EN 50160, IEC 61000 series) plus its own national/region guidelines (VDE, D-A-CH-CZ) to limit harmonic emissions and ensure network power quality.
- For residential consumers the immediate regulatory obligations often lie with the equipment (via harmonics emission limits) and with the grid operators (ensuring supply voltage distortion stays within EN 50160). Large consumers or injectors may have direct obligations.
- If a consumer installs equipment that generates excessive harmonics or injection (e.g., large PV + inverter), the DSO may require filtering, limiting or additional conditions.

What can be done to improve power factor and reduce harmonics / improve power quality

Here are practical and technical measures that can be implemented in a residential or small-commercial context to improve power factor and mitigate harmonics.

Improving Power Factor

- **Capacitor banks**: Installing reactive power compensation (capacitors) to reduce reactive power draw and thereby improve displacement PF. Especially useful for inductive loads (motors, transformers).
- **Synchronous condensers or STATCOMs**: More advanced, may not apply typical residence but for larger installations, devices that supply reactive current.
- **Active power factor correction devices**: Devices that dynamically control reactive current to maintain near-unity power factor.
- **Load balancing and phasing**: Ensuring loads are well balanced across phases reduces neutral currents and improves overall PF and reduces distortion contribution.
- **Use of energy-efficient equipment**: Modern equipment tends to have built-in PF correction (switching supplies with PFC) – replacing older gear helps.
- **Battery storage with active control**: A battery system can be used not only for shifting energy but also to inject or absorb reactive current (or harmonic compensation) under some controllers, thereby improving PF and mitigating harmonics.

Mitigating Harmonics

- **Passive harmonic filters**: RLC circuits tuned to specific harmonic orders to bypass those harmonic currents or filter them out. For example, filters tuned to 5th and 7th harmonic for a drive. (irem.it)
- **Detuned capacitor banks**: Capacitor banks that include reactor in series (to avoid resonance at harmonic frequencies) are used instead of "straight" capacitors to avoid amplifying harmonics.
- **Active power filters (APF)**: These are power-electronics devices that inject counter-harmonic currents to cancel out harmonic currents at the point of coupling. They can handle multiple orders dynamically and also provide reactive compensation. (Wikipedia)
- **Harmonic injection limitation at the source**: Ensuring equipment connected (inverter, charger) meets harmonic emission standards (IEC 61000-3-2/-3-12), reducing harmonic generation in the first place.
- **Monitoring and measurement**: Use power quality analysers to measure harmonic currents and voltages, identify dominant orders, evaluate network impedance and locate compensation or filtering need. (A. Eberle)
- **Upgrading cable/transformer/connection if impedance high**: High source-impedance networks amplify the voltage distortion for a given harmonic current. By reducing impedance (e.g., larger conductor, better transformer) the voltage distortion reduces for same harmonic current.
- **Limiting number of harmonic-generating units**: For example in a neighbourhood many EV chargers or PV inverters, the DSO may require individual limiting, phase-shifting, or scheduling to avoid simultaneous distortion peaks.
- **Use of battery/inverter systems with grid support functionality**: Modern battery-inverter systems may include harmonic compensation, reactive current injection, and active filtering capability, improving both PF and harmonic profile.

Practical steps for a residence / small feeder

1. Conduct a power-quality measurement at the PCC (verify THD of voltage, individual harmonic orders, PF).
2. Identify large nonlinear loads (EV charger, heat pump inverter, major PV inverter) and check their emission/harmonic specification.
3. Review whether reactive power compensation is needed (especially if many induction motors etc).
4. Consider installing a passive filter (for known dominant orders like 5th, 7th) or active filter if budget allows.

5. Work with the DSO: if many PV/EV installations are present, check if the network connection conditions require harmonic mitigation.
6. Maintain good load balance across phases (especially in three-phase supply).
7. Replace old equipment that has poor PF or high harmonic emission (e.g., old switch-mode power supplies without PFC).
8. Monitor periodically, as load patterns change (e.g., EV chargers added).

Power factor & harmonic interplay

It’s important to note that harmonics and poor PF are linked: harmonic currents contribute to the “distortion” component of apparent power, meaning that even if displacement PF is good (phase shift small), distortion PF may be poor because of harmonic currents. Improving PF therefore must consider both reactive current and harmonic currents. Some solutions (active filters) can address both simultaneously.

Summary

- Harmonics from the 2nd to the 31st order can be present in a 50 Hz residential distribution line, with the lower odd orders (3rd, 5th, 7th, etc) being most prominent, but also higher orders matter.
- The main sources in a modern European residential grid are non-linear loads: switching supplies, inverters (PV, EV), variable drives, UPS, LED lighting, etc.
- Poor power quality (harmonics + poor PF) leads to increased losses, overheating, equipment ageing/failure, fire risk, malfunction of sensitive devices, increased costs.
- Germany (and the broader D-A-CH region) uses standards such as EN 50160, IEC 61000-3-2, and the Technical Rules for the Assessment of Network Disturbances to regulate harmonic emissions and supply voltage quality. Installations may be required to limit harmonic current emissions (for example for orders 16–30 up to ~1 % of rated current) and supply distortion at the supplier side must meet THD limits.
- Mitigation measures include: improving PF via capacitors/active devices, harmonic filtering (passive, active), ensuring equipment meets emission standards, measurement/monitoring, upgrading network impedance, battery/inverter systems with compensation function, balancing loads.

REGULATION DETAILS

Here are two detailed tables of reference-values: (1) for emission limits from the standard IEC 61000-3-2 (equipment with input current ≤ 16 A per phase) and (2) for grid connection limits from the D-A-CH-CZ guideline for harmonic currents in Germany/Austria/Switzerland/Czech (for orders ~16-40). These tables are reference only — actual permissible values in a specific installation may vary by utility/DSO, network impedance, connection contract, etc.

Table 1: Harmonic current emission limits (IEC 61000-3-2)

(this applies to equipment connected to the public low-voltage distribution system, input current ≤ 16 A per phase)
From article summaries of IEC 61000-3-2:2005/2014/2018. (allaboutcircuits.com)

Harmonic order (n)	**Max permissible harmonic current I_n for Class A equipment***
2	1.08 A (Reliantemc)
3	2.30 A (Reliantemc)
4	0.43 A (allaboutcircuits.com)
5	1.14 A (Reliantemc)
6	0.30 A (allaboutcircuits.com)
7	0.77 A (allaboutcircuits.com)
8 ≤ n ≤ 40 (even)	(0.23 × (8/n)) A (allaboutcircuits.com)
9	0.40 A (Scribd)
11	0.33 A (Scribd)
13	0.21 A (Scribd)
15 ≤ n ≤ 39 (odd)	(0.15 × (15/n)) A (Reliantemc)

*Class A = "balanced three-phase equipment, household equipment (excluding class D) etc." (Academy of EMC)
Note: For other equipment classes (B, C, D) the limits differ (Class B = Class A × 1.5, Class C for lighting equipment uses % of fundamental current, Class D for certain IT/TV equipment uses mA/W) according to the standard. (allaboutcircuits.com)

Interpretation / usage: For a piece of equipment rated say I_1 (fundamental current) you check the harmonic current I_n must not exceed the above values (or formulas) for the given order under the test conditions. This helps ensure that equipment does not inject excessive harmonic currents into the supply. Then network operators rely on these emissions limits to maintain overall power-quality.

Table 2: Grid connection / installation limits – D-A-CH-CZ Guideline (Germany/Austria/Switzerland/Czech)

(from the document "Technical Rules for the Assessment of Network Disturbances – D-A-CH-CZ, 3rd Ed 2021")
This covers harmonic current emission from installations (loads or generators) and provides simplified permissible values for orders especially ν = 16-40, given in terms of a percentage of the rated current IA of the installation.

Harmonic order ν	**Permitted emission (installation harmonic current)**
ν = 16 … 30	Up to **1 % of IA** (i.e., $I_n \leq 1$ % of rated current)
ν = 31 … 40	Up to **0.8 % of IA**

In the guideline the simplified formulas for orders 7-25 are also given (with resonance factor kν etc) but the explicit numeric values for each individual order are not provided in the publicly-available summary I found.

Also, the guideline includes a formula to convert harmonic current emissions into equivalent harmonic voltage emission at the point of connection (POC):
[
u_{ν,permPOC} = p_{ν} \cdot \frac{S_A}{S_{sc,POC}} \cdot k_{corr,ν} \cdot \dots
]
where p_n, S_A (installation power), S_sc,PCC (short-circuit power at point of coupling) and correction/resonance factors apply.

Interpretation / usage:

For a customer installation (e.g., residential + PV + EV charger) connected to the grid, the DSO will check that the harmonic currents injected (or drawn) by that installation (for orders 16-30 and 31-40) do not exceed 1 % and 0.8 % of the rated current respectively (unless a more detailed study is required).

Then using network parameters (short-circuit power, impedance etc) one can compute the resulting voltage distortion and verify the supply remains within voltage-quality requirements (e.g., per EN 50160).

If the installation is large or there is high simultaneous pollution, a full detailed harmonic study may be required.

Comments & caveats

- The IEC 61000-3-2 table (Table 1 above) is **equipment-emission** limits, not network connection limits. It applies to each piece of equipment drawing ≤ 16 A per phase. So it is good for e.g., household appliances, small PV inverters (if within that rating), chargers etc.
- The D-A-CH-CZ guideline (Table 2 above) is **installation / customer-connection** limits (for loads/ injectors) in the low-voltage network in the D-A-CH region (including Germany). It gives allowed harmonic current as a % of rated current for higher orders (16–40) and includes the method to derive permissible voltage emission.
- These tables do *not* list every harmonic order (2nd to 31st) explicitly with numeric values (especially for residential supply). For many harmonic orders the limits follow a formula or are "≤ X% of IA" without a distinct number for each harmonic order.
- For harmonics below order ~16 (i.e., 2nd, 3rd, 4th, 5th, 7th, 9th, 11th, 13th) connection-limits in the D-A-CH guideline may require a detailed study or be derived via network impedance/resonance calculations rather than fixed values alone.
- The actual permissible voltage distortion at the supply point is governed by standards such as EN 50160 (for example "95 % of the time the total harmonic voltage distortion THD_U ≤ 8 %" in many European countries) though national implementation may differ.
- Residential networks are often dominated by many small loads/injectors, so cumulative harmonics, diversity, network impedance/resonance become critical. Monitoring is strongly recommended.

THE IEC 61000-3-2 AND THE EN 50160

Here are **two detailed tables**:

1. **Permissible harmonic current emission limits** (for equipment) — giving what is available from IEC 61000-3-2 and its European adoption.
2. **Permissible harmonic voltage levels** (at the point of common coupling) — giving what is available from EN 50160 / IEC compatibility levels for LV supply.
   I also include notes on *typical measured ranges* in residential/small-consumer LV networks (where available).

1. Equipment harmonic current emission limits (IEC 61000-3-2)

This table covers equipment with input current ≤ 16 A per phase (single-phase/three-phase) that connects to public low-voltage supply. The limits are per harmonic order (up to 40th order) as specified by IEC 61000-3-2 (equipment emission standard). (cdn.tmi.yokogawa.com)

Harmonic order (n)	Typical limit (for Class A equipment) – harmonic current I_n (approx)
2nd	~1.08 A for small equipment (see table) (happylibnet.com)
3rd	~2.30 A (happylibnet.com)
4th	~0.43 A (happylibnet.com)
5th	~1.14 A (happylibnet.com)
6th	~0.30 A (happylibnet.com)
7th	~0.77 A (happylibnet.com)
8th & higher (even)	The standard gives a formula: e.g., ~0.23 A × (8/n) for 8th order onward (even) in older tables (happylibnet.com)
9th	~0.40 A (happylibnet.com)
11th	~0.33 A (happylibnet.com)
13th	~0.21 A (happylibnet.com)
15th and above (odd)	Formula given: ~0.15 A × (15/n) for odd orders 15 to 39 in older version. (happylibnet.com)

Notes & caveats:

- These are *equipment emissions* limits — i.e., how much harmonic current the piece of equipment is allowed to inject into the mains.

- For different classes (Class B, C, D) the limits differ (often more restrictive for lighting/PCs/TVs). (LISUN)
- The limits are given in absolute current (A) rather than percent of fundamental current for many orders in older text; newer standards may revise this.
- For an installation or consumer connection (rather than single equipment) different evaluation rules apply (see next sections).
- The standard goes up to 40th harmonic for many equipment types. (Wikipedia)

2. Harmonic voltage limits at the supply point (EN 50160 / compatibility levels)

These are *voltage* limits at the consumer supply point (low voltage) – i.e., what the public distribution network must supply or must not exceed in terms of harmonic voltage distortion. These values matter for your scenario (residential in Germany/Benelux).

From EN 50160 (and compatible sources) we have something like:

Harmonic order (h)	**Relative amplitude limit (U_h / U_1) – Low Voltage supply (percent of fundamental)**
2nd	2.0 % (Product Info)
3rd	5.0 % (multiples of 3) (Product Info)
4th	1.0 % (Product Info)
5th	6.0 % (not multiples of 3) (Product Info)
6th	0.5 % (Iteh Standards)
7th	5.0 % (Product Info)
9th	1.5 % (Product Info)
11th	3.5 % (Product Info)
13th	3.0 % (Product Info)
15th	0.5 % (Product Info)
17th	2.0 % (Product Info)
19th	1.5 % (Product Info)
21st	0.5 % (Product Info)
23rd	1.5 % (Product Info)
25th	1.5 % (Scribd)
>25th (even & odd)	0.5 % (some sources say even and odd above 25th) (Iteh Standards)

Harmonic order (h)	Relative amplitude limit (U_h / U_1) – Low Voltage supply (percent of fundamental)
Total Harmonic Distortion (THD) of voltage	≤ 8 % for LV supply (95% of the time)

Interpretation: For a typical 230 V (or 400 V three-phase) low-voltage residential supply in Europe, the voltage harmonics at each order must not exceed the percentages above (95% of the time). For example the 5th harmonic voltage must stay under ~6% of the fundamental for most of the time.

Typical measured ranges in practice

Although public data for each harmonic order in residential LV networks (Germany/Benelux) is somewhat limited, available measurement reports indicate:

- The 15th harmonic (and multiples of 3: 15th, 21st etc) are commonly among the more problematic orders in residential/small commercial LV networks. For example one German measurement found the 15th harmonic voltage exceeding the limit during office hours in a three-phase four-wire installation. (A. Eberle)
- Measurement campaigns indicate that as more nonlinear loads (LED lighting, EV chargers, inverters) are connected, higher order harmonics (above 13th) show significant presence especially if there are resonance conditions. (A. Eberle)
- Some reports refer to THD values (voltage) in residential grids being around a few percent (e.g., under ~5 % in many normal cases) but with occasional spikes above limits when many non-linear loads act simultaneously.
- Because each installation is different (transformer impedance, cable lengths, diversity of loads) actual values vary significantly.

3. Combined “full table style” for orders 2-31

Here below is a merged “reference table” for orders 2 through 31 combining what is available (limits) plus indicating “typical measured comment” where known. For many orders the exact limit is identical (or not special) and for some higher orders the standard gives “>25th” category.

Order	Approx limit (voltage)	Remarks / typical measured behaviour
2	2.0 %	Even harmonic; usually small; presence often indicates asymmetry or DC offset.
3	5.0 %	Triplen order; special concern in three-phase four-wire (neutral currents).
4	1.0 %	Even; less common.
5	~6.0 %	One of the predominant odd non-triplen harmonics; common in PWM, rectifiers.

Order	Approx limit (voltage)	Remarks / typical measured behaviour
6	0.5 %	Even; often small.
7	~5.0 %	Another common odd non-triplen; many nonlinear loads generate 5th and 7th.
8	0.5 %	Even; higher orders drop in magnitude.
9	1.5 %	Triplen (3×3) – in three-phase systems can sum in neutral; often monitored.
10	(even) – often <0.5 % by standard above 6th; not always listed specially.	
11	3.5 %	Odd non-triplen; present in many LV networks.
12	(even) ~0.5 % or less	
13	3.0 %	Odd; higher but still relevant.
14	(even) ~0.5 % or less	
15	0.5 %	Triplen (3×5) order; often cited as problematic.
16	(even >25th? — the “>25th” category says ~0.5 % for even)	For orders >25 generally 0.5 % (or 0.3 %) allowed.
17	2.0 %	Odd; present but less than lower orders.
18	(even) ~0.5 % or less	
19	1.5 %	Odd; still measurable.
20	(even) ~0.5 % or less	
21	0.5 %	Triplen order (3×7); usually small limit.
22	(even) ~0.5 % or less	
23	1.5 %	Odd; higher order.
24	(even) ~0.5 % or less	
25	1.5 %	Odd; up to 25th order still listed.
26	(even) >25th category ~0.5 %	
27	(odd) >25th category ~0.5 %	
28	(even) >25th category ~0.5 %	
29	(odd) >25th category ~0.5 %	
30	(even) >25th category ~0.5 %	

Order	Approx limit (voltage)	Remarks / typical measured behaviour
31	(odd) >25th category ~0.5 %	

Important caveats:

- For orders >25th the standard often gives a single unified category (“>25th”) rather than distinct limit per order.
- These values represent *voltage* distortion limits at the supply terminal, not current emissions per equipment.
- “Typical measured behaviour” is approximate and may vary widely by country, network impedance, time of day, consumer loads.
- Often the network operator or connection contract may impose even stricter limits locally, or require monitoring of higher orders up to 40th or even “supraharmonics”.

THE SIMULATION SOFTWARE

To complement the experimental measurements and analytical evaluation of harmonic distortion in residential power systems, a **custom simulation software** tool was developed. The main objective of this software is to provide a **visual and quantitative representation** of sinusoidal waveforms under varying levels of harmonic distortion, as typically observed in low-voltage (220 V AC, 50 Hz) power distribution networks. The tool was designed to aid researchers, engineers, and students in understanding how harmonic components influence the shape of the electrical voltage waveform supplied to consumers.

The software generates **two-dimensional (2D) graphical plots** representing the instantaneous waveform of the alternating voltage as delivered by a distribution provider to a household load. Its core functionality allows full **configurability of amplitude** and **selective adjustment of harmonic content**, expressed as a percentage of the fundamental component. This flexibility enables users to model and visualize realistic network conditions corresponding to specific Total Harmonic Distortion (THD) levels.

Mathematical Model

The waveform is generated numerically according to the standard Fourier series representation:

$$v(t) = V_1 \sin(2\pi f_1 t + \phi_1) + \sum_{n=2}^{N} V_n \sin(2\pi n f_1 t + \phi_n)$$

where:

- (V_1) is the RMS amplitude of the fundamental component (configurable),
- (f_1 = 50,\text{Hz}) is the nominal supply frequency,
- (V_n) represents the amplitude of the nth harmonic, expressed as a **percentage** of (V_1),
- (\phi_n) is the phase angle of the nth harmonic, and
- (N) is the maximum harmonic order considered (typically up to the 31st harmonic).

The software allows direct control over the percentage amplitude of each harmonic (V_n/V_1), either individually or as grouped sets (e.g., 3rd, 5th, 7th, 9th, etc.), thus enabling simulation of real-world conditions observed in different network configurations or equipment load profiles.

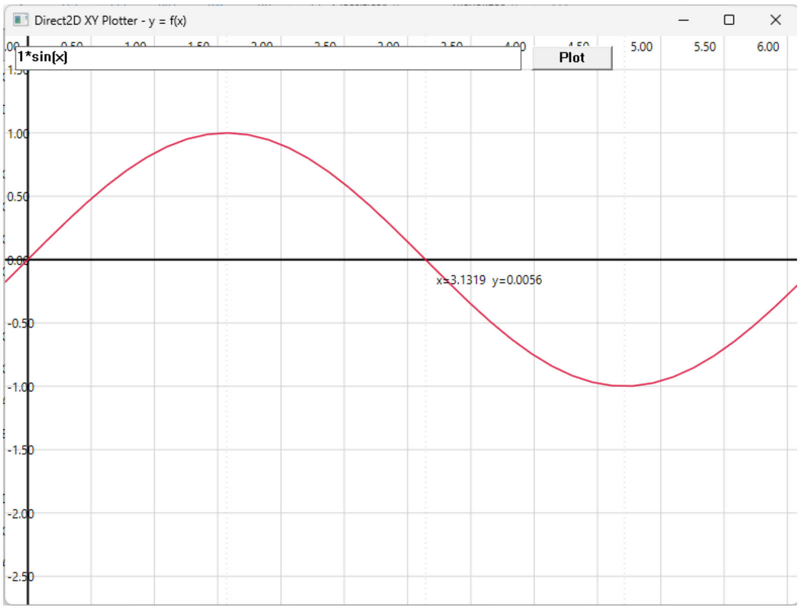
4.3 Implementation Details

The simulation engine was implemented in C++ 11 for Windows application, on the free development environment Microsoft Visual Studio Code, supporting numerical computation and dynamic plotting (Direct2D library). The graphical interface consists of a simple input panel and an interactive waveform viewer. The main features include:

- **Amplitude Control:** The user can set the RMS value of the base 50 Hz waveform, typically 220 V, adjustable to simulate undervoltage or overvoltage conditions.
- **Harmonic Injection:** Configurable harmonic distortion can be applied by setting a percentage contribution (e.g., 5% of 3rd harmonic, 3% of 5th harmonic, etc.).
- **Real-Time Graphing:** The resulting waveform is plotted as a **2D time-domain signal**, showing both the fundamental sine wave and the composite waveform including harmonics.

Visualization and Examples

Figure 1 shows an example of a simulated pure 220VAC waveform.

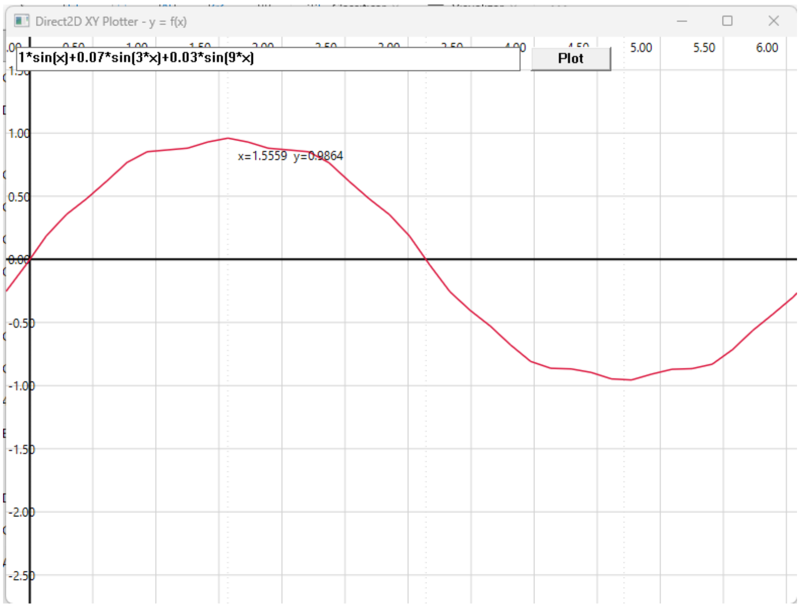


1*sin(x)

x=3.1319 y=0.0056

Figure 1 – simulation software, pure sinusoidal plot.

Figure 2 shows an example of a 220VAC waveform with 7% 3rd-harmonic and 3% 9th-harmonic.



1*sin(x)+0.07*sin(3*x)+0.03*sin(9*x)

x=1.5559 y=0.9864

Figure 2 – sinusoidal plot with 7% 3rd-harmonic and 3% 9th-harmonic.

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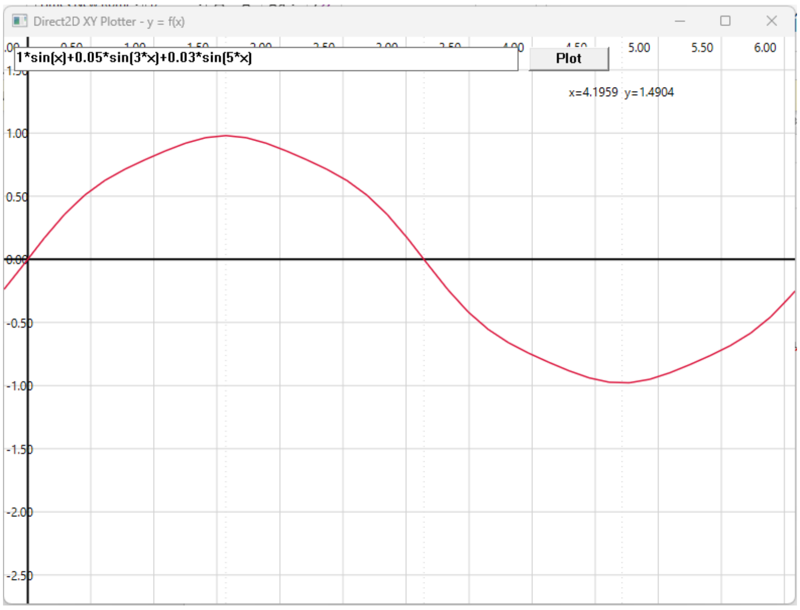
Figure 3 shows a 220VAC waveform with 5% 3rd-harmonic and 3% 5th-harmonic.



1*sin(x)+0.05*sin(3*x)+0.03*sin(5*x)

x=4.1959 y=1.4904

Figure 3 – sinusoidal plot with 5% 3rd-harmonic and 3% 5th-harmonic.

Figure 4 shows worst-case scenario according to European EN 50160 rules.

*sin(17*x)+0.015*sin(19*x)+0.005*sin(21*x)+0.015*sin(23*x)+0.015*sin(25*x)

x=4.6359 y=1.4904

Figure 4 – sinusoidal plot with worst-case according to European EN 50160.

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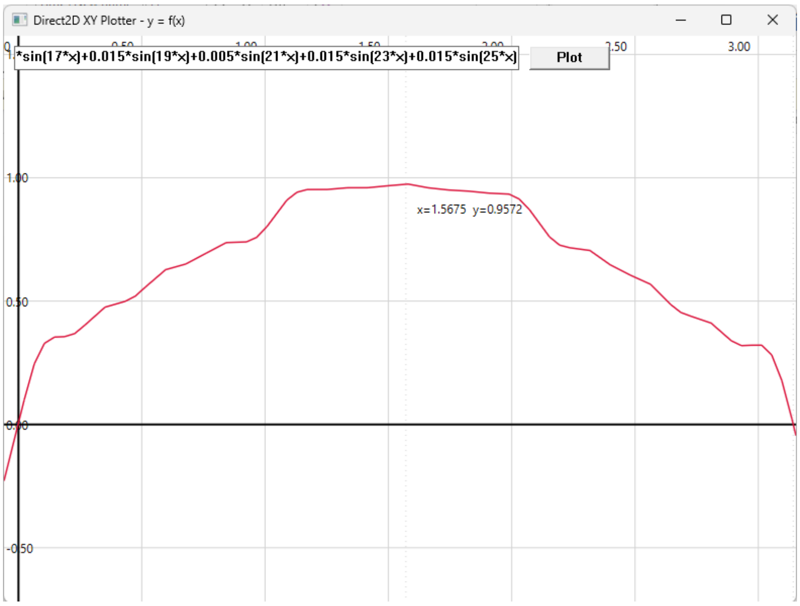
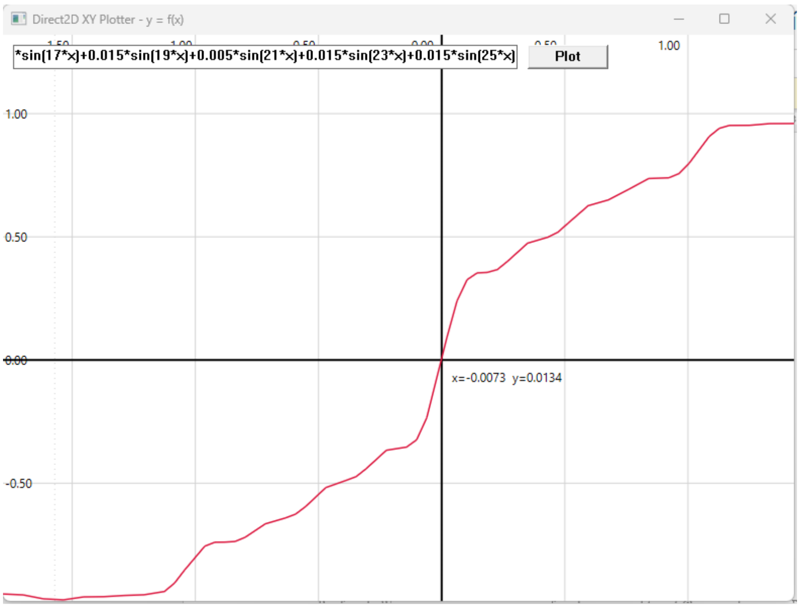
Figure 5 is figure 4 zoomed in.



```
*sin(17*x)+0.015*sin(19*x)+0.005*sin(21*x)+0.015*sin(23*x)+0.015*sin(25*x)
```

Figure 5 – zoomed-in worst-case according to European EN 50160.

Figure 6 is figure 4 zoomed in on zero-crossing.



```
*sin(17*x)+0.015*sin(19*x)+0.005*sin(21*x)+0.015*sin(23*x)+0.015*sin(25*x)
```

Figure 6 – zero-crossing worst-case according to European EN 50160.

As higher harmonics are introduced (e.g., 7th, 9th, 11th), the waveform displays increasingly sharper transitions, leading to distortion patterns similar to those observed in real grid voltage traces measured during load peaks with multiple nonlinear devices connected. The software thus provides a clear and pedagogical visualization of how cumulative harmonics affect waveform smoothness and electrical power quality.

Applications and Benefits

The developed simulation tool serves both **educational and diagnostic** purposes:

- It helps illustrate how specific harmonic components modify the waveform in time domain, supporting teaching and training in electrical engineering and power quality analysis.
- It can be used to **predict waveform distortion** before actual installation of nonlinear loads, supporting design decisions for residential or small commercial systems.
- It assists in **harmonic mitigation studies**, by enabling parametric "what-if" scenarios when testing filter designs or active compensation algorithms.

Moreover, by integrating artificial intelligence (AI)-based analytical modules, the software can be extended to automatically identify harmonic signatures from measured waveforms and compare them to simulated patterns, further bridging experimental and simulated analyses.

In summary, the developed simulation software provides a flexible, accurate, and accessible platform for studying the effects of harmonic distortion on 50 Hz AC supply waveforms. Through configurable amplitude and harmonic percentage parameters, it reproduces a wide range of realistic conditions found in modern residential grids. Its 2D graphical visualization enhances the understanding of Total Harmonic Distortion (THD) and its practical implications on power quality, serving as an effective complement to both laboratory measurement and theoretical study.

CONCLUSION

The investigation presented in this study provides a comprehensive overview of the harmonic distortion phenomena affecting 220 V / 50 Hz residential distribution networks across several European countries, with emphasis on Germany and neighboring regions such as the Netherlands, Belgium, Luxembourg, France, Italy, and the United Kingdom. The combination of theoretical analysis, reference to established standards, empirical findings from literature, and simulation-based visualization has enabled a detailed understanding of how non-fundamental components—harmonics from the 2nd to the 31st order—affect modern low-voltage electrical systems.

Harmonic distortion is an inherent byproduct of today's increasingly nonlinear and digitally controlled electrical environment. While traditional residential loads such as resistive heating and induction motors drew nearly sinusoidal currents, the widespread integration of **power electronic converters**—including switching-mode power supplies, LED drivers, PWM-controlled motors, photovoltaic (PV) inverters, and electric vehicle (EV) chargers—has altered the current waveform composition dramatically.

The study confirms that the **dominant harmonic orders** in residential systems are typically the **3rd, 5th, 7th, 9th, 11th, and 13th**, all odd multiples of the fundamental frequency. These harmonics are primarily produced by six-pulse rectifier structures and switching converters. The **triplen harmonics** (multiples of the 3rd) deserve special attention in three-phase four-wire systems, as they accumulate in the neutral conductor rather than cancel out, often leading to neutral overloading and excessive heating.

Even-order harmonics (2nd, 4th, 6th, etc.) are generally of lower magnitude and usually symptomatic of **asymmetrical load operation, DC offsets, or waveform clipping**. However, their presence should not be neglected, as they may indicate faults or malfunctioning power electronic interfaces.

Beyond the 15th harmonic, magnitudes generally decrease, yet higher-order harmonics (up to the 31st and even into the so-called "supraharmonic" range beyond 2 kHz) are becoming more prevalent due to modern fast-switching converters and pulse-width-modulated (PWM) inverters. These higher frequencies, although smaller in amplitude, can interact with system impedances, causing resonances, electromagnetic interference, and accelerated component aging.

The total harmonic distortion (THD) of voltage in low-voltage networks is typically expected to remain below **5–8 %**, as defined in EN 50160. Nevertheless, field observations in several European monitoring campaigns have shown instances where specific harmonic orders, particularly the **15th and 21st**, exceed permissible limits under high load or inverter activity conditions.

The implications of poor power quality extend beyond waveform aesthetics. From an electrical engineering standpoint, harmonics and poor power factor jointly deteriorate system efficiency, reliability, and safety. Increased RMS currents caused by harmonic components lead to **higher I^2R losses**, excessive heating in conductors, transformers, and switchgear, and elevated neutral currents in unbalanced systems.

Transformers are particularly vulnerable; harmonic-rich currents induce additional eddy current and hysteresis losses in cores, potentially leading to **magnetic saturation and insulation breakdown**. Motors and drives may experience torque pulsations and overheating. In severe cases, harmonic resonance between capacitor banks and line impedance can cause **overvoltage conditions**, triggering protective trips or even equipment failure.

Low power factor—whether due to reactive power or distortion power—forces the distribution network to carry larger apparent current for the same real power delivery. The result is **increased energy losses, higher voltage drops, reduced available capacity**, and potential utility penalties. The cumulative economic impact, although subtle at a per-household level, scales significantly across regional grids, contributing to billions of euros in annual inefficiency and infrastructure degradation across Europe.

European and national regulations play a central role in mitigating harmonic emissions. The **IEC 61000-3-2** standard limits the harmonic current emissions for equipment up to 16 A per phase, ensuring that end-user devices do not excessively pollute the grid. The **EN 50160** standard defines voltage quality at the point of common coupling (PCC), including permissible limits for individual harmonic voltages and total harmonic distortion.

In Germany, the **D-A-CH-CZ Technical Rules for the Assessment of Network Disturbances** provide detailed criteria for evaluating harmonic current emissions from installations. For harmonic orders **16–30**, emissions up to **1 % of the rated current (IA)** are permissible, and for **31–40**, up to **0.8 % of IA**. These rules are complemented by **VDE-AR-N 4105** and related standards governing the grid connection of generating units such as PV inverters, which must ensure compliance with harmonic and DC injection limits.

Collectively, these frameworks maintain a delicate balance: protecting grid integrity while allowing the growth of distributed generation and new load technologies. Adherence to these standards is critical to prevent local harmonic amplification, interconnection issues, and equipment incompatibilities.

The study identified a range of practical and technical methods for harmonic reduction and power factor enhancement, applicable both at the household and distribution network levels.

Passive filtering remains a simple and cost-effective approach, utilizing tuned L-C filters to attenuate specific low-order harmonics (typically 5th and 7th). However, passive filters are fixed-frequency devices and may interact unfavorably with varying system impedance. For more dynamic and broadband suppression, **active power filters**

(APFs) offer adaptive compensation by injecting counter-phase harmonic currents and reactive power, simultaneously improving both THD and power factor.

Capacitor banks continue to serve as traditional reactive power compensation tools, especially for inductive loads. When used in harmonic-rich environments, however, they should be **detuned with series reactors** to avoid resonance effects. Modern **battery energy storage systems (BESS)** and **smart inverters** can now perform active harmonic and reactive compensation, supporting grid stability while serving their primary energy-shifting functions.

Load balancing across phases, periodic power-quality audits, and replacement of outdated devices lacking power factor correction (PFC) circuitry are equally essential for long-term harmonic management.

The self-developed **harmonic simulation software** proved to be a valuable analytical instrument in this study. By enabling the user to configure amplitude and individual harmonic percentages, the software visualizes the gradual deformation of the sinusoidal waveform as distortion increases. The generated 2D plots effectively illustrate how even small harmonic contributions (e.g., 5 % of 3rd or 5th order) introduce visible flattening, asymmetry, or peaking, making the abstract concept of THD tangible for researchers and students alike.

This visualization capability bridges the gap between theoretical Fourier analysis and real-world waveform observation, providing a didactic and diagnostic tool that can support further research on grid modeling, filtering design, and AI-based harmonic prediction.

The findings of this research underscore the **growing importance of harmonic management** in residential and small-scale distributed networks as electrification, digitalization, and renewable integration accelerate. The coexistence of multiple nonlinear devices within limited low-voltage feeders demands continuous monitoring, adherence to international standards, and deployment of adaptive compensation technologies.

Ensuring **power quality compliance** is not merely a matter of regulatory conformity but a prerequisite for **energy efficiency, equipment reliability, and grid resilience** in Europe's evolving electrical landscape. By combining measurement, simulation, and intelligent control, the impact of harmonics can be minimized, enabling a cleaner and more stable transition toward carbon-neutral power systems.

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