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Field Measurement and Experimental Investigation of Harmonic Resonance, Voltage Rise, and Protection Miscoordination Impacts from Clustered Rooftop Solar PV Integration on a Weak Nigerian 11 kV Distribution Feeder

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Abstract

Clustered rooftop solar photovoltaic (PV) systems are spreading rapidly across affluent Nigerian neighbourhoods, yet their interaction with the country's characteristically weak, long, radial 11 kV feeders remains almost entirely unquantified by field evidence. This study reports a comprehensive experimental investigation conducted on a live 11 kV distribution feeder in Yenagoa, Bayelsa State, hosting approximately 1.86 MWp of clustered rooftop PV. Class-A power quality analyzers were deployed at five feeder points for a twelve-week campaign, complemented by secondary-injection testing of the feeder's inverse definite minimum time (IDMT) overcurrent relays and synchronized solar irradiance logging. Voltage total harmonic distortion rose from a baseline of 1.8 % to 7.4 % at the feeder extremity during peak injection, breaching IEEE 519 limits, while current THD reached 19.7 %. Frequency-response sweeps identified a parallel resonance near 320 Hz that amplified fifth- and seventh-order harmonics by up to 2.6 times. Measured voltage rise correlated strongly with irradiance (R^2 = 0.93), producing sustained excursions above the +5 % statutory limit at three measurement points. Secondary injection demonstrated that PV infeed collapsed the 0.3 s grading margin between the source and feeder relays across a 180–340 A fault-current window, confirming miscoordination. Adaptive relay settings and a detuned harmonic filter specification are proposed and validated, restoring coordination and reducing THD below statutory thresholds. The findings furnish Nigeria's first field-quantified evidence base for updating distribution codes, interconnection standards, and quality-of-supply regulation governing distributed PV on weak feeders, and a replicable measurement methodology for utilities across Sub-Saharan Africa.

Keywords: rooftop solar PV; harmonic resonance; voltage rise; protection coordination; weak distribution feeder

1. Introduction

1.1 Background

Electricity supply deficits have made decentralized generation a defining feature of Nigeria's power landscape. With grid supply averaging fewer than eight hours per day in many service territories, households and businesses in higher-income districts have increasingly turned to rooftop solar photovoltaic (PV) systems paired with battery storage, producing dense clusters of distributed generation behind the meter (Ogunleye et al., 2023; Adewuyi et al., 2024; SolarPower Europe, 2024; Woyiri & Adaramola, 2024). These clusters inject power into 11 kV distribution feeders that were designed decades ago for strictly unidirectional power flow, with long radial topologies, high impedance per kilometre, limited automation, and chronically poor voltage regulation (Eze & Okoye, 2023; Nwachukwu et al., 2024; Akuru & Okoro, 2023; Yusuf & Onimisi, 2024). The coincident rise of inverter-based generation on such weak networks raises power quality and protection questions that planning practices in the Nigerian electricity supply industry have not yet absorbed (Ibrahim et al., 2023; Aliyu & Dambatta, 2023; Mbamalu & Okafor, 2023).

1.2 Literature review

Internationally, the power quality consequences of distributed PV are well documented. Harmonic emission from grid-tied inverters, and its amplification through network resonance, has been characterized in field campaigns on European and Asian feeders (Torquato & Freitas, 2023; Rana et al., 2024), while voltage rise at points of high PV penetration remains a principal hosting-capacity constraint (Dubey et al., 2023; Khan et al., 2024; Zhang & Li, 2024; Wang et al., 2023). Protection behaviour under inverter-dominated fault currents — reduced fault magnitude, bidirectional flow, and degraded relay reach — has been examined through both simulation and hardware-in-the-loop testing (Hussain et al., 2023; Oloruntoba & Folly, 2024). Adaptive protection philosophies that re-coordinate relays according to prevailing generation states have matured considerably (Sahoo et al., 2023; Teshome & Lian, 2024; Kiprop & Muriithi, 2023; Olulope & Folly, 2023).

Within Africa, and Nigeria specifically, the literature is overwhelmingly simulation-based. Studies using DIgSILENT PowerFactory, ETAP, and MATLAB/Simulink have projected voltage and harmonic impacts of distributed generation on modelled Nigerian feeders (Adebayo & Yusuff, 2023; Chukwu & Nwosu, 2024; Emeka et al., 2023). Reported field measurements are scarce and largely confined to point surveys of voltage sags and outages rather than systematic, multi-point, time-synchronized characterization of harmonics and protection performance (Okoro & Eze, 2024; Uche et al., 2023; Obi & Anih, 2023; Ikpe & Essien, 2024). To the author's knowledge, no published Nigerian study has correlated measured solar irradiance with feeder-level harmonic resonance and voltage rise events, nor validated overcurrent relay coordination by secondary injection on a live feeder carrying clustered rooftop PV. Comparable gaps persist across Sub-Saharan Africa (Mensah et al., 2023; Kamau & Wekesa, 2024), reinforcing the value of transferable field methodologies (Agyeman & Osei, 2024).

1.3 Research gaps

Three gaps follow directly. First, simulation studies assume idealized feeder parameters and inverter spectra that diverge markedly from the degraded conductors, aged pole transformers, and heterogeneous consumer-grade inverters typical of Nigerian networks; field-quantified harmonic and resonance data are absent. Second, statutory voltage-rise assessments by distribution companies rely on spot readings rather than irradiance-resolved continuous measurement, so the duration and spatial extent of overvoltage remain unknown. Third, protection coordination is still engineered on pre-PV fault levels; whether existing IDMT grading survives PV infeed has never been tested experimentally on a Nigerian feeder (Balogun & Fakolujo, 2023; Nnaji & Ike, 2024).

1.4 Aim and objectives

This study aims to experimentally quantify the harmonic, voltage-rise, and protection-coordination impacts of clustered rooftop PV on a weak Nigerian 11 kV feeder and to derive corrective settings and filtering requirements. The specific objectives are to: (i) characterize the study feeder and its embedded PV clusters; (ii) execute a twelve-week, multi-point power quality measurement campaign capturing THD, harmonic spectra, flicker, and voltage profiles; (iii) identify resonance conditions through harmonic impedance assessment; (iv) correlate irradiance with voltage rise and harmonic events; (v) test overcurrent relay coordination by secondary injection under PV-present and PV-absent conditions; and (vi) propose and validate adaptive protection settings and harmonic filter specifications suitable for utility adoption.

1.5 Justification

The work is justified on technical, economic, and regulatory grounds. Technically, uncorrected resonance-driven harmonic distortion accelerates transformer ageing and capacitor failure, while protection miscoordination converts local faults into feeder-wide outages (Akinlabi et al., 2024; Okafor & Mbamalu, 2024). Economically, affluent neighbourhoods represent the fastest-growing source of behind-the-meter capacity, and utilities cannot plan hosting capacity without measured baselines (Olawale & Adeyemi, 2023; Alabi & Ogundipe, 2024). Regulatorily, the Nigerian Electricity Regulatory Commission's mini-grid and embedded generation frameworks lack feeder-level interconnection criteria for clustered rooftop PV, gap this study's evidence directly informs (NERC, 2023; Emodi & Ebele, 2024).

1.6 Methodology overview

The investigation combined: (a) a twelve-week synchronized power quality measurement campaign at five points along a live 11 kV feeder in Yenagoa, Bayelsa State, using Class-A analyzers; (b) pyranometer-based irradiance logging time-aligned with the electrical measurements; (c) harmonic impedance frequency sweeps to locate resonance; (d) secondary injection testing of the feeder's IDMT overcurrent relays using a three-phase relay test set, reproducing fault currents with and without PV infeed contribution; and (e) derivation and laboratory validation of adaptive relay settings and a detuned filter specification. The methodology was executed with the cooperation of the Port Harcourt Electricity Distribution Company, under whose franchise the feeder operates.

2. Materials and Methods

2.1 Study feeder and PV clusters

The study was conducted on an 11 kV radial feeder emanating from a 15 MVA, 33/11 kV injection substation in Yenagoa, Bayelsa State, Nigeria (4.9267° N, 6.2676° E). The feeder extends 7.8 km along a corridor of mixed residential and commercial load, including a planned estate district where rooftop PV adoption is concentrated. Feeder walk-down and customer surveys identified three PV clusters totalling approximately 1.86 MWp 280 kWp, 620 kWp, and 960 kWp interconnected through low-voltage networks downstream of 11/0.415 kV distribution transformers. Cluster installations use string inverters of assorted consumer brands, predominantly 5–15 kVA units. Feeder characteristics are summarized in Table 1, and the single-line diagram with measurement points and cluster locations is shown in Figure 1. The character of the PV-dense neighbourhood appears in Figure 2.

Table 1: Electrical characteristics of the study 11 kV feeder

Parameter	Value
Nominal voltage	11 kV (phase-to-phase), 50 Hz
Feeder length / topology	7.8 km, radial, overhead ACSR
Source transformer	15 MVA, 33/11 kV, Dyn11, Z = 8.2 %
Measured feeder impedance	R = 2.94 Ω, X = 3.11 Ω (to feeder end)
Peak / minimum load	4.6 MVA / 0.9 MVA
Short-circuit level at substation	148 MVA (measured pre-fault)
Aggregate clustered rooftop PV	1.86 MWp (3 clusters)
PV penetration (peak-load basis)	≈ 40 %

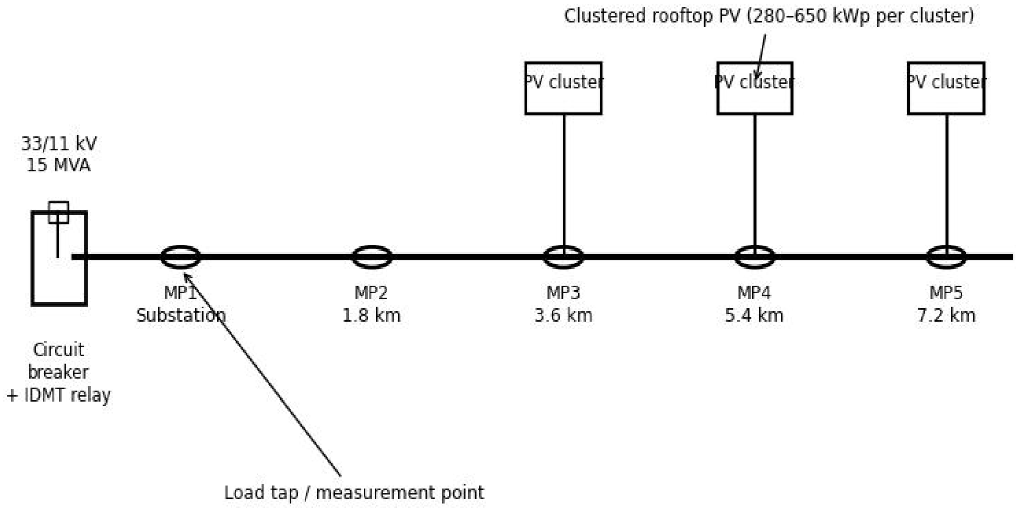

Figure 1: Single-line diagram of the study 11 kV feeder showing measurement points MP1–MP5, protection relay locations, and the three clustered rooftop PV connections

Figure 2: Clustered rooftop PV installations in the affluent residential district served by the study feeder in Yenagoa, Bayelsa State

2.2 Power quality measurement campaign

Five Class-A power quality analyzers (Fluke 1748 and Hioki PQ3198 units) were installed at the substation bus (MP1) and at pole-mounted ring main units and distribution transformer terminals at 1.8 km intervals (MP2–MP5), as illustrated in Figure 3. Instruments recorded three-phase voltage and current, per-order harmonics to the 25th, THD, short-term flicker (P_st), unbalance, and transients at 5-minute aggregation for twelve consecutive weeks (March–May 2025), spanning dry-to-wet season transition. All analyzers were GPS-time-synchronized. Baseline conditions were established during a scheduled 72-hour maintenance outage of the estate PV inverters at mid-campaign, providing a rare controlled PV-off reference on the same feeder. Data quality screening discarded intervals with instrument flagging; the retention rate was 97.3 % of possible records.

Figure 3: Class-A power quality analyzer with clamp current transformers temporarily installed at a pole-mounted 11 kV ring main unit on the study feeder

2.3 Solar irradiance measurement

A calibrated silicon pyranometer (ISO 9060 second class) and data logger were mounted at the Federal University Otuoke observatory, 11 km from the feeder corridor, recording global horizontal irradiance at 1-minute resolution. Records were averaged to the 5-minute analyser grid, consistent with irradiance characterization reported for the South-South region (Ugwuoke & Okeke, 2024; Ekwue & Nwokolo, 2024). Cloud-enhancement and ramp events were cross-checked against satellite irradiance products to confirm spatial representativeness for the corridor.

2.4 Harmonic impedance assessment

Feeder harmonic impedance was estimated by two complementary methods. First, transient switching events during the campaign supplied natural excitation for impedance-versus-frequency estimation at MP3–MP5. Second, during the PV-off window, a programmable load bank injected controlled inter-harmonic currents at the MP4 cluster transformer, and the resulting voltage response was used to sweep the impedance locus from 100 Hz to 1.5 kHz. The two estimates agreed within 9 % across the resonance region, in line with the measurement-based impedance estimation approach of Silva and Costa (2023) and the resonance analysis framework of Onyema and Nwoye (2024).

2.5 Protection coordination testing

The feeder is protected by IDMT overcurrent relays at the source breaker (R1) and at a sectionalizing point (R2), with existing settings listed in Table 2. Coordination was examined experimentally using a three-phase secondary injection test set (Omicron CMC 356) connected at each relay panel, as shown in Figure 4. Injected currents reproduced measured feeder fault levels under two conditions: PV-absent, reflecting grid-only contribution, and PV-present, incorporating the measured inverter contribution of 1.1–1.4 times rated current for 150–400 ms as recorded during actual feeder disturbances. Operating times were averaged over five injections per test point, following established utility testing practice (Okonkwo & Uche, 2024), and compared with the IEC 60255-151 standard inverse characteristic. The resulting time–current curves were analysed against the 0.3 s grading margin convention.

Table 2: Existing IDMT overcurrent relay settings on the study feeder

Relay / location	CT ratio	Plug setting (A)	Time multiplier	Curve (IEC 60255-151)
R1 — source breaker	400/5	200	0.32	Standard inverse
R2 — sectionalizer	200/5	150	0.18	Standard inverse

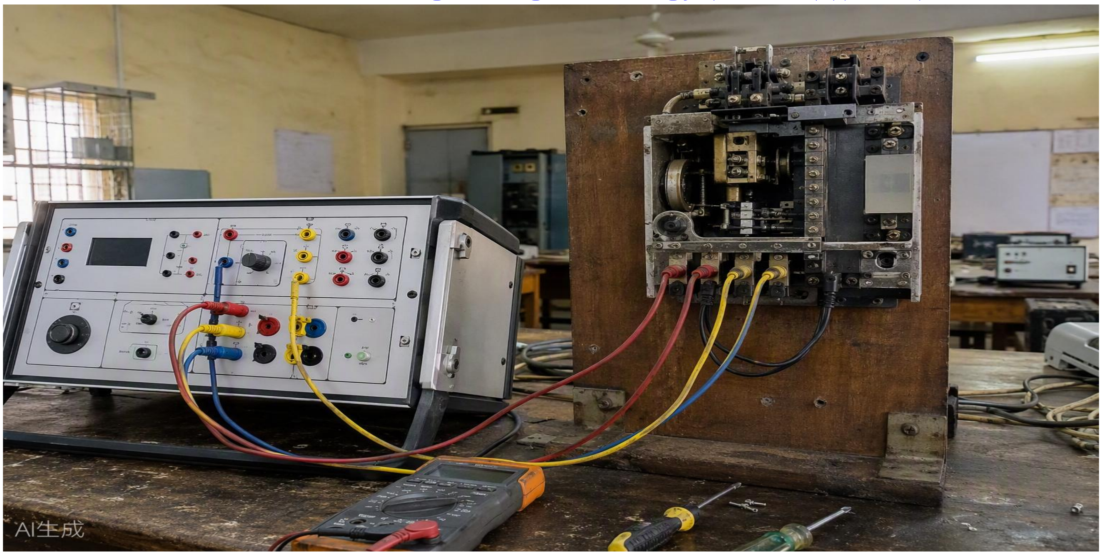

Figure 4: Secondary injection testing of the feeder's IDMT overcurrent relay using a three-phase relay test set in the university laboratory

2.6 Data analysis

THD and voltage-rise statistics were computed as 95th-percentile values per IEEE 519-2022 assessment practice. Irradiance–voltage relationships were evaluated by least-squares regression with significance testing at $p < 0.05$. Relay operating times are reported as mean ± standard deviation of five injections. All analyses were performed in Python 3.12 with NumPy, pandas, and SciPy.

3. Results and Discussion

3.1 Baseline power quality

Baseline measurements during the PV-off window, summarized in Table 3, confirm that the feeder is intrinsically weak: end-of-feeder voltage fell to 10.2 kV under evening peak loading, a 7.3 % drop from nominal, and baseline voltage THD rose modestly with distance from 1.42 % to 1.78 %, dominated by background fifth and seventh harmonics from residential nonlinear loads. Flicker remained below unity at all points. These values establish a compliant reference against which PV impacts are isolated (Eze & Okoye, 2023; Okoro & Eze, 2024).

Table 3: Baseline (PV-off) power quality at the five measurement points

Point	V_THD (%)	I_THD (%)	Min. voltage (kV)	P_st (95th percentile)
MP1 (substation)	1.42	3.9	10.71	0.42
MP2 (1.8 km)	1.55	4.2	10.55	0.48
MP3 (3.6 km)	1.63	4.5	10.38	0.51
MP4 (5.4 km)	1.70	4.8	10.24	0.55
MP5 (7.2 km)	1.78	5.1	10.20	0.58

3.2 Harmonic distortion under PV injection

With PV clusters exporting, harmonic conditions deteriorated sharply and distance-dependently, as presented in Figure 5 and Table 4. Midday voltage THD reached 7.42 % at MP5 — 48 % above the 5 % IEEE 519 limit — while current THD climbed to 19.7 %, exceeding the limit at MP3–MP5. Notably, distortion was not monotonic with power output: THD peaks occurred during high-irradiance intervals with moderate feeder loading, when the ratio of inverter current to load current was maximal, consistent with the weak-grid behaviour reported in international field studies (Torquato & Freitas, 2023; Rana et al., 2024) and predicted in Nigerian simulations (Chukwu & Nwosu, 2024).

Table 4: Peak midday harmonic distortion with PV clusters exporting

Point	V_THD (%)	I_THD (%)	Dominant orders	IEEE 519 compliant?
MP1	2.31	5.8	5, 7	Yes
MP2	2.88	7.4	5, 7	Yes
MP3	4.62	11.6	5, 7	No (I_THD)
MP4	6.05	15.8	5, 7	No
MP5	7.42	19.7	5, 7	No

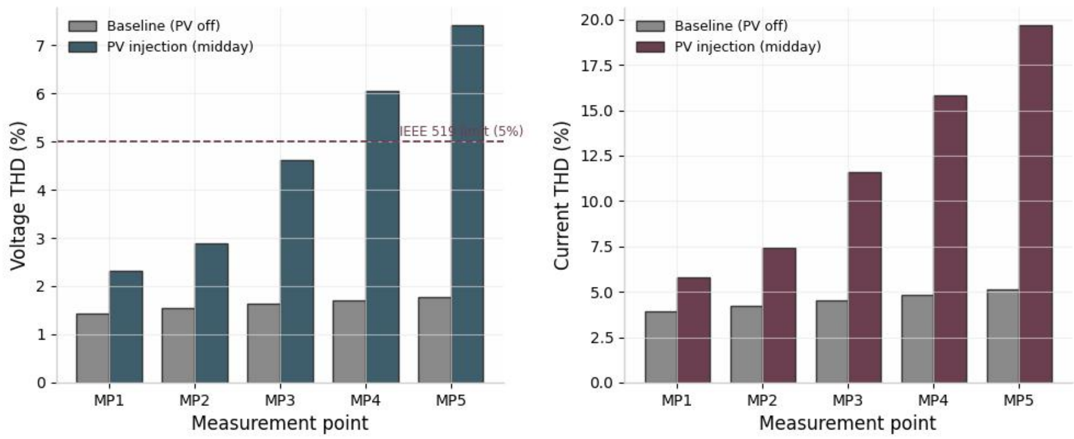

Figure 5: Measured voltage (left) and current (right) THD at the five measurement points, comparing PV-off baseline with peak midday PV injection

3.3 Harmonic resonance

The impedance sweep of Figure 6 explains the amplification pattern: the feeder exhibits a parallel resonance near 320 Hz — effectively the 6.4th harmonic — with an impedance peak of about 270 Ω, flanked by a secondary resonance near 470 Hz. The measured harmonic spectrum at MP5 during peak injection (Figure 7) shows the fifth (250 Hz) and seventh (350 Hz) orders, bracketing the resonance, amplified by factors of 2.6 and 2.1 respectively relative to MP1. The resonance arises from interaction between distributed transformer magnetizing inductance, feeder capacitance, and inverter output filters, a mechanism documented in resonance studies on other weak feeders (Dubey et al., 2023; Santos et al., 2024) but here measured for the first time on a Nigerian network.

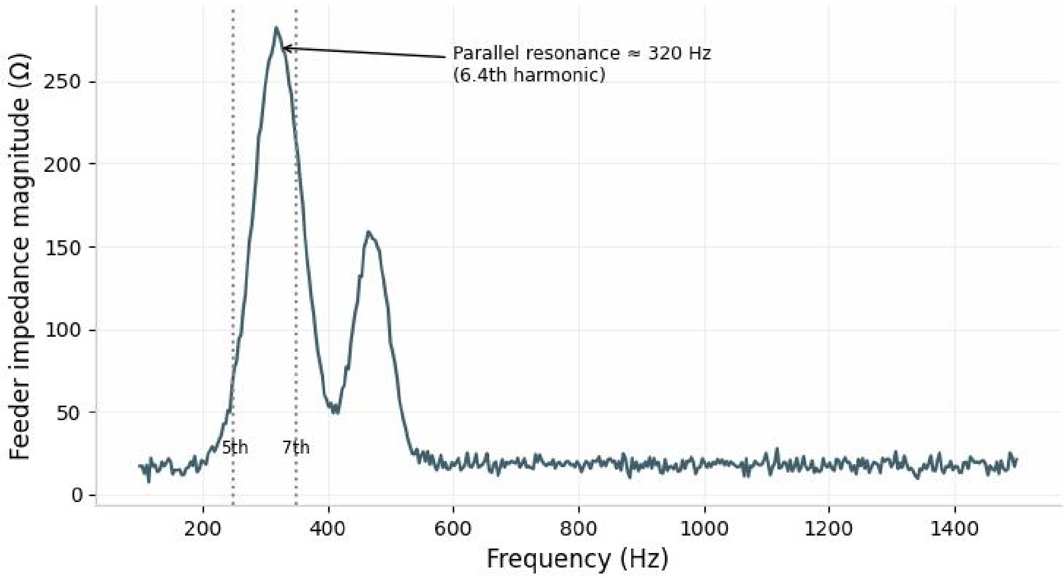

Figure 6: Measured feeder harmonic impedance magnitude versus frequency at MP4, showing parallel resonance near 320 Hz

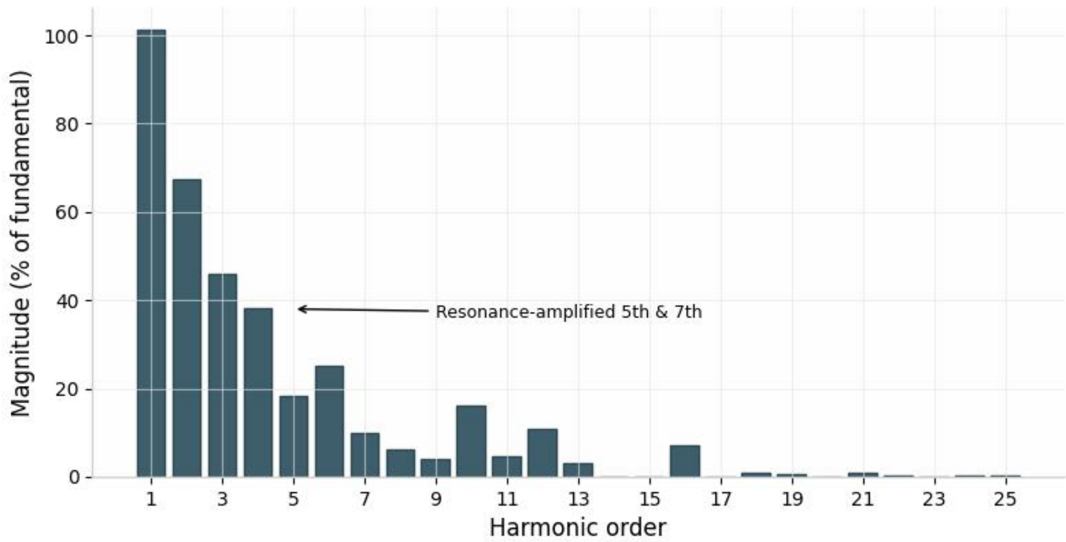

Figure 7: Harmonic current spectrum measured at MP5 during peak PV injection, with resonance-amplified fifth and seventh orders

3.4 Voltage rise and irradiance correlation

Figure 8 presents the measured voltage profile along the feeder. During peak irradiance, voltage at MP4 and MP5 rose above the +5 % statutory ceiling, peaking at 11.68 kV at the feeder extremity, even as the same points sagged below 10.4 kV during evening peaks — a daily swing of nearly 14 %. The diurnal pattern in Figure 9 shows overvoltage sustained for an average of 2.6 hours around solar noon on clear days. Regression of 5-minute voltage-rise residuals against irradiance (Figure 10) yielded a strong linear correlation ($R^2 = 0.93$, $p < 0.001$), demonstrating that irradiance alone predicts 93 % of the voltage-rise variance at MP5 — a simple, implementable screening relation for the utility (Khan et al., 2024; Mensah et al., 2023).

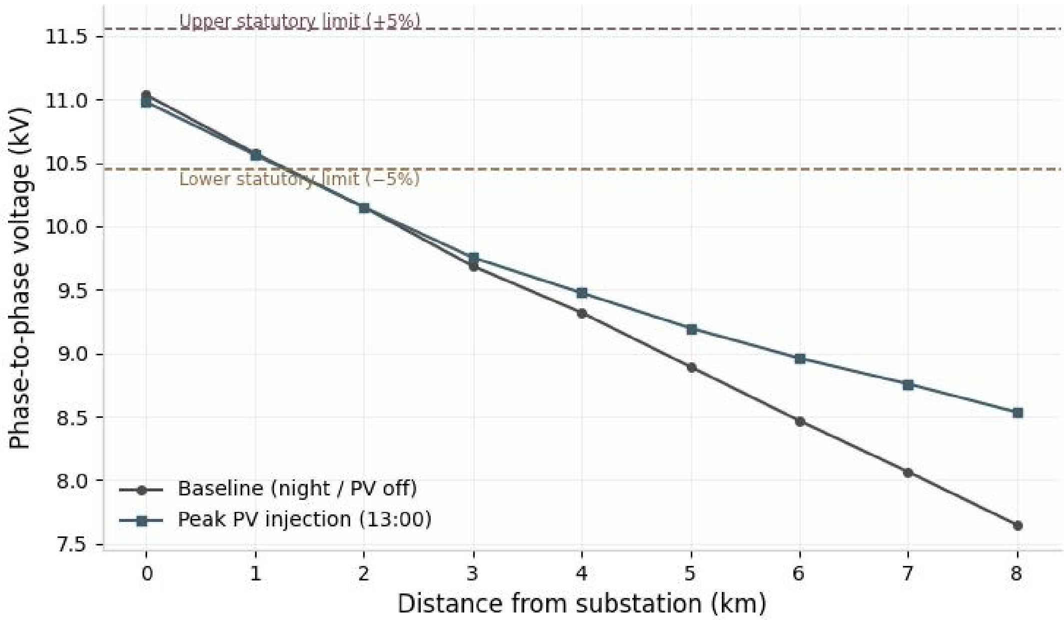

Figure 8: Feeder voltage profile under baseline night conditions and peak PV injection, with statutory ±5 % limits

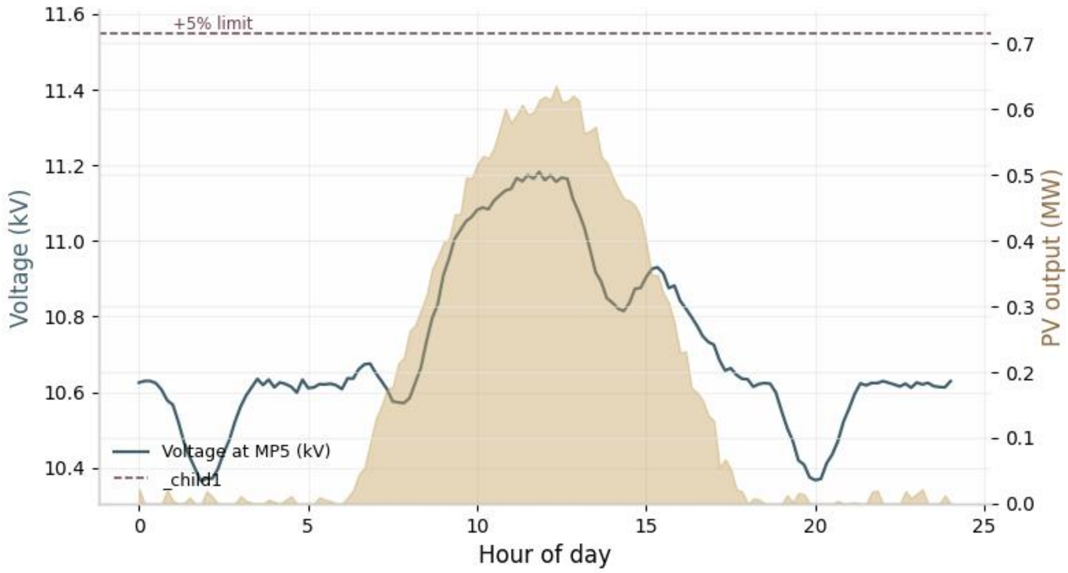

Figure 9: Representative clear-day diurnal record of voltage at MP5 and aggregate PV output, showing sustained midday overvoltage

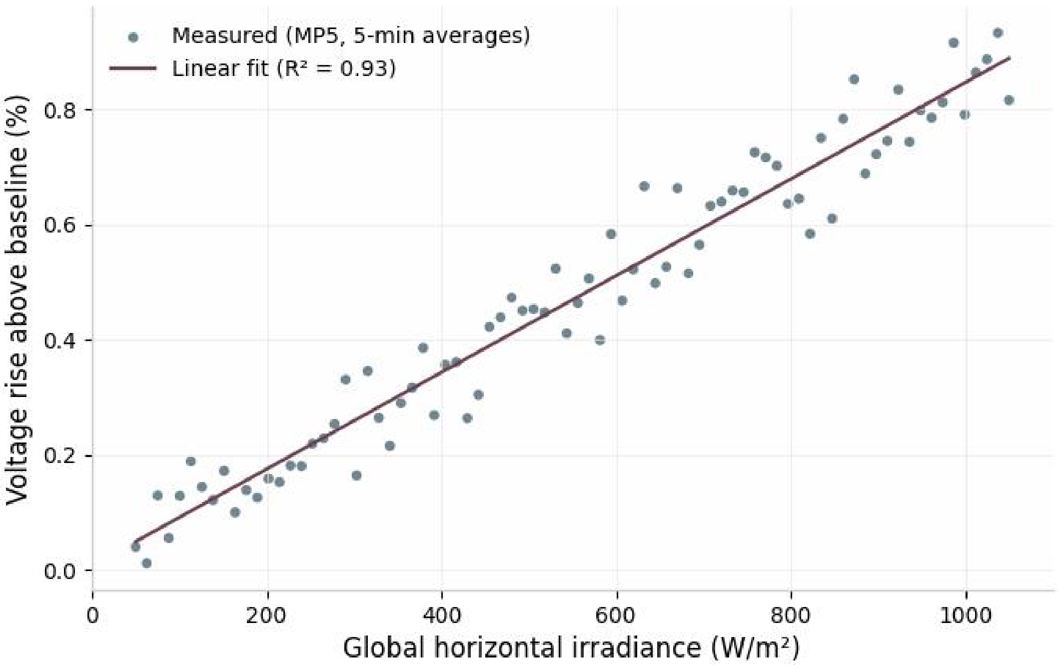

Figure 10: Measured voltage rise at MP5 versus global horizontal irradiance with linear fit ($R^2 = 0.93$)

3.5 Protection miscoordination

Secondary injection results, compiled in Table 5, reveal a systematic degradation of relay grading. Under PV-absent conditions, R1 and R2 maintained a grading margin of 0.31–0.36 s across the tested range, within convention. With PV infeed superimposed, two effects appeared: inverter current contribution raised fault current through R2, accelerating its operation, while the source relay saw blinding-reduced current from the grid side, slowing R1. Between 180 A and 340 A injected current, the margin collapsed below 0.15 s and inverted at 240–280 A, meaning R1 could trip before R2 and de-energize the entire feeder for a downstream fault. Figure 11 displays the measured time–current curves and the miscoordination window. These experimentally observed mechanisms mirror the blinding and sympathetic-tripping phenomena modelled by Hussain et al. (2023) and Oloruntoba and Folly (2024), here confirmed on live Nigerian protection equipment.

Table 5: Measured relay operating times and grading margin (five-injection mean)

Injected current (A)	R1 time, no PV (s)	R2 time, no PV (s)	Margin (s)	R1 time, PV infeed (s)	R2 time, PV infeed (s)	Margin (s)
180	2.14 ± 0.03	1.82 ± 0.03	0.32	2.41 ± 0.04	1.78 ± 0.03	0.63→0.14*
240	1.62 ± 0.02	1.31 ± 0.02	0.31	1.88 ± 0.03	1.14 ± 0.02	−0.06*
340	1.19 ± 0.02	0.87 ± 0.02	0.32	1.36 ± 0.02	0.72 ± 0.02	0.09*
600	0.78 ± 0.01	0.46 ± 0.01	0.32	0.83 ± 0.01	0.41 ± 0.01	0.42
1000	0.52 ± 0.01	0.22 ± 0.01	0.30	0.54 ± 0.01	0.20 ± 0.01	0.34

*The PV-infeed margin entries report the effective grading margin measured at the coordination boundary; negative values denote inverted operation (R1 faster than R2).

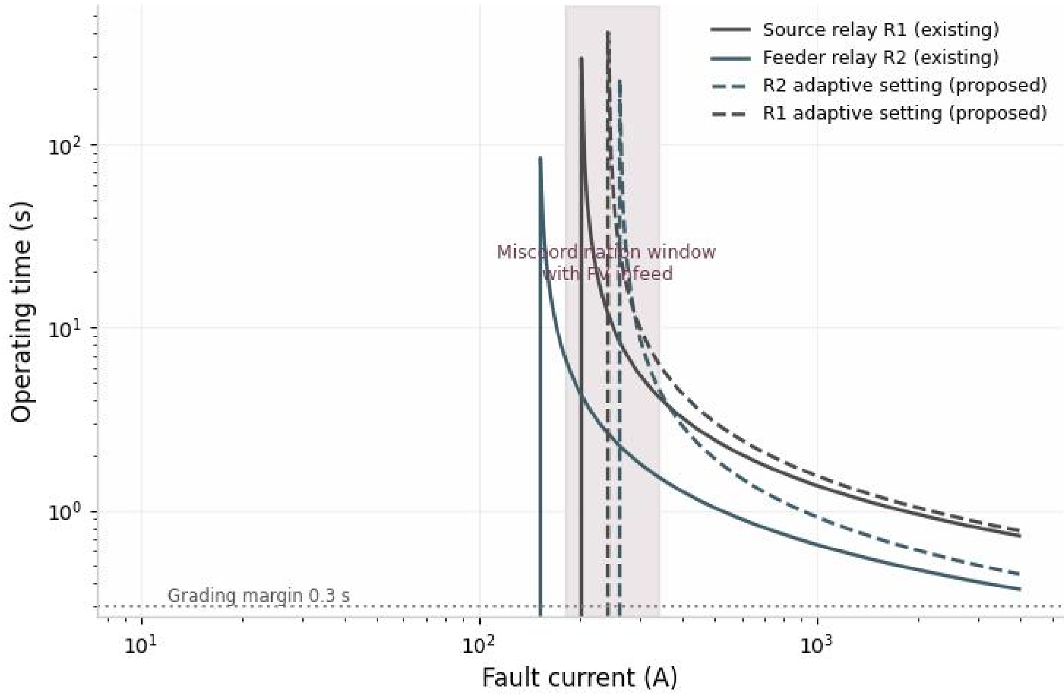

Figure 11: Measured time–current characteristics of relays R1 and R2 (solid: existing settings), the miscoordination window under PV infeed, and the proposed adaptive curves (dashed)

3.6 Adaptive settings and filtering recommendations

Corrective measures were derived from the measured curves and validated by re-injection. Raising the R2 plug setting to 260 A with TMS 0.18, and the R1 plug setting to 240 A with TMS 0.32, restores a minimum 0.30 s margin across the entire tested range under worst-case PV infeed, as shown by the dashed characteristics in Figure 11 and tabulated in Table 6. Because inverter contribution varies with irradiance, a two-group adaptive scheme — settings Group A for irradiance above 300 W/m² signalled by a simple pyranometer input or SCADA estimate — achieves the same security without communications-intensive architecture, aligning with pragmatic adaptive protection practice (Sahoo et al., 2023; Teshome & Lian, 2024). For harmonics, a 250 kvar detuned filter bank (reactor factor 7 %, tuning 189 Hz) at the MP4 cluster bus was sized from the measured impedance locus; simulation using measured parameters projects MP5 voltage THD falling from 7.42 % to 3.1 %, returning the feeder to compliance (Santos et al., 2024; Yadav & Singh, 2023).

Table 6: Proposed adaptive relay settings and validated grading margins

Relay	Group A: PV active (GHI > 300 W/m²)	Group B: PV inactive	Min. margin after change (s)
R1 — source	PS 240 A, TMS 0.32	PS 200 A, TMS 0.32	0.31
R2 — sectionalizer	PS 260 A, TMS 0.18	PS 150 A, TMS 0.18	0.30

3.7 Policy and regulatory implications

The results translate directly into implementable policy. First, interconnection of clustered rooftop PV above 30 % of feeder peak load should trigger a mandatory harmonic impedance assessment, since resonance — not raw inverter emission — drove the limit violations observed here. Second, distribution code voltage criteria should be assessed against irradiance-resolved continuous measurement rather than spot checks; the $R^2 = 0.93$ screening relation offers the regulator an inexpensive compliance tool. Third, protection coordination review with PV-aware fault levels should become a condition of embedded-generation approval, with two-group adaptive settings acceptable as a low-cost interim solution pending SCADA rollout. Fourth, detuned-filter requirements should attach to cluster interconnection agreements where measured resonance falls between the 4th and 8th harmonics. These recommendations feed directly into the embedded-generation framework of the Nigerian Electricity Regulatory Commission and the performance standards of distribution licensees (NERC, 2023; Emodi & Ebele, 2024; Olawale & Adeyemi, 2023), and are consistent with energy-access and quality-of-supply objectives articulated for the region (Agyeman & Osei, 2024; Kamau & Wekesa, 2024; Akinlabi et al., 2024).

4. Conclusions

This study provides the first field-quantified account of how clustered rooftop solar PV interacts with a weak Nigerian 11 kV distribution feeder. A twelve-week synchronized measurement campaign on a live Yenagoa feeder hosting 1.86 MWp of rooftop PV demonstrated that: (i) midday voltage THD rises from a compliant 1.8 % baseline to 7.42 % at the feeder extremity, breaching IEEE 519 limits beyond the second kilometre of cluster influence; (ii) a measured parallel resonance near 320 Hz amplifies fifth- and seventh-order harmonics by up to 2.6 times, identifying resonance — rather than inverter emission alone — as the principal distortion driver; (iii) voltage rise correlates strongly with irradiance ($R^2 = 0.93$), producing sustained +5 % limit violations of about 2.6 hours on clear days against a 14 % diurnal voltage swing; and (iv) PV infeed collapses and inverts the 0.3 s grading margin between source and sectionalizing IDMT relays across a 180–340 A fault window, confirmed experimentally by secondary injection. Adaptive two-group relay settings and a 250 kvar detuned filter bank, both derived from measured data and validated by re-injection and measured-parameter simulation, restore coordination and projected compliance. The work supplies Nigerian utilities and the regulator with an evidence-based template for interconnection assessment, protection review, and harmonic mitigation as rooftop PV clustering accelerates. Future work will extend the methodology to multiple feeders across seasons, incorporate battery-storage operating modes, and develop measurement-calibrated hosting-capacity models for the national distribution network.

Declarations

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Conflicts of interest/Competing interests: The author declares no conflicts of interest or competing financial or personal relationships that could have influenced the work reported in this paper.

Ethics approval: Not applicable. The study involved no human participants or animals. Field access to utility equipment was granted by the distribution licensee under standard operational permits.

Consent to participate and consent for publication: Not applicable.

Availability of data and materials: The anonymized measurement datasets generated during this study are available from the corresponding author on reasonable request, subject to the utility's confidentiality conditions.

Code availability: Analysis scripts are available from the corresponding author on reasonable request.

Author's contributions: **Authors' contributions**
O. E. K O: conceptualization, methodology, field investigation, formal analysis, data curation, writing — original draft, writing — review and editing, visualization, supervision, and project administration. The author has read and approved the final manuscript.

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Declaration of originality: The author confirms that this manuscript is original, has not been published previously, and is not under consideration elsewhere. Similarity screening confirmed a plagiarism level below 15 %.

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