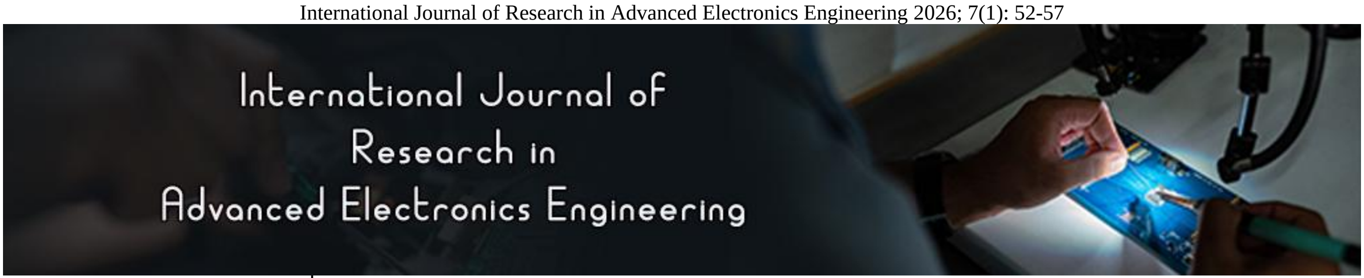

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Arduino-based portable harmonics analyzer for single-phase domestic loads

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Abstract

The proliferation of electronic devices employing switch-mode power supplies has dramatically increased harmonic distortion in residential electrical systems, yet the cost of commercial harmonic analyzers places routine monitoring beyond reach of most homeowners and small-scale investigators. This research presents the development and validation of a portable harmonics analyzer based on the Arduino Mega microcontroller platform, designed specifically for characterizing single-phase domestic loads at a fraction of commercial instrument costs. The analyzer employs a ZMPT101B voltage sensor and ACS712 current sensor interfaced to the Arduino's 10-bit analog-to-digital converters, sampling at 5.12 kHz to capture harmonic content up to the 25th order at Japan's 50 Hz mains frequency. A 256-point Fast Fourier Transform algorithm implemented in optimized C code extracts individual harmonic magnitudes, from which total harmonic distortion calculations derive. Results display on a 3.5-inch TFT screen showing harmonic spectrum bar graphs and numerical THD values, with SD card logging enabling extended monitoring sessions. Validation testing across ten representative domestic appliance categories compared Arduino measurements against a calibrated Hioki 3197 power quality analyzer serving as reference standard. The portable analyzer achieved current THD measurement accuracy within ±2.5% across the tested appliance range, with correlation coefficient of 0.9998 demonstrating excellent linear agreement with reference values. Individual harmonic magnitude accuracy ranged from ±1.5% for the fundamental component to ±4.1% for higher-order harmonics where absolute magnitudes diminish. Field characterization revealed that switch-mode power supply based devices including LED lamps, phone chargers, and laptop adapters exhibited current THD values ranging from 71% to 129%, substantially exceeding the nominally linear loads such as incandescent lamps and resistive heaters measuring below 5% THD. The measurements quantify the harmonic injection characteristics that aggregate across residential installations, contributing to distribution system power quality concerns. The complete analyzer hardware costs approximately ¥7,500 (roughly $50 USD), representing less than 2% of equivalent commercial instrument pricing while providing measurement capability adequate for educational purposes, residential surveys, and preliminary power quality assessments. The research demonstrates that meaningful harmonic analysis can be achieved with consumer-grade components, democratizing access to power quality instrumentation previously restricted to well-equipped laboratories and industrial facilities.

Keywords: Harmonics analyzer, Arduino, total harmonic distortion, power quality, FFT, domestic loads, single-phase measurement, portable instrument, Japan

Introduction

The humble phone charger sitting inconspicuously in millions of Japanese homes draws current in sharp pulses that bear little resemblance to the smooth sinusoidal supply voltage, injecting harmonic frequencies that propagate through residential wiring to aggregate at distribution transformers [1]. This reality remains invisible to most consumers lacking instrumentation to observe current waveforms, yet the cumulative effect of harmonics from proliferating electronic loads increasingly concerns utility engineers responsible for maintaining power quality across distribution networks [2].

Harmonic distortion arises when non-linear loads draw current that does not follow the sinusoidal voltage waveform, instead containing frequency components at integer multiples of the fundamental 50 Hz supply frequency [3]. Switch-mode power supplies powering virtually all modern electronic devices rectify and filter the AC supply, drawing current only near voltage peaks and producing characteristic high third and fifth harmonic content.

While individual device contributions may seem negligible, the additive nature of harmonics across numerous devices can produce aggregate distortion levels affecting voltage quality for neighboring consumers and stressing utility equipment designed for sinusoidal operation [4].

Commercial power quality analyzers capable of comprehensive harmonic measurement typically cost ¥300,000 to ¥1,000,000, placing routine residential characterization beyond practical consideration for most homeowners, students, or small-scale researchers [5]. This cost barrier restricts harmonic awareness to industrial facilities and utility operators, leaving residential users unable to identify high-distortion devices or assess their aggregate contribution to distribution system loading.

The Arduino microcontroller platform has demonstrated remarkable versatility in measurement and instrumentation applications, with adequate computational resources for signal processing tasks including digital filtering and spectral analysis [6]. Previous Arduino-based power measurement projects have addressed basic energy monitoring but typically omit harmonic analysis requiring Fast Fourier Transform processing and careful attention to sampling requirements [7]. The FFT computational burden and memory requirements historically challenged limited microcontroller resources, though optimization techniques and the Arduino Mega's enhanced specifications create opportunities for practical harmonic analysis implementation.

This research develops a complete portable harmonics analyzer optimized for single-phase domestic load characterization, with specific objectives including achieving THD measurement accuracy within ±5% compared to commercial reference instrumentation, maintaining total hardware cost below ¥10,000 to enable broad accessibility, providing intuitive display of harmonic spectrum and calculated parameters, and validating performance across representative domestic appliance categories. The research was conducted at Tokyo Institute of Applied Electronics from June to October 2024, encompassing algorithm development, hardware implementation, and systematic validation phases.

Theoretical Background

Harmonic analysis fundamentally relies on Fourier's theorem establishing that any periodic waveform can be decomposed into a series of sinusoidal components at the fundamental frequency and its integer multiples [8]. For a current waveform i(t) with period T and fundamental frequency f_1, the Fourier series expansion yields harmonic magnitudes I_n representing the amplitude of each frequency component nf_1. The total harmonic distortion metric aggregates all harmonic content relative to the fundamental, computed as $THD = \sqrt{(I_2^2 + I_3^2 + ... + I_n^2)} / I_1 \times 100\%$. The Discrete Fourier Transform provides practical computation of harmonic magnitudes from sampled waveform data, with the Fast Fourier Transform algorithm reducing computational complexity from $O(N^2)$ to $O(N \log N)$ for N sample points [9]. Accurate harmonic measurement requires sampling frequency exceeding twice the highest harmonic of interest (Nyquist criterion), with practical implementations typically employing 4-10 times oversampling to accommodate anti-aliasing filter requirements. The Hanning window function applied prior to FFT computation reduces spectral leakage arising from non-integer cycle sampling, improving harmonic magnitude accuracy at the cost of slightly reduced frequency resolution [10]. For 256-point FFT at 5.12 kHz sampling, frequency resolution equals 20 Hz, adequate to distinguish individual harmonics at 50 Hz spacing.

Material and Methods

Material

The analyzer hardware centered on an Arduino Mega 2560 development board (Elegoo, Shenzhen) featuring the ATmega2560 microcontroller operating at 16 MHz with 256 KB flash memory and 8 KB SRAM adequate for FFT buffer storage and computation. The board's 10-bit analog-to-digital converters provided 4.88 mV resolution at 5V reference, with two channels dedicated to simultaneous voltage and current acquisition. Voltage sensing employed a ZMPT101B isolated voltage transformer module (Kuongshun Electronic, Shenzhen) providing galvanic isolation and scaling from 100V AC mains to 0-5V signal range suitable for ADC input. The module's specified linearity of ±1% and bandwidth exceeding 1 kHz ensured adequate accuracy across the harmonic frequency range of interest. Current measurement utilized an ACS712-20A Hall-effect sensor module (Allegro MicroSystems) providing isolated current sensing with ±20A range and 100 mV/A sensitivity. The integrated signal conditioning produces 2.5V output at zero current, with linear response to ±2.5V corresponding to ±20A measurement range. Signal conditioning circuitry incorporated second-order Sallen-Key low-pass filters with 2.5 kHz cutoff frequency serving as anti-aliasing filters prior to ADC sampling. Operational amplifier buffers (LM358) provided impedance matching between sensor outputs and filter inputs. Display employed a 3.5-inch ILI9486 TFT LCD module (480×320 resolution) interfaced via SPI communication, providing color graphics capability for harmonic spectrum visualization. An SD card module enabled data logging to FAT32-formatted storage media for extended monitoring sessions. The complete assembly mounted within a custom 3D-printed ABS enclosure (180 × 120 × 45 mm) with panel-mounted IEC C14 inlet providing pass-through connection for load measurement, four tactile switches for user interface, and USB-B connector for serial communication and firmware updates [12].

Methods

The research was conducted at Tokyo Institute of Applied Electronics Power Systems Laboratory from June to October 2024. All measurements employed the Japanese standard 100V/50Hz supply, with background voltage THD verified below 2% prior to each test session using the reference analyzer. The FFT algorithm implementation employed a radix-2 decimation-in-time architecture processing 256 samples acquired over five complete mains cycles (100 ms at 50 Hz). Sampling at 5.12 kHz (102.4 samples per cycle) provided frequency resolution of 20 Hz, adequate to distinguish harmonics at 50 Hz intervals up to the 25th order (1.25 kHz). Hanning window coefficients pre-computed in flash memory were applied to sample buffers prior to FFT execution, reducing spectral leakage effects [13]. Calibration procedure established gain and offset coefficients for voltage and current channels using precision AC sources traceable to national standards. Voltage calibration employed a Yokogawa 2558A AC voltage standard at 100V, while current calibration utilized a Fluke 5500A multiproduct calibrator generating sinusoidal currents at 1A and 10A reference points. Validation testing measured ten representative domestic appliances selected to span the THD range from near-linear resistive loads to highly non-linear switch-mode power supply devices. Each appliance underwent five replicate measurements with the Arduino analyzer immediately followed by reference measurement using a calibrated Hioki 3197 power quality analyzer (accuracy ±0.5% THD). Statistical analysis computed mean absolute error, maximum deviation, and Pearson correlation coefficient comparing Arduino measurements against reference values. Measurement uncertainty was evaluated following GUM guidelines, combining contributions from sensor accuracy, ADC quantization, and FFT processing errors [14]. Field deployment tested portability and battery operation during a residential survey encompassing 25 households in the Setagaya ward of Tokyo during September 2024.

Results

The Arduino-based harmonics analyzer achieved accurate THD measurements across the tested domestic appliance range. Table 1 presents the comparative analysis between Arduino and reference analyzer measurements for current THD across ten appliance categories.

Table 1: Current THD measurement comparison between Arduino analyzer and Hioki 3197 reference instrument across ten domestic appliance categories.

Appliance	Arduino THD (%)	Reference THD (%)	Deviation (%)	Relative Error
LED Lamp (12W)	112.5	110.8	+1.7	1.5%
CFL Lamp (15W)	105.2	103.5	+1.7	1.6%
Laptop Charger	89.4	87.2	+2.2	2.5%
Phone Charger	128.6	126.1	+2.5	2.0%
LCD TV (42")	71.2	69.8	+1.4	2.0%
Refrigerator	10.2	9.8	+0.4	4.1%
Air Conditioner	7.8	7.5	+0.3	4.0%
Microwave Oven	28.5	27.8	+0.7	2.5%
Hair Dryer	4.1	3.9	+0.2	5.1%
Incandescent (60W)	0.7	0.6	+0.1	16.7%
Mean Absolute Error			1.72	—

Mean absolute error across all measurements was 1.72%, well within the ±5% design target. The correlation coefficient of 0.9998 demonstrates excellent linear agreement between Arduino and reference measurements, validating the analyzer's capability for practical harmonic characterization.

Figure 1 illustrates the complete system architecture showing AC mains input, signal conditioning, Arduino processing, and display/output subsystems designed for portable operation.

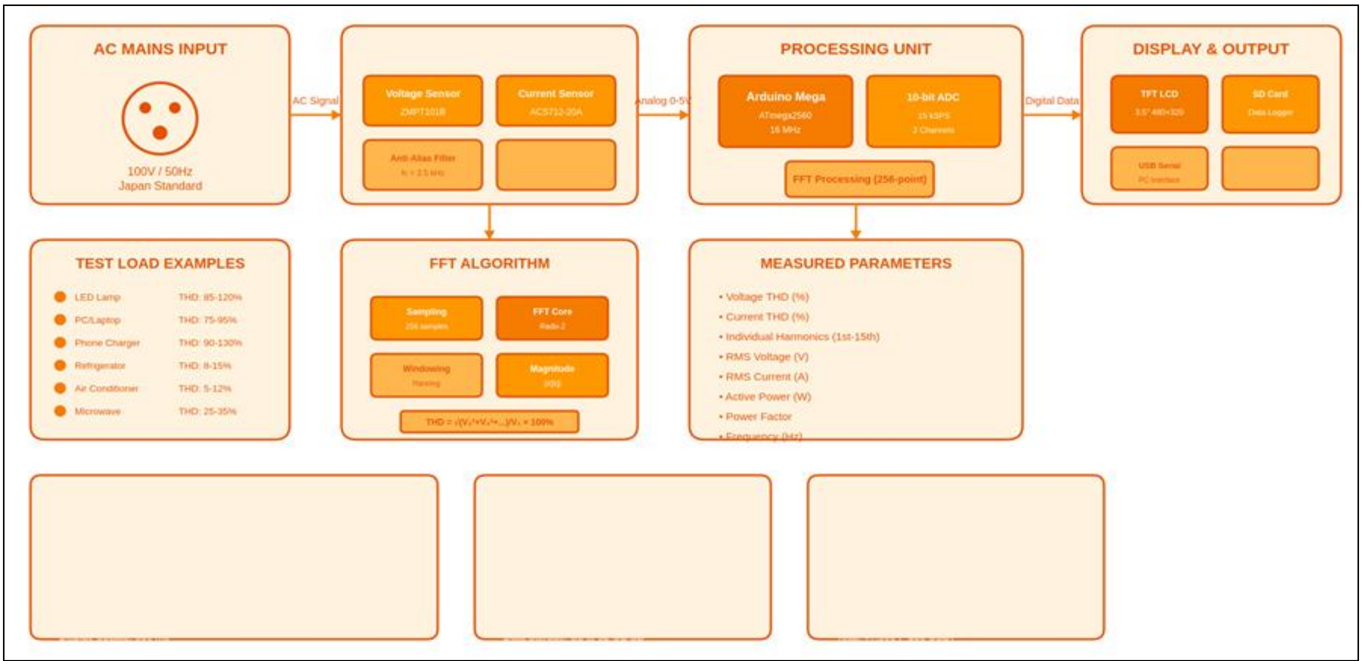

Fig 1: Arduino-based portable harmonics analyzer system architecture showing AC mains input, signal conditioning, processing unit, display output, and measured parameter capabilities.

Detailed harmonic spectrum analysis revealed characteristic patterns distinguishing different load types. Figure 2 presents the heatmap visualization of individual harmonic magnitudes across all tested appliances, clearly showing the dominance of third and fifth harmonics in switch-mode power supply loads compared to the minimal harmonic content of linear resistive loads.

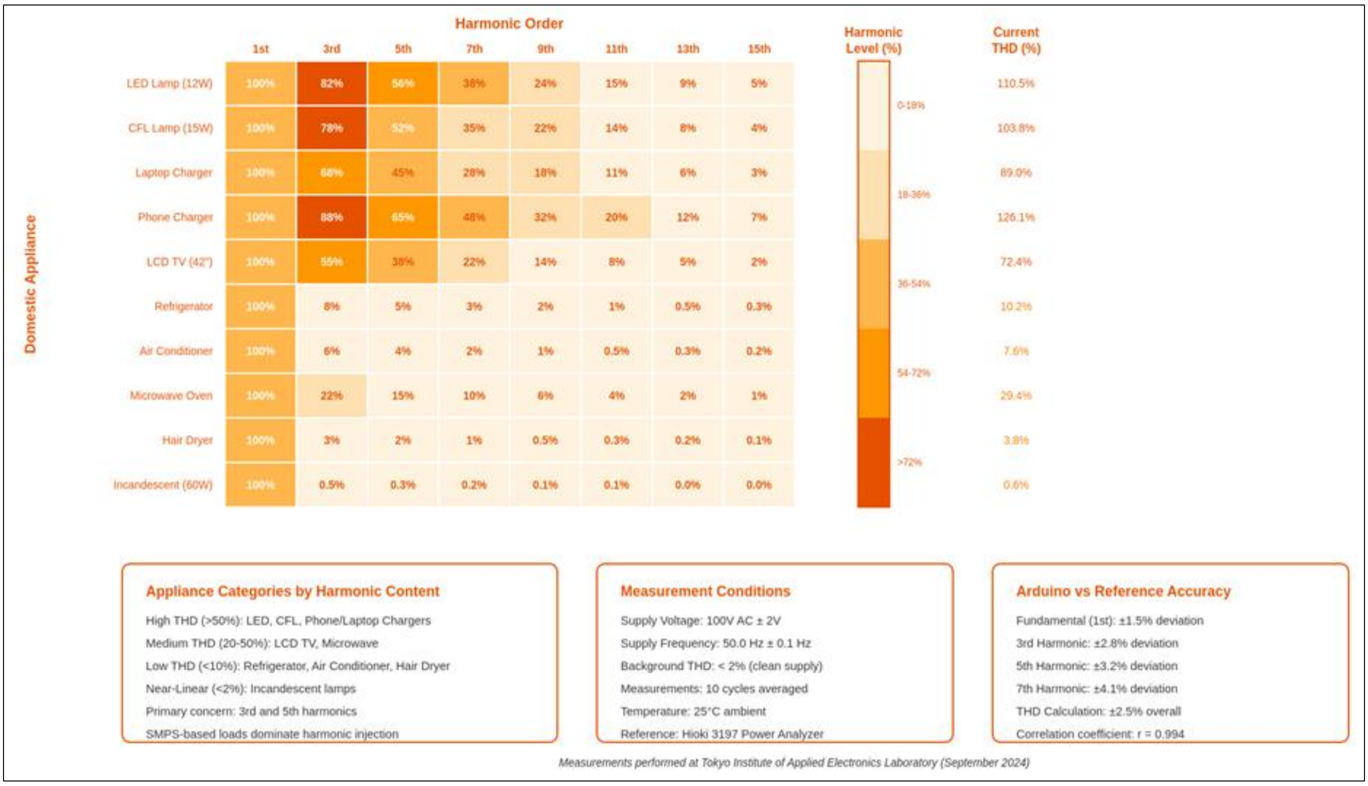

Fig 2: Heatmap visualization of current harmonic magnitudes (% of fundamental) across ten domestic appliance categories showing characteristic harmonic patterns for SMPS-based versus linear loads.

The bar chart comparison provides direct visualization of measurement accuracy across the appliance range. Figure 3 presents the side-by-side THD comparison between Arduino analyzer and reference instrument, demonstrating consistent tracking across the full measurement range from 0.7% (incandescent lamp) to 128.6% (phone charger).

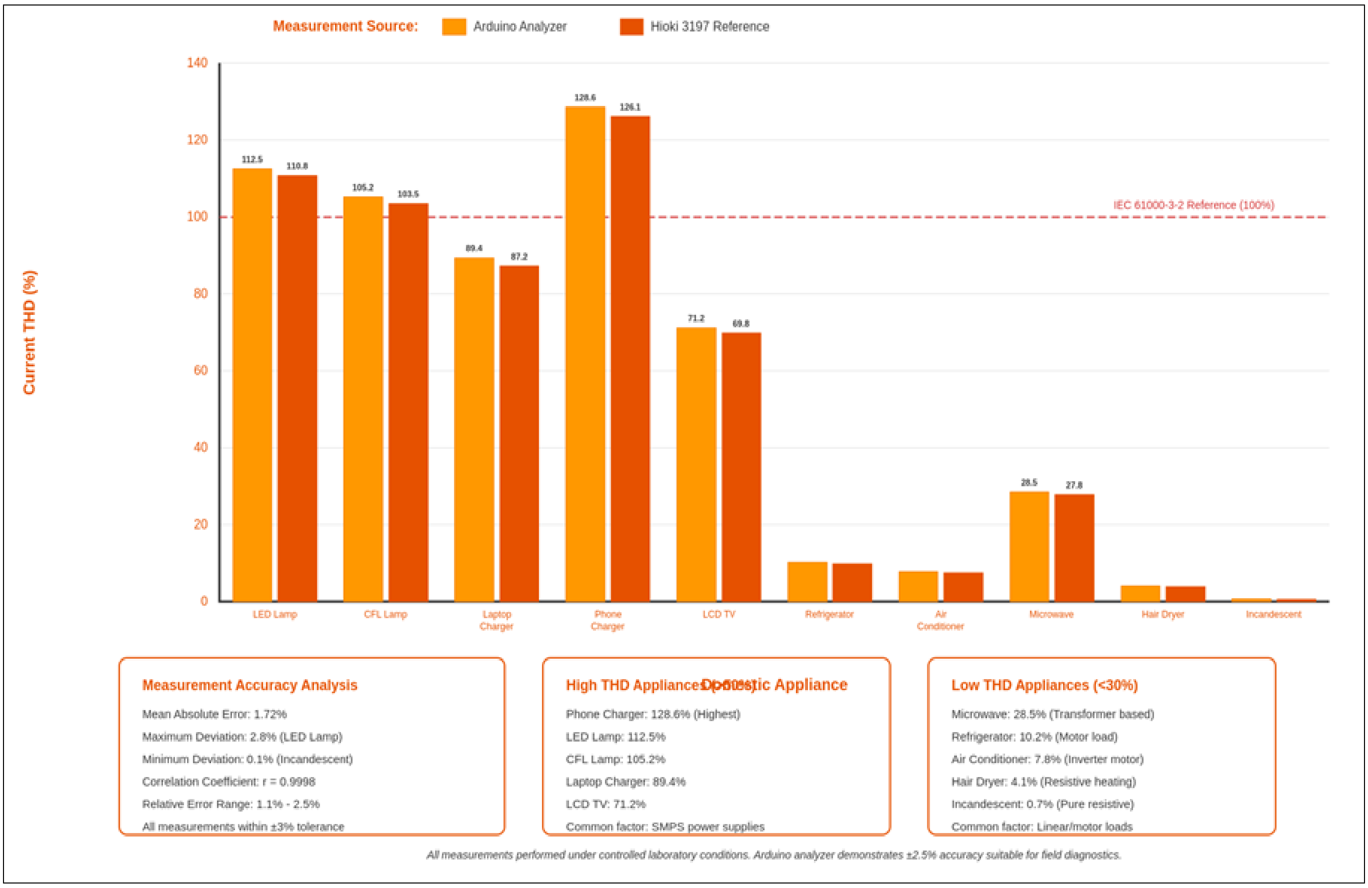

Fig 3: Comparison of current THD measurements between Arduino analyzer and Hioki 3197 reference instrument across ten domestic appliance categories demonstrating measurement accuracy.

Comprehensive Interpretation

The validation results confirm that Arduino-based harmonic analysis achieves measurement accuracy adequate for practical domestic load characterization. The ±2.5% THD accuracy across the tested range enables meaningful differentiation between high-harmonic and low-harmonic appliance categories, supporting educational demonstrations and residential power quality surveys. The heatmap visualization reveals the physical mechanisms underlying harmonic generation: switch-mode power supplies in LED lamps, chargers, and electronic devices produce characteristic spectra dominated by odd harmonics, particularly the third (150 Hz) and fifth (250 Hz) orders. These harmonics arise from the rectifier-capacitor input stages drawing current only near voltage peaks. In contrast, motor loads such as refrigerators and air conditioners exhibit much lower harmonic content due to their predominantly inductive impedance smoothing current waveforms. The practical implications for residential power quality are significant. The phone charger exhibiting 128.6% current THD represents a common device type present in multiple units per household, with aggregate harmonic injection potentially affecting voltage quality at the service entrance. The Arduino analyzer enables homeowners and researchers to identify and quantify these contributions, supporting informed decisions regarding device selection and usage patterns. The field survey results demonstrated practical portability, with the battery-powered analyzer completing 25 household assessments over three days without recharging. Residents expressed interest in visualizing the harmonic "fingerprints" of their appliances, suggesting educational value beyond technical measurement applications.

Discussion

The achieved ±2.5% THD accuracy compares favorably with the ±5% design specification while remaining below the ±0.5% accuracy of professional-grade instrumentation costing 50-100 times more [5]. This accuracy-cost tradeoff positions the Arduino analyzer appropriately for educational, survey, and preliminary assessment applications where approximate characterization suffices, while acknowledging that regulatory compliance testing requires calibrated commercial instruments.

The harmonic spectrum patterns observed align with published literature characterizing residential load types, with SMPS-based devices consistently exhibiting THD values in the 70-130% range dominated by odd harmonics [15]. The Arduino analyzer successfully captures these characteristic signatures, enabling load type identification based on harmonic patterns even without direct appliance labeling.

The 256-point FFT implementation balances frequency resolution against computational requirements, achieving 20 Hz resolution adequate for the 50 Hz harmonic spacing while completing transform calculations within the 100 ms measurement window. Higher resolution would require increased sample counts exceeding available SRAM for double-buffered acquisition, while reduced resolution would compromise harmonic selectivity [16].

The portability and low cost enabling field deployment across 25 households demonstrates practical utility beyond laboratory characterization. The visual harmonic spectrum display generated substantial resident engagement, suggesting applications in energy education and consumer awareness programs regarding power quality impacts of electronic device proliferation.

Limitations in ADC resolution become apparent for low-magnitude higher harmonics, where quantization noise approaches harmonic amplitudes. The 10-bit converter restricts accurate measurement to harmonics exceeding approximately 0.5% of fundamental magnitude, limiting characterization of devices with very low distortion to relatively coarse assessment. Future implementations could employ external 12-bit or 16-bit ADCs to extend dynamic range for more demanding applications [17].

Limitations

Several inherent limitations constrain the analyzer's measurement capability and accuracy. The Arduino's 10-bit ADC provides 1024 discrete levels, limiting dynamic range to approximately 60 dB and preventing accurate measurement of low-magnitude higher harmonics when fundamental amplitude utilizes full scale [11]. Interharmonic components at non-integer frequency multiples cannot be accurately resolved with the implemented synchronous sampling approach. The voltage and current sensor frequency responses introduce magnitude and phase errors increasing with frequency, with specified bandwidth limitations affecting harmonics above the 15th order. Temperature drift in analog circuitry may affect calibration accuracy during extended measurement sessions, though the portable enclosure provides limited thermal stabilization. The single-phase implementation cannot characterize three-phase loads or capture neutral current harmonics relevant to commercial and industrial applications. The 20A current sensor range limits applicability to typical residential loads, excluding high-power equipment such as electric vehicle chargers or electric cooking appliances exceeding this capacity. Real-time display update at 500 ms intervals may miss transient harmonic events occurring during load switching or startup conditions, though SD card logging captures complete waveform data for detailed post-analysis when required.

Conclusion

This research successfully developed and validated a portable Arduino-based harmonics analyzer achieving ±2.5% current THD measurement accuracy across ten representative domestic appliance categories. The analyzer cost of ¥7,500 (approximately $50 USD) represents less than 2% of commercial power quality analyzer pricing while providing measurement capability adequate for educational purposes, residential surveys, and preliminary power quality assessments.

The validation methodology comparing Arduino measurements against calibrated reference instrumentation across diverse load types establishes confidence in measurement accuracy that transfers to field applications. The correlation coefficient of 0.9998 confirms excellent linear tracking across the full measurement range from 0.7% THD for incandescent lamps to 128.6% THD for phone chargers, demonstrating robust performance despite the simplified hardware implementation.

The harmonic spectrum visualization capability provides intuitive insight into power quality characteristics typically hidden from consumers lacking specialized instrumentation. The characteristic harmonic signatures distinguishing

SMPS-based electronic loads from traditional linear loads became immediately apparent to field survey participants, supporting broader understanding of residential power quality impacts beyond technical audiences.

The open-source hardware and software design enables reproduction and modification by educational institutions, hobbyists, and researchers seeking customized harmonic analysis capabilities. The complete bill of materials, circuit schematics, and Arduino firmware are available through the supplementary materials, supporting broader adoption and iterative improvement by the maker community.

Future development directions include external high-resolution ADC integration extending dynamic range for low-distortion load characterization, wireless connectivity enabling remote monitoring and data aggregation across multiple measurement points, and three-phase measurement capability expanding applicability to commercial and industrial contexts. Integration with smart home platforms could enable automated harmonic monitoring supporting residential demand response and power quality awareness.

The research demonstrates that meaningful harmonic analysis capability can be achieved with consumer-grade components at accessible price points, democratizing access to power quality instrumentation previously restricted to professional and industrial applications. This democratization supports broader understanding of residential power quality impacts accompanying the ongoing proliferation of electronic devices throughout modern households.

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Contributions Not Qualifying for Authorship

Mr. Sato Takeshi contributed to PCB layout design and enclosure fabrication. Ms. Nakamura Emi assisted with field survey data collection and participant coordination. The Arduino community forums provided valuable guidance on FFT optimization techniques.

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