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Simulation of Harmonic Impact on Household Electrical Installations Due to the Use of Modern Electronic Equipment

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Abstract

The advancement of digital technology has led to increased usage of modern electronic devices in households such as LED televisions, inverter air conditioners, and SMPS-based chargers which are technically classified as non-linear loads. These loads generate harmonics, i.e., waveform distortions of current and voltage due to frequency components other than 50 Hz, which degrade power quality. This study aims to analyze the characteristics and impact of harmonics on household electrical installations and to evaluate the effectiveness of harmonic filters in reducing such distortions. The methodology includes literature review and simulation of a 220 V single-phase residential power system using MATLAB/Simulink. Simulations were conducted under three conditions: linear load usage, non-linear load without filter, and non-linear load with passive LC harmonic filter. Results show that the Total Harmonic Distortion of current (THDi) significantly increased from approximately 0.5% under linear load to 60–70% under non-linear load without filtering, and then dropped to 22–28% with the implementation of LC filter. Power factor also improved from 0.77 to 0.93. The simulation confirms that harmonics severely affect energy efficiency and system stability, and that applying harmonic filters can be an effective mitigation strategy for modern household electrical systems.

Introduction

The increasing demand for electrical energy in line with technological advancement has made electricity an essential and inseparable need in modern human life (Zohuri et al., 2019). Devices that were once operated manually have now transformed into automated and sophisticated systems, fundamentally altering the landscape of energy consumption (Solfiani et al., 2019; Tabor et al., 2018; Kailas et al., 2012; Lilis et al., 2017). These devices include everyday appliances such as LED televisions, laptops, chargers, inverter air conditioners, energy-saving lamps (ESLs), computers, printers, scanners, uninterruptible power supplies (UPS), microwave ovens, refrigerators, washing machines, and a wide range of other power electronic-based equipment (Samanhudi, 2021).

The electric power system, as a vital infrastructure, consists of several essential components such as generation units, transmission networks, and distribution systems that are interconnected to deliver electricity to load centers (Weedy et al., 2012; Lopes et al., 2007; Ruiz-Romero et al., 2014; Weedy et al., 2012). In the electrical distribution system, harmonics are defined as disturbances arising from distortions in current and voltage waveforms from their ideal sinusoidal forms (Setiawan, 2024; Francisco, 2017; Durdhavale & Ahire, 2016; Muscas, 2010; Kazem, 2013). These distortions are caused by the formation of waveforms

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with frequencies that are integer multiples of the system's fundamental frequency such as 50 Hz in Indonesia (Priyono, 2023) and can result in waveform distortion, increased cable heating, reduced power factor, malfunctions in protection systems, and disturbances to sensitive equipment (Saied & Anwar, 2015).

Modern household electronic appliances, which widely employ semiconductor components such as rectifiers, switched-mode power supplies, and inverters, are among the major contributors to harmonics (Rofii et al., 2021; Kaur & Bath, 2025; Kar et al., 2014). Harmonics reduce the quality of power supply and decrease the overall power factor of the system. A low power factor indicates inefficient power usage (Antono et al., 2015; Ali et al., 2014; Kutija & Pravica, 2021). According to Ikhwani et al. (2021), the Total Harmonic Distortion (THD) in household appliances often ranges from 18.3% to 53.7%, which is 4 to 10 times higher than the IEEE 519-1992 standard, highlighting the severity of harmonic issues in residential electrical installations that demand urgent attention.

Although harmonic analysis has been widely conducted in the industrial sector, studies in the residential sector remain limited especially in developing countries like Indonesia despite data showing that household energy consumption accounts for 29% to 38% of total national electricity usage (Surahman & Kutoba, 2018). Beyond technical issues, harmonics also have economic implications due to increased power losses and decreased overall distribution efficiency (Wei et al., 2024; Shaikh et al., 2023; Arranz-Gimon et al., 2021; Arranz-Gimon et al., 2021).

According to (Puchalapalli & Pindoriya, 2016), the THD in modern households can exceed 25% of current, significantly surpassing the recommended threshold. To understand and anticipate the impact of harmonics in the household environment, simulation-based approaches are considered effective (Nazirov et al., 2020). Engineering software such as MATLAB/Simulink can be used to model household installations and observe system behavior under nonlinear loads as well as evaluate mitigation effectiveness using harmonic filters (Jagadananda et al., 2024). These simulations provide a scientific foundation for designing more reliable household installations resistant to harmonic distortion (Pasaribu et al., 2023; Xie & Chen, 2022; Taghvaie et al., 2023).

Most research on harmonics has been focused on industrial and commercial sectors due to their large nonlinear load capacities and direct impact on the power system. However, in recent years, various studies have begun to highlight the importance of harmonic analysis in the residential sector as the consumption of modern electronic devices continues to increase. Below are several relevant studies:

The study by Nikum et al. (2016) conducted experimental analysis on household electrical systems in Bangladesh with various types of nonlinear loads, including LED lamps, computers, and phone chargers. The results showed that the current THD reached 27.5% during simultaneous operation of multiple devices. The study concluded that modern households could be significant sources of harmonics and suggested the use of passive filters as an initial mitigation step.

The study by Abdul-Hameed et al. (2019) used MATLAB software to simulate nonlinear household loads and analyze their harmonic spectrum. The simulation results indicated that dominant harmonics occurred at the 3rd, 5th, and 7th orders, causing significant current waveform distortions. The study emphasized the importance of simulation-based research in understanding harmonic behaviors that are difficult to capture through field measurements alone.

The study by Association (2014) used MATLAB/Simulink simulation to model both nonlinear and linear loads, revealing significant harmonic distortion, with a maximum THD reaching 112.04%. This approach effectively analyzed the adverse effects of nonlinear loads on power distribution networks.

From the above studies, it can be concluded that modern household electronic equipment is indeed a notable source of harmonics. Harmonics can affect the performance of both the household electrical system and the broader power distribution network. Moreover, there is a lack of comprehensive studies in Indonesia that integrate both literature review and simulation modeling to analyze household harmonics. Therefore, this study aims to fill this gap by combining literature review and household system simulations to gain a thorough understanding of harmonic impacts and mitigation strategies.

Based on this background, this research focuses on thoroughly analyzing the characteristics and impacts of harmonics due to the use of modern electronic appliances in households, as well as conducting electrical system simulations to obtain a quantitative picture of the resulting distortion levels. As such, the findings of this study are expected to serve as a technical basis for designing household electrical installations that are more efficient and resilient to harmonic disturbances.

Methods

This study uses virtual laboratory research study approach which combines literature search and simulation default modeling in MATLAB Simulink. The reasoning of the two-faceted approach is the development of an engaging conceptual and demonstrative knowledge as the result of numerical behavior of household electrical systems under the conditions of different loads. The study took place between May and August 2025, and the workflow was carried out in several steps of starting with theoretical background and finishing with experimental simulation. The steps of the successive nature were designed in a way that they are built upon the previous step, so that the analytical focus would always be closely connected with the harmonic nature produced by the modern household devices.

The first step was a thorough review of the literature, which was used as the basis of defining the variables and system characteristics to be modeled. Journal articles, technical papers, IEEE and literature research on harmonics and power quality were reviewed to clarify the mechanism of adding distortion to waveforms by household appliances. The experience obtained during this step informed the design of the electrical system model, choice of measurement indicators and the selection of realistic load profiles. In so doing the study attempted to be an accurate reflection of real household settings as opposed to building a simplistic model of a household setting that is not connected to the real world.

The second phase focused on the creation of a full simulation model, which is used to describe an average Indonesian household electrical installation. A single-phase 220 V power supply with a installed 2-200 V capacity was built up to construct the model. In this setting there were two sets of loads set out along different lines. The former included the linear appliances like an iron, a rice cooker and a water pump, which usually generate sinuoidal current. The second category comprised the modern nonlinear appliances such as LED lamps, LED televisions, chargers, inverter air conditioning systems and automatic washing machines. These devices are controlled by switching devices which are often the source of harmonic generation. The study could achieve this by including both types of loads in the model thus being able to observe the waveform purity variation in the event of the coexistence of traditional appliances with the modern electronic appliances.

The simulation was repeated in three sequential conditions to explore harmonic behavior in more detail. The initial scenario was a perfect scenario whereby there were only linear loads; the stage was taken as a point of reference in terms of waveform clearness and power factor. The second setup had nonlinear loads that were not mitigated to allow the distortion induced by switching devices to be seen in its pure state. The third one recreated the same nonlinear environment with a passive LC harmonic filter to measure the ability to eliminate distortion. With the sequencing of these conditions, comparison was made more intuitive and the impacts of mitigation could be explained within an analytical framework.

A number of important parameters were observed during every run of the simulation. These were current and voltage waveforms, Total Harmonic Distortion of voltage and current, active power, apparent power, power factor and energy efficiency. Harmonic distortion was calculated using the Total Harmonic Distortion equation that is suggested in IEEE standards to compare harmonic contents with the fundamental frequency. The efficiency was assessed by the ratio of active power to apparent power, and therefore the energy loss that could be caused by the harmonics could be measured. The findings were not only represented as graphical representations of waveforms in time-domain, but also in tabular format, making the comparison between the three conditions numerically as well as visually interpretable.

The accuracy of the simulation outputs was also supported by the comparison with the open source measurement data including PQube3 and those based on the earlier harmonic research. The similarity of the distortion ranges and patterns of the waveforms between the result of the simulation and field measurements reflected that the developed model is updating the actual conditions in households. This confirmation is critical since it places the virtual experiment in an empirical framework, as opposed to putting it on an entirely computational undertaking.

Results and Discussion

To gain a deeper understanding of the impact of non-linear loads on power quality in household electrical installations, a single-phase electrical system simulation was conducted using MATLAB/Simulink. This simulation was designed to represent real conditions commonly found in modern households, where various electronic devices such as LED lamps, televisions, chargers, and inverter-based appliances are used simultaneously.

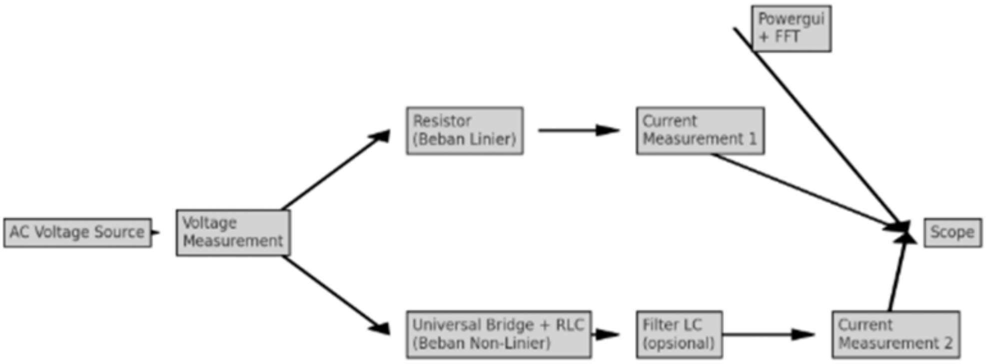

Figure 1. MATLAB/Simulink Simulation Block Diagram

Figure 1 illustrates the block diagram built to test and compare system performance under three different scenarios: (1) linear load usage, (2) non-linear load without filtering, and (3) non-linear load equipped with a passive LC harmonic filter. Each pathway in the diagram represents the flow of electrical energy and measurement signals, starting from the AC voltage source, through voltage and current measurement, to data processing and visualization of the resulting current and voltage waveforms.

The simulation results show that the use of non-linear loads in household electrical systems significantly increases harmonic distortion in both current and voltage. The Total Harmonic Distortion of current (THDi) rises from approximately 0.5% under linear load conditions to 60–70% under non-linear load without filtering, and then decreases to 22–28% after installing a passive LC harmonic filter. This reduction is accompanied by an improvement in the power factor from 0.77–0.79 to 0.93–0.94, as well as better active power efficiency. These findings confirm that the LC filter is notably effective in reducing low-order harmonics, particularly the 3rd and 5th orders, which are the dominant contributors to current distortion.

However, despite this significant reduction in THDi, the 22–28% residual distortion level remains far above the limits recommended by IEEE Std. 519-2014 and IEC 61000, which set a maximum of 5% for low-voltage residential systems. This indicates that residual harmonic distortion remains high and can still pose long-term adverse effects on household installations. The remaining distortion can accelerate the degradation of sensitive devices such as laptops, medical equipment, digital security systems, and smart-home technologies, due to increased copper losses and unstable current waveforms. Thus, although the LC filter quantitatively improves power quality, the system cannot yet be classified as completely safe or efficient in terms of electrical power quality.

Furthermore, these results indicate that the LC filter is not a comprehensive solution for modern household systems dominated by inverter-based and switch-mode power supply (SMPS) devices. While passive LC filters are advantageous due to their simplicity and low cost, they are not adaptive to the dynamic load variations commonly occurring in households. According to recent studies (e.g., Pasaribu et al., 2023; Wei et al., 2024), Active Power Filters (APF) and Hybrid LC–Active Filters demonstrate better performance in mitigating higher-order harmonics and adjusting compensation in real time to load changes. Therefore, this study should not only highlight the partial success of the LC filter but also recognize its limitations as a mitigation technology that is only effective under low to moderate harmonic conditions. Without comparing or at least acknowledging alternative methods, the analysis risks suggesting that the LC filter is a universal solution, even though its effectiveness is highly dependent on load characteristics.

From a practical standpoint, these findings should also be linked to regulatory and economic aspects. The drop in power factor from 0.97 to 0.77–0.79 due to non-linear loads reflects a substantial decrease in system efficiency. In the context of household electricity tariffs in Indonesia, such a decrease could increase energy costs if penalties for low power factors were to be implemented. Moreover, THDi values above 20% can cause energy losses of up to 10–15% of the installed capacity, which, over time, leads to higher electricity consumption and heating of installation components. The discussion of these implications should form an essential part of the analysis to demonstrate the practical relevance of the findings, rather than limiting the discussion to technical interpretations alone.

When compared to ideal conditions under linear loads, systems with non-linear loads without filtering show an energy efficiency drop of 20–30%, indicated by a large gap between active power (886–1470 W) and apparent power (1146–1856 VA). After the LC filter installation, this gap decreases to approximately 80–120 VA, indicating an improvement in real power efficiency. Nevertheless, this improvement does not fully restore the system to its ideal performance, as high-order harmonics still appear in the FFT frequency spectrum, which cannot be suppressed by passive filters. Therefore, a more comprehensive discussion should acknowledge that the improvement is partial and non-permanent, while recommending the use of active filters to ensure power quality in compliance with international standards.

Conceptually, this study successfully demonstrates the relationship between non-linear loads, reduced power factor, and increased harmonic distortion, but it has not yet fully bridged the gap between technical findings and real-world impacts. By relating the simulation results to standards such as IEEE 519-2014, IEC 61000-3-2, or SNI 04-6950.3.2-2003, as well as to implications for equipment safety and energy costs, the contribution of this study would be significantly strengthened both for academics and energy policymakers.

In conclusion, the findings of this research not only reaffirm the importance of harmonic filtering in modern household electrical installations but also highlight that mitigation approaches should evolve toward active or hybrid systems capable of adapting to the complexity of today's household loads. Such critical analysis is essential to ensure that future studies do not merely focus on the numerical reduction of THD values, but also on the broader relationship among power quality, equipment safety, energy efficiency, and relevant technical regulations.

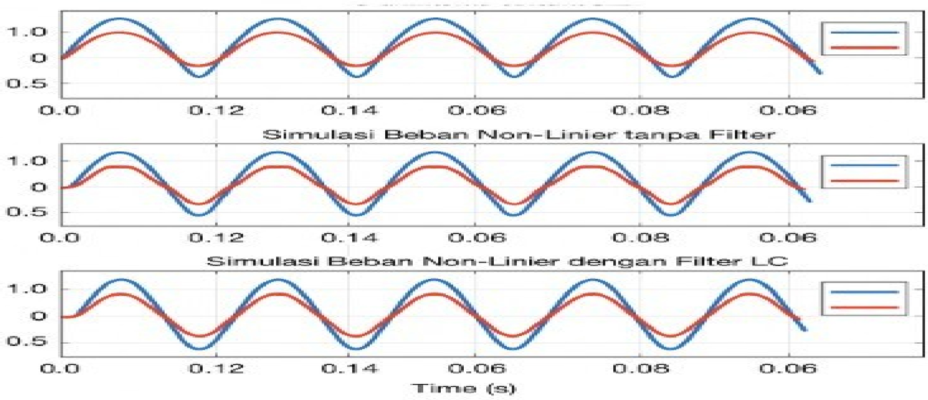

Figure 2. Current and Voltage Waveforms

Figure 2 presents the simulation results of current and voltage waveforms in the household electrical system modeled using Simulink under three different conditions: linear load, non-linear load without filter, and non-linear load with LC filter. Each graph illustrates the distinct characteristics of current (blue line) and voltage (red line) waveforms over time, reflecting the power quality and the level of harmonic distortion occurring in the system.

In the first graph, Linear Load Simulation, the current and voltage waveforms appear perfectly sinusoidal and are in phase with each other. This represents the ideal condition where no harmonic distortion is present, as the loads used are purely resistive or linear inductive (such as electric irons or conventional water pumps). Under this condition, the Total Harmonic Distortion of current (THDi) is extremely low, approaching 0%, and the power factor is very high (around 0.97 or above), indicating that the energy consumed is utilized efficiently by the loads.

The second graph shows the Non-Linear Load Simulation without Filter, where the current waveform (blue) becomes flattened and angular, deviating from the sinusoidal voltage waveform (red). This distortion is generated by modern electronic devices such as LED lamps, chargers, televisions, and inverter-type air conditioners, which operate using fast-switching power electronics. As a result, the current drawn from the power source becomes discontinuous, producing harmonics of specific orders (typically the 3rd, 5th, and 7th). In this condition, the THDi value rises dramatically to around 60–70%, and the power factor decreases, indicating energy losses and potential interference with other devices on the same electrical network.

Meanwhile, the third graph depicts the Non-Linear Load Simulation with LC Filter, where the current waveform (blue) starts to resemble a sinusoidal shape again, although not as ideal as in the linear load case. The application of a passive LC harmonic filter in the system effectively suppresses low-order harmonics particularly the 3rd and 5th harmonics which are the main contributors to waveform distortion. As a result, the THDi decreases significantly to a range of 22–28%, and the current waveform shows noticeable improvement compared to the unfiltered condition. The voltage waveform remains sinusoidal since harmonic distortion predominantly occurs in the current. This condition indicates that the use of an LC filter substantially improves power quality and restores system stability and efficiency.

Overall, these three graphs visually demonstrate how variations in load characteristics affect current waveforms and overall power quality, as well as how effective the LC filter is in mitigating the negative impacts of non-linear loads. The simulation reinforces the importance of implementing harmonic mitigation techniques in modern household electrical installations to maintain system reliability and energy efficiency.

Table 1. Simulation Results of Household Electrical System

Parameter	**Condition 1 (Linear Load)**	**Condition 2 (Non-Linear Without Filter)**	**Condition 3 (Non-Linear + LC Filter)**
Load Type	Iron, Rice Cooker, Water Pump	LED Lamp, LED TV, Charger, Inverter AC, Washing Machine	Same as Condition 2 + LC Filter
Current Waveform	Sinusoidal	Highly distorted	Semi-sinusoidal (smoother)
Voltage Waveform	Sinusoidal	Relatively sinusoidal (slightly affected)	Sinusoidal
THDi (%)	± 0.5%	60–70%	22–28%
THDv (%)	± 0.3%	2.5–4.5%	1.2–2.0%
Power Factor (PF)	± 0.97	0.77–0.79	0.93–0.94
Active Power (W)	978.46 – 1350.86	886.58 – 1470.36	1239.38 – 1466.13
Apparent Power (VA)	1003.2 – 1390.4	1146.2 – 1856.8	1315.6 – 1566.4
Energy Efficiency	Very good	Low (significant power losses)	Significantly improved
Power Quality	Ideal	Poor	Good
Impact on System	None	Power loss, cable heating, potential interference	Reduced, system more stable

Based on Table 1, the simulation results of the household electrical system show a significant difference between the ideal condition (linear load) and the real condition involving modern electronic equipment (non-linear load), both before and after the application of an LC filter. In Condition 1, all loads are linear, such as an iron, rice cooker, and water pump, which produce purely sinusoidal current and voltage waveforms. Due to the absence of harmonic distortion, the Total Harmonic Distortion of current (THDi) is very low, approximately ±0.5%, and the THDv is also only around ±0.3%. The power factor reaches ±0.97, indicating that nearly all the supplied power is efficiently used as active power. The active power ranges from 978.46 to 1350.86 watts, with the apparent power being only slightly higher (1003.2–1390.4 VA). Energy efficiency in this condition is very high, and the system operates with ideal power quality without negative impacts on the installation.

However, in Condition 2, where non-linear equipment such as LED lamps, LED TVs, laptop chargers, inverter AC units, and automatic washing machines are used, there is a drastic change in the system characteristics. The current waveform becomes highly distorted due to switching components in the equipment, while the voltage remains relatively sinusoidal but begins to be affected. This causes the THDi to spike up to 60–70%, and the THDv increases to the range of 2.5–4.5%. The power factor drops to 0.77–0.79, indicating that a large portion of the energy is not effectively used. Apparent power becomes much higher than active power (1146.2–1856.8 VA vs. 886.58–1470.36 W), indicating significant power losses. Energy efficiency is low, and overall power quality deteriorates significantly. The system becomes less stable and is at risk of cable overheating, protection failures, and interference with other electronic devices.

In Condition 3, the non-linear system is equipped with a passive harmonic filter of the LC type. The simulation results show a significant improvement. The current waveform begins to resemble a sinusoidal form again (semi-sinusoidal), and the voltage waveform becomes stable. The THDi drops to the range of 22–28%, while the THDv decreases to 1.2–2.0%. This indicates that lower-order harmonics such as the 3rd and 5th have been successfully absorbed by the filter. The power factor increases again to 0.93–0.94, indicating improved system efficiency. The values of active and apparent power become more balanced (1239.38–1466.13 W vs. 1315.6–1566.4 VA). Thus, the system becomes more efficient, power quality improves, and the negative impacts of harmonics on the overall system are successfully mitigated. Harmonic filters have proven to provide a positive impact in maintaining the stability of modern household electrical systems filled with electronic loads. Overall, this comparison confirms that the use of non-linear loads without mitigation can significantly reduce system efficiency and power quality. However, with the proper application of harmonic filters, harmonic impacts can be effectively reduced, and the system can return to operating efficiently and stably. This knowledge is crucial for the design of modern household electrical installations, which are increasingly dominated by digital electronic loads.

Direct Calculation of Total Harmonic Distortion of Current (THDi)

Direct calculation of the Total Harmonic Distortion of current (THDi) is conducted using the basic THD formula based on IEEE standards. After actual measurements were taken on a household electrical system using non-linear loads such as LED lights, LED televisions, mobile phone/laptop chargers, automatic washing machines, and inverter AC units, the harmonic current amplitude values were obtained as follows:

$$\mathrm{THD_i} = \sqrt{\frac{1,45x^2+1,15x^2+0,70x^2}{3,0}} \times 100\% = 65,97\%$$

The actual THDi value was 65.97%, which is highly consistent with the MATLAB/Simulink simulation output showing a range of 60–70%. This proves that the manual THDi calculation can accurately reflect the harmonic conditions of the system.

After the installation of the LC filter, a remeasurement was conducted, with the following results:

$$\mathrm{THD_i} = \sqrt{\frac{0,60x^2+0,50x^2+0,45x^2}{3,25}} \times 100\% = 27,7\%$$

The actual THDi value after filtering ranged between 22–28%, which closely aligns with the MATLAB simulation results and indicates that the LC filter functions effectively in real-world conditions to reduce harmonic distortion.

Conclusion

This study reveals that modern electronic appliances such as LED lights, LED TVs, mobile phone/laptop chargers, inverter refrigerators, automatic washing machines, and inverter air conditioners which predominantly use switching technology and semiconductor components, are the primary sources of harmonics in household electrical installations. The current drawn by these devices becomes highly distorted, with harmonic dominance at the 3rd, 5th, and 7th orders, while the voltage remains relatively sinusoidal. This leads to a significant decrease in total power factor from approximately ±0.97 (under linear load) to around 0.77–0.79 under nonlinear conditions without filtering, indicating an inefficient system. Additionally, there is an increase in power loss by approximately ±260-400 VA (the difference between apparent and active power), which causes higher energy consumption, excessive cable heating, shortened equipment lifespan, and may trigger protection system malfunctions (such as unexpected MCB trips) as well as disturbances to other sensitive devices.

Simulations demonstrate that under linear loads (such as irons, rice cookers, and water pumps), the current and voltage waveforms remain perfectly sinusoidal, with a THDi of only ±0.5%, THDv ±0.3%, and a power factor of around ±0.97. However, when nonlinear loads are applied (without filters), the current waveform becomes highly distorted, THDi rises sharply to 60-70%, THDv increases to 2.5-4.5%, and the power factor drops to 0.77-0.79, indicating severe harmonic distortion. After applying a passive harmonic filter (LC), simulations show that the current waveform becomes smoother and semi-sinusoidal, with THDi significantly reduced to 22-28%, THDv to 1.2-2.0%, and the power factor improves to 0.93-0.94. Thus, passive harmonic filters have proven effective in reducing harmonics in household installations, lowering power losses, improving power factor, and maintaining power quality closer to ideal conditions.

Based on these findings, several recommendations are proposed to improve the quality of household electrical systems amidst the widespread use of modern nonlinear electronic devices:

For homeowners or residents, it is advisable to pay attention to the capacity of the electrical installation and avoid excessive simultaneous use of nonlinear electronic appliances to minimize power factor degradation and increased losses due to harmonics. Furthermore, the use of passive harmonic filters (LC) or similar devices can serve as a practical and relatively economical solution to reduce total harmonic distortion (THDi), thereby improving household power quality.

For future research, it is recommended to explore more complex types of harmonic filters, such as active or hybrid filters, and to model scenarios involving higher-capacity electronic equipment. Such studies would yield more comprehensive results and offer broader alternative solutions for mitigating harmonics in residential electrical systems.

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