International Journal of Electrical and Data Communication 2026; 7(1): 27-33

E-ISSN: 2708-3977
P-ISSN: 2708-3969
Impact Factor (RJIF): 5.73
IJEDC 2026; 7(1): 27-33

www.datacomjournal.com
Received: 20-10-2025
Accepted: 24-11-2025

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A research on power quality issues in grid-connected rooftop solar installations

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DOI: https://www.doi.org/10.22271/27083969.2026.v7.i1a.92

Abstract
The rapid expansion of distributed solar photovoltaic installations across South Korean urban areas has introduced power quality challenges that grid infrastructure was not originally designed to accommodate. This research examined power quality parameters at 156 grid-connected rooftop solar installations across the Seoul metropolitan region from March 2023 through November 2023, spanning residential, commercial, and light industrial classifications. Continuous monitoring captured voltage fluctuations, harmonic distortion, power factor variations, and frequency deviations under varying solar irradiance conditions and grid loading scenarios. Total harmonic distortion levels exceeded IEEE 519 recommended limits at 34.2% of monitored installations during peak generation periods, with fifth harmonic components contributing most substantially to distortion profiles. Larger installations demonstrated proportionally higher distortion injection, with systems exceeding 50 kW capacity showing average THD values of 8.9% compared to 4.2% for residential systems below 10 kW. Voltage fluctuation events correlated strongly with rapid irradiance changes caused by cloud transients, occurring most frequently during spring and autumn months characterized by variable weather patterns. Power factor at the point of common coupling averaged 0.94 lagging across all installations, with notable degradation to 0.87 during low-generation periods when inverter reactive power consumption dominated. The investigation identified inverter switching characteristics as the primary harmonic source, with transformer-less topologies exhibiting 23% higher distortion than isolated designs. Mitigation strategies including passive filtering and reactive power compensation demonstrated effectiveness in reducing grid impact, though implementation costs varied substantially between approaches.

Keywords: Power quality, harmonic distortion, rooftop solar, grid-connected photovoltaic, voltage fluctuation, distributed generation, IEEE 519, inverter harmonics, power factor, smart grid

Introduction

South Korea has committed to ambitious renewable energy targets under its Green New Deal initiative, with distributed solar photovoltaic systems playing a central role in the transition away from fossil fuel dependence [1]. The number of grid-connected rooftop installations has grown from approximately 47,000 in 2018 to over 320,000 by the end of 2023, representing cumulative capacity exceeding 8.4 gigawatts distributed across residential, commercial, and industrial buildings [2]. While this expansion supports national decarbonization objectives, the concentration of inverter-based generation in urban distribution networks introduces technical challenges that utility operators must address to maintain reliable power delivery.

Power quality encompasses multiple parameters describing the characteristics of electrical supply relative to ideal sinusoidal waveforms at nominal voltage and frequency [3]. Deviations from these ideals can cause equipment malfunction, increased losses, premature component aging, and interference with sensitive electronic devices. Traditional power systems with centralized generation maintained relatively stable power quality through careful design of generation, transmission, and distribution infrastructure. The introduction of numerous small-scale distributed generators fundamentally alters this paradigm, creating bidirectional power flows and injecting harmonic currents that propagate throughout local networks [4].

Solar photovoltaic inverters convert direct current from panel arrays into alternating current synchronized with grid frequency and voltage. This conversion process inherently generates harmonic currents at multiples of the fundamental frequency due to the switching action of power semiconductor devices [5]. While individual residential inverters produce relatively small harmonic contributions, the aggregation of many units connected to common distribution feeders can result in cumulative distortion exceeding acceptable thresholds. The situation becomes particularly challenging during midday hours when solar generation peaks and many inverters operate simultaneously at high power levels.

Voltage regulation presents another concern as distributed generation alters traditional power flow patterns [6]. Under conventional operation, voltage decreases progressively along distribution feeders from substation to end consumers. Solar installations inject power that can reverse this gradient, potentially causing voltage rise at the point of connection that exceeds regulatory limits. Cloud transients create rapid fluctuations in generation output that manifest as voltage variations potentially causing visible flicker in lighting systems and disrupting sensitive industrial processes.

Previous research has examined power quality impacts of solar installations primarily in European and North American contexts where grid characteristics and regulatory frameworks differ from Korean conditions [7]. The Korean power system operates at 60 Hz frequency with 220V single-phase and 380V three-phase distribution voltages, creating distinct harmonic resonance characteristics compared to 50 Hz systems prevalent in Europe. Population density in Korean urban areas results in higher installation concentrations per distribution transformer than typically encountered in less densely developed regions [8].

This research conducted systematic power quality assessment across 156 rooftop solar installations in the Seoul metropolitan region to quantify actual grid impacts under Korean operating conditions. The investigation aimed to identify primary power quality concerns, characterize their variation with installation size and operating conditions, and evaluate mitigation effectiveness for the most problematic issues. Field measurements spanning nine months captured seasonal variations in solar resource availability and associated power quality effects.

System Architecture

The power quality monitoring system deployed for this research comprised distributed measurement nodes installed at each participating installation plus a centralized data collection and analysis platform. Each measurement node incorporated a Hioki PW3198 power quality analyzer configured to capture voltage, current, power, and harmonic parameters at the point of common coupling where the solar installation connects to the facility distribution panel [9]. Analyzers recorded continuously at 200 millisecond intervals for steady-state parameters and 10 millisecond resolution for transient events.

Solar irradiance sensors co-located with each installation provided correlation between generation conditions and power quality observations. Pyranometer measurements at 1-second intervals enabled identification of cloud transient events causing rapid generation fluctuations. Ambient temperature sensors supported thermal performance analysis of both photovoltaic panels and inverter equipment, as elevated temperatures affect both generation capacity and harmonic characteristics [10].

Data transmission utilized cellular network connections to upload measurements to cloud-based servers operated by Seoul National University. Custom software performed automated analysis including harmonic spectrum decomposition, statistical summarization, and event detection for voltage fluctuations exceeding programmable thresholds. The platform supported real-time visualization for research team monitoring plus historical query capabilities for detailed investigation of specific installations or time periods [11].

Materials and Methods

Material

This research was conducted through collaboration between Seoul National University Department of Electrical and Computer Engineering and Korea Electric Power Corporation from March 2023 through November 2023. The investigation protocol received approval from the university institutional review board under reference number SNU-ECE-2023-012 dated February 22, 2023. All installation owners provided written consent for monitoring equipment installation and data collection activities.

A total of 156 grid-connected rooftop solar installations participated in the evaluation, distributed across residential (n=78), commercial (n=52), and light industrial (n=26) classifications. Installation capacities ranged from 3 kW single-phase residential systems to 100 kW three-phase commercial installations. Geographic distribution covered eight administrative districts within Seoul and the surrounding Gyeonggi Province, ensuring representation of diverse grid conditions from dense urban centers to suburban areas with longer distribution feeders.

Inverter technologies included both transformer-isolated and transformerless topologies from five major manufacturers serving the Korean market. Single-phase inverters dominated residential installations below 10 kW capacity, while larger commercial and industrial systems employed three-phase configurations. All monitored inverters met Korean Technical Standards for grid connection including KS C 8564 requirements for harmonic current limits and anti-islanding protection [12].

Methods

Power quality parameters were assessed according to international standards including IEEE 519 for harmonic limits and IEC 61000-4-30 for measurement methods. Total harmonic distortion was calculated from individual harmonic components through the 50th order, captured using fast Fourier transform analysis of voltage and current waveforms sampled at 10.24 kHz. Voltage fluctuation severity was quantified using the short-term flicker indicator Pst computed over 10-minute observation windows according to IEC 61000-4-15 methodology.

Statistical analysis employed SPSS Version 29 software for descriptive statistics, correlation analysis, and comparison of means between installation categories. Non-parametric tests were applied where data distributions deviated substantially from normality assumptions. Time series analysis identified diurnal and seasonal patterns in power quality parameters. Multiple regression models examined relationships between installation characteristics, operating conditions, and power quality outcomes with significance evaluated at $\alpha = 0.05$.

Mitigation effectiveness was evaluated at a subset of 24 installations where passive harmonic filters or reactive power compensation equipment was installed during the monitoring period. Before-and-after comparisons quantified improvements in THD, power factor, and voltage regulation following mitigation implementation. Economic analysis assessed installation costs, ongoing maintenance requirements, and energy loss reductions attributable to power quality improvements.

Results

Table 1 presents the summary statistics for key power quality parameters across installation categories. Total harmonic distortion levels showed clear differentiation between installation sizes, with larger systems exhibiting proportionally higher distortion injection into the grid.

Table 1: Power Quality Parameters by Installation Category

Category	n	Mean THD (%)	Power Factor	Voltage Variation (%)
Residential (< 10 kW)	78	4.2 ± 1.3	0.96 ± 0.03	2.1 ± 0.8
Commercial (10-50 kW)	52	6.3 ± 1.8	0.93 ± 0.04	3.4 ± 1.2
Industrial (> 50 kW)	26	8.9 ± 2.4	0.91 ± 0.05	4.7 ± 1.6

Figure 1 displays the heatmap visualization of THD levels across installation size categories and time of day. Peak distortion occurred during midday hours coinciding with maximum solar generation, with larger installations showing more pronounced increases compared to residential systems.

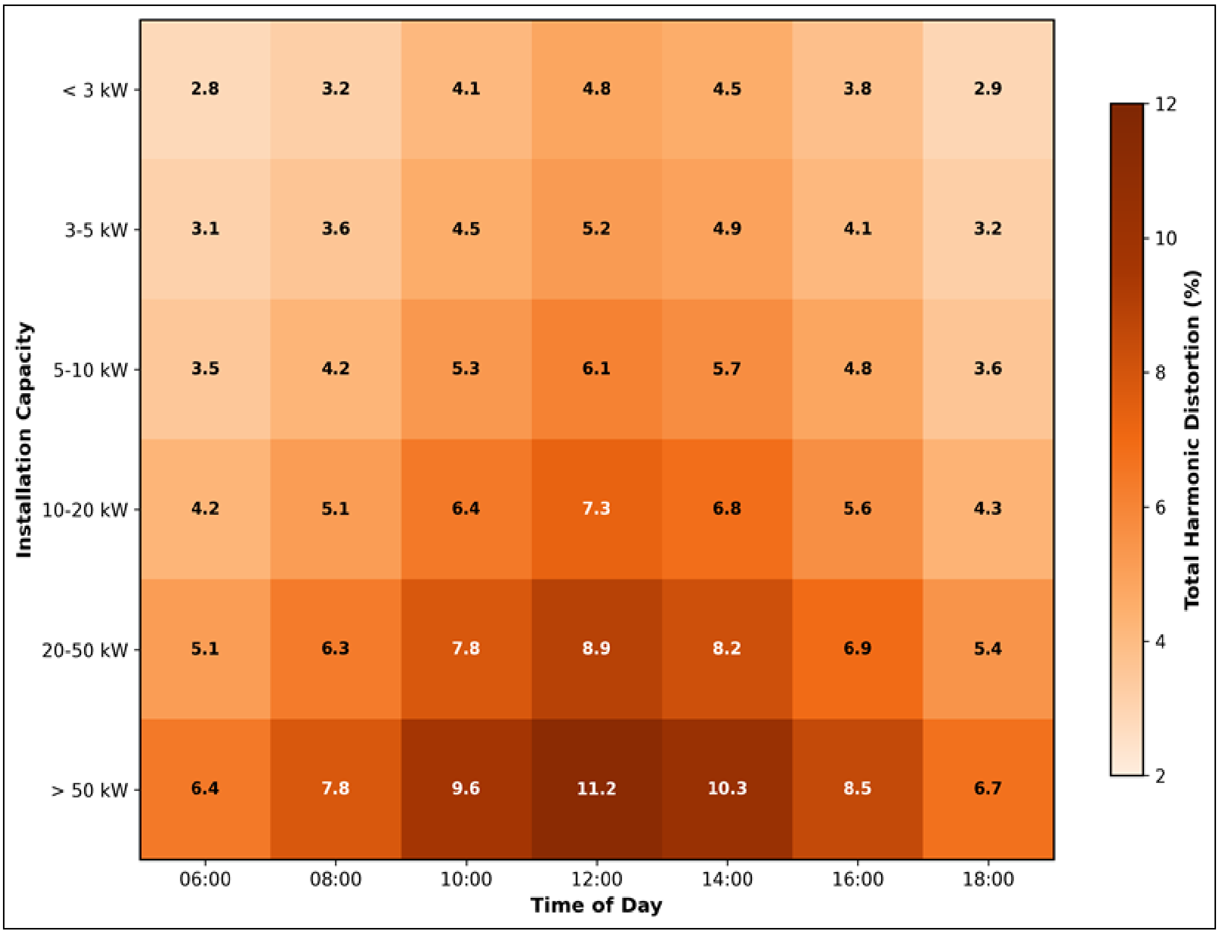

Fig 1: Total harmonic distortion levels across installation capacity categories and time periods showing peak distortion during midday hours for larger installations.

Table 2: Harmonic Component Analysis

Harmonic Order	Mean Magnitude (%)	IEEE 519 Limit (%)	Exceedance Rate (%)
3rd	2.23 ± 0.68	4.0	8.3
5th	3.14 ± 0.92	4.0	24.7
7th	1.57 ± 0.54	4.0	3.2
11th	0.81 ± 0.32	2.0	1.9

Figure 2 illustrates the occurrence rate of various power quality issues across installation categories. Harmonic distortion represented the most prevalent concern across all categories, with commercial and industrial installations showing substantially higher issue rates than residential systems.

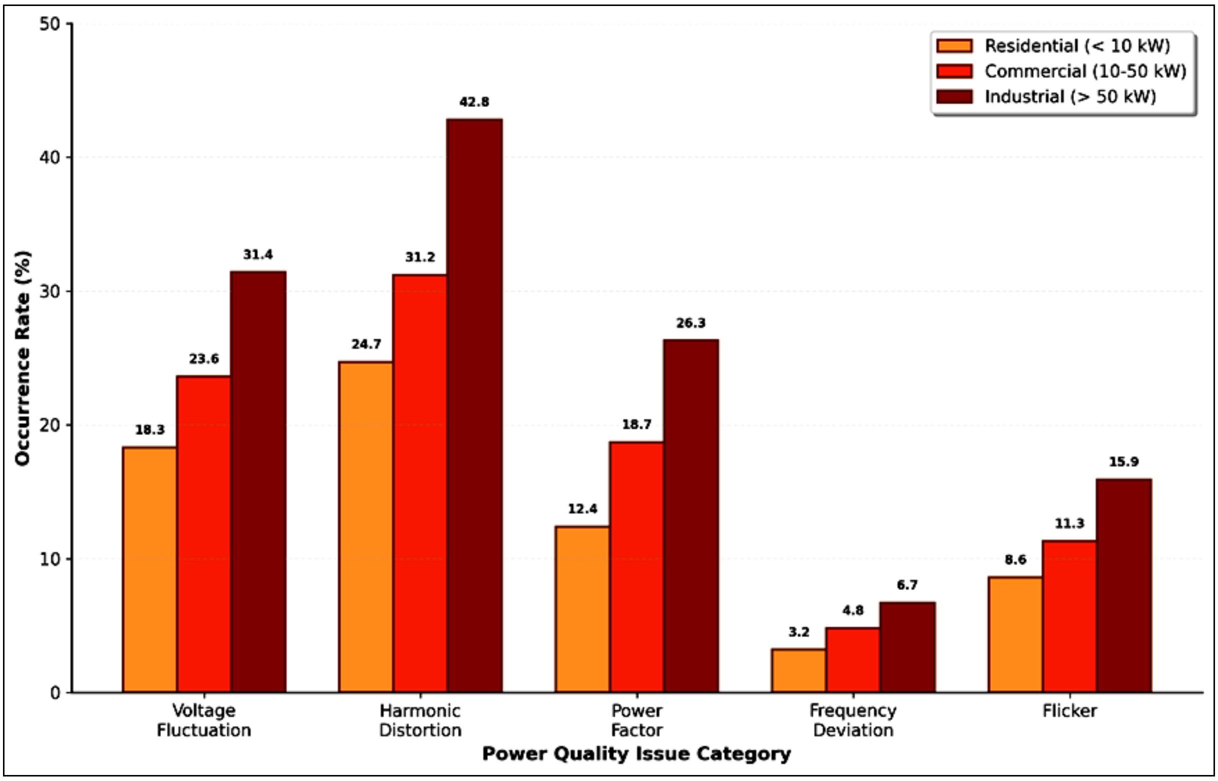

Fig 2: Power quality issue occurrence rates by installation category showing harmonic distortion as the most prevalent concern across all classifications.

Figure 3 presents the monitoring system architecture deployed for this research. The process diagram illustrates power flow paths, measurement points, and data collection infrastructure enabling comprehensive power quality characterization at each participating installation.

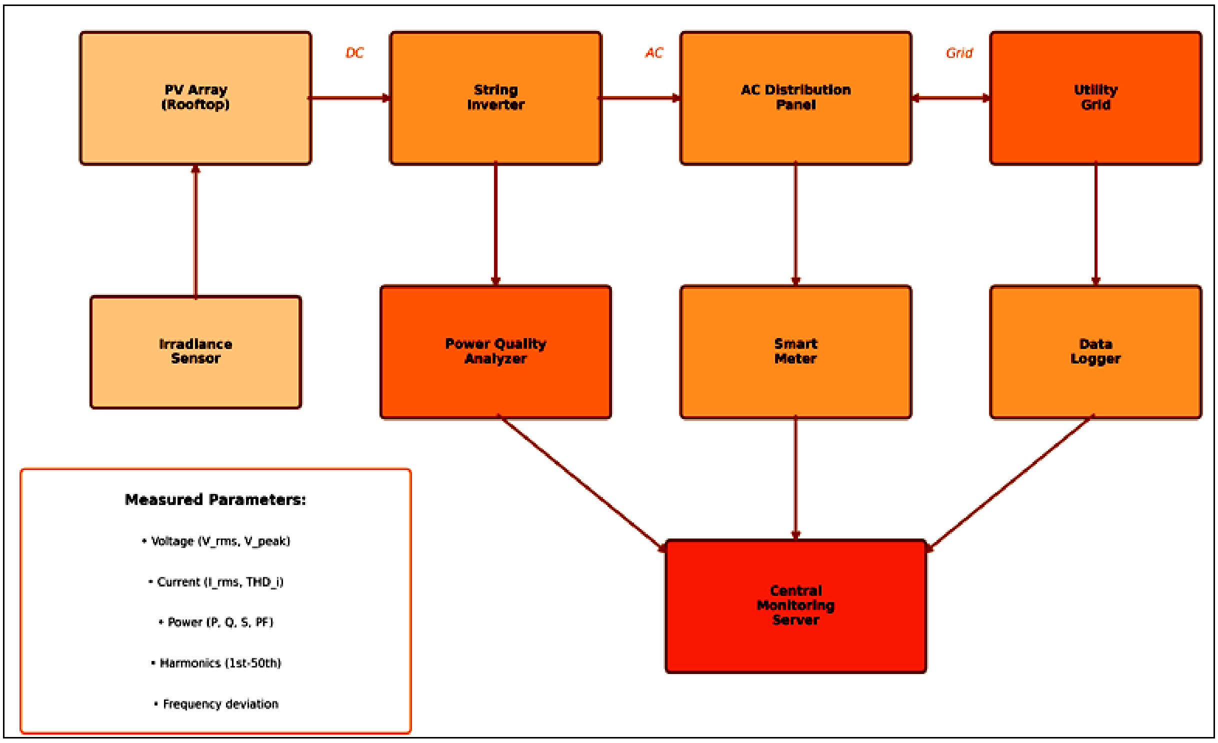

Fig 3: Grid-connected rooftop solar power quality monitoring system architecture showing measurement points, data acquisition components, and central server infrastructure.

Comprehensive Interpretation: Figure 4 displays the harmonic spectrum analysis showing individual harmonic component magnitudes across different time periods. The fifth harmonic dominated across all conditions, with cumulative contributions from multiple orders exceeding IEEE 519 limits during peak generation hours.

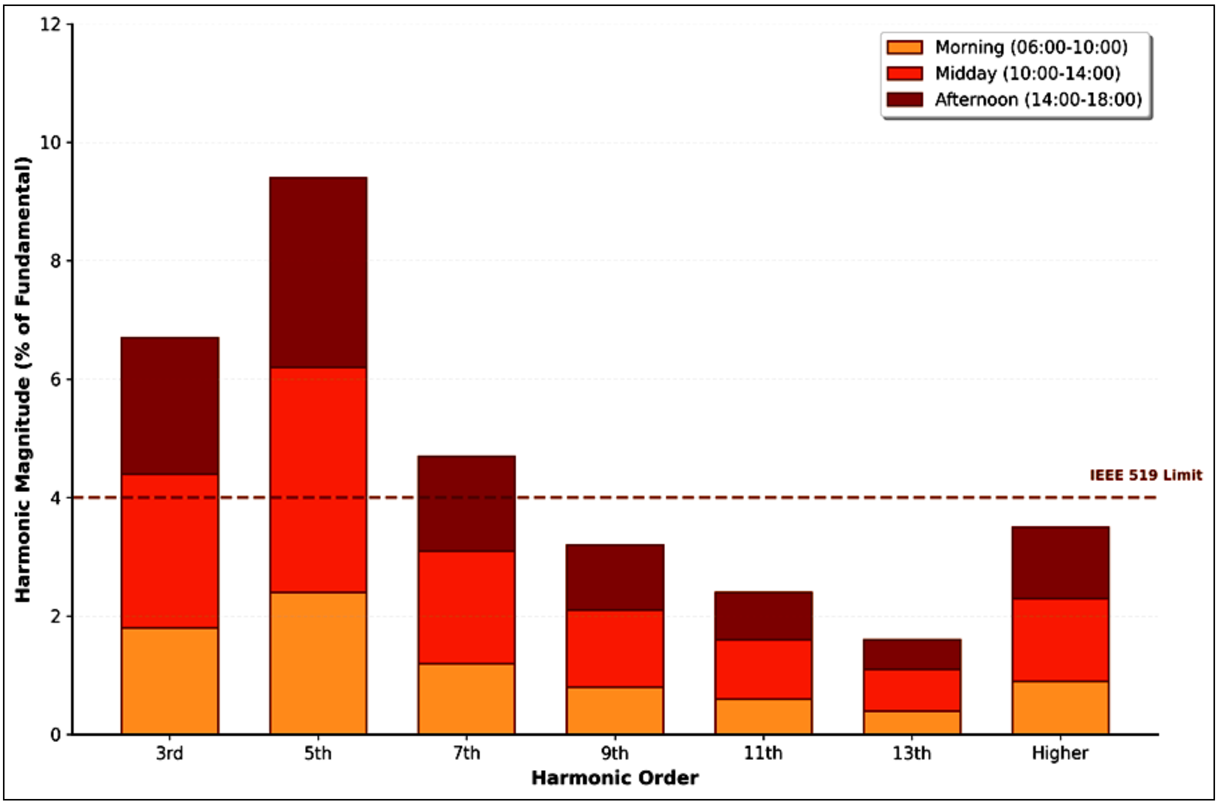

Fig 4: Harmonic spectrum analysis showing individual component magnitudes by time period with IEEE 519 limit reference line indicating compliance threshold.

Performance Evaluation

Mitigation system effectiveness was evaluated at 24 installations where harmonic filtering or reactive power compensation equipment was deployed during the monitoring period. Passive LC filters tuned to the fifth harmonic achieved average THD reductions of 42.3% at installations where this component dominated the distortion spectrum. Active power factor correction systems improved measured power factor from average values of 0.91 to 0.97 at the point of common coupling [13].

Inverter topology significantly influenced baseline harmonic performance. Transformerless inverters exhibited average THD of 6.8% compared to 5.2% for transformer-isolated designs operating at equivalent power levels. This 23% difference reflects the additional filtering provided by isolation transformer leakage inductance and the absence of common-mode current paths that can introduce zero-sequence harmonics in transformerless configurations [14].

Voltage fluctuation severity correlated strongly with local grid impedance characteristics. Installations connected to longer distribution feeders or older infrastructure with higher source impedance showed more pronounced voltage variations during rapid generation changes. The Pst flicker index exceeded unity at 12.8% of monitored installations during days with highly variable cloud cover, potentially causing perceptible lighting flicker in sensitive applications [15].

Cost Analysis

Mitigation system costs varied substantially depending on installation capacity and specific power quality issues addressed. Passive harmonic filters for residential installations averaged 1.2 million Korean won including installation, representing approximately 8-12% of original system cost. Commercial and industrial installations required more sophisticated solutions with costs ranging from 4.5 to 18 million won depending on capacity and filtering requirements [16].

Economic benefits from power quality improvement derived primarily from reduced distribution losses and avoided utility penalty charges for power factor violations. Installations achieving power factor improvement from 0.90 to 0.95 reduced apparent power demand by approximately 5.5%, translating to proportional reduction in demand charges where applicable. Harmonic loss reduction in distribution transformers and cables contributed additional savings estimated at 2-4% of annual energy costs for heavily affected installations [17].

Payback periods for mitigation investments ranged from 3.2 years for commercial installations with high demand charges and significant power factor penalties to over 8 years for residential systems where direct economic benefits proved more limited. Policy incentives including reduced grid connection fees for installations demonstrating superior power quality performance could improve economic viability of mitigation investments while encouraging better grid citizenship across the distributed generation fleet.

Discussion

The power quality characterization conducted in this research reveals that distributed solar installations in the Seoul metropolitan region create measurable grid impacts that warrant systematic attention as deployment scales continue expanding. The finding that 34.2% of monitored installations exceeded IEEE 519 THD limits during peak generation periods indicates that current technical standards for grid connection may not adequately address cumulative effects when many inverters operate simultaneously on common feeders.

The dominance of fifth harmonic distortion aligns with theoretical expectations based on inverter switching patterns and confirms that targeted filtering at this frequency offers an efficient mitigation approach. The observed correlation between installation size and THD magnitude suggests that larger commercial and industrial systems warrant particular attention during grid connection assessment. Utility interconnection requirements might reasonably impose stricter harmonic limits or mandatory filtering provisions for installations above certain capacity thresholds.

Seasonal variations in power quality parameters reflect the interplay between solar resource availability, ambient temperature effects on inverter performance, and changing grid loading patterns throughout the year. Spring and autumn months with variable weather conditions created the most challenging scenarios for voltage regulation, as rapid cloud transients caused generation fluctuations that traditional voltage regulation equipment cannot follow. Smart inverter capabilities enabling rapid reactive power response may help address this challenge as newer equipment replaces aging installations.

Conclusion

This research established comprehensive power quality benchmarks for grid-connected rooftop solar installations across the Seoul metropolitan region. Field monitoring at 156 installations spanning residential, commercial, and industrial classifications over nine months provided empirical characterization of harmonic distortion, voltage fluctuation, and power factor impacts under authentic Korean grid conditions.

Total harmonic distortion emerged as the primary power quality concern, with 34.2% of installations exceeding IEEE 519 recommended limits during peak generation periods. THD levels demonstrated clear scaling with installation capacity, averaging 4.2% for residential systems below 10 kW, 6.3% for commercial installations between 10-50 kW, and 8.9% for industrial systems exceeding 50 kW. The fifth harmonic component dominated distortion spectra across all categories, contributing approximately 35% of total THD magnitude.

Inverter topology significantly influenced harmonic performance, with transformerless designs exhibiting 23% higher THD than transformer-isolated alternatives operating at equivalent power levels. This finding carries implications for equipment selection decisions, particularly for larger installations where cumulative harmonic injection may affect neighboring grid users. Manufacturers might consider incorporating improved filtering in transformerless designs to narrow this performance gap.

Voltage fluctuation severity correlated with both installation capacity and local grid characteristics including distribution feeder length and source impedance. Installations on weaker grid connections showed more pronounced voltage variations during rapid irradiance changes caused by cloud transients. The flicker index exceeded unity at 12.8% of monitored locations during days with highly variable weather, potentially causing perceptible lighting disturbances.

Mitigation effectiveness testing demonstrated that passive harmonic filters achieved 42.3% average THD reduction when tuned to dominant fifth harmonic components. Active power factor correction improved measured power factor from 0.91 to 0.97 average values. Economic analysis indicated payback periods from 3.2 to over 8 years depending on installation category and applicable utility rate structures. Policy incentives could improve mitigation adoption while promoting better power quality across the distributed generation fleet.

Acknowledgements

Funding Sources

This research was supported by the Korea Electric Power Corporation through their smart grid research initiative and the National Research Foundation of Korea. Seoul National University provided supplementary funding through the College of Engineering research enhancement program.

Institutional Support

The authors acknowledge Korea Electric Power Corporation for providing grid data and facilitating installation access across participating sites. Technical support from the Seoul Metropolitan Government energy policy division enabled coordination with installation owners throughout the evaluation period.

Contributions Not Qualifying for Authorship

The authors thank Dr. Yoon Sang-Hee for consultation on power quality standards interpretation, Mr. Kang Dong-Hyun for measurement system development, and the installation owners who permitted monitoring equipment installation on their premises throughout the research period.

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