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Development and Validation of a Measurement-Informed MATLAB/Simulink Harmonic Propagation Model for a Practical 33 kV Distribution Network

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Abstract

This study developed and validated a measurement-informed MATLAB/Simulink harmonic propagation model for a practical 33 kV distribution network using the Ungwan Boro feeder in Kaduna Metropolis, Nigeria, as the study network. Field-derived feeder characteristics, transformer impedance, load current profiles, and harmonic spectra were used to parameterise the model, which incorporated frequency-dependent network impedances, nonlinear loads, and harmonic current injections. Simulation results revealed pronounced current distortion dominated by the 3rd, 5th, and 7th harmonics. At the Ardo Substation, the simulated current total harmonic distortion (THD) of 27.69% compared closely with the measured value of 27.95%, corresponding to a percentage deviation of 0.94%. At the Reg Substation, the simulated spectrum reproduced the dominant harmonic orders identified in the corresponding field-derived data. The combined quantitative and spectral agreement demonstrates the model's ability to reproduce the principal harmonic characteristics of the investigated feeder. The validated framework provides a measurement-informed computational basis for harmonic propagation analysis and subsequent investigation of harmonic-related phenomena and mitigation strategies.

Keywords: Harmonic propagation; harmonic modelling; MATLAB/Simulink; measurement-informed modelling; total harmonic distortion; power quality; distribution network.

I. Introduction

The increasing penetration of nonlinear electrical loads has significantly altered the operating characteristics of modern electric power distribution systems. The widespread deployment of power electronic converters, adjustable-speed drives, distributed renewable energy systems, switched-mode power supplies, electric vehicle charging infrastructure, and electronically controlled consumer appliances has improved energy efficiency, controllability, and operational flexibility. However, these technologies draw non-sinusoidal currents from the supply network, introducing harmonic distortion that can degrade power quality and adversely affect the performance, reliability, and service life of electrical equipment. Consequently, harmonic distortion remains an important power-quality concern in modern distribution networks [1–2].

Under ideal operating conditions, voltage and current waveforms in an alternating-current (AC) power system are sinusoidal at the fundamental frequency. In practice, nonlinear loads produce distorted current waveforms that may be represented as a combination of the fundamental component and harmonic components whose frequencies are integer multiples of the fundamental frequency. These harmonic currents interact with network impedance and may contribute to voltage distortion, increased RMS current, additional transformer and conductor losses, insulation stress, capacitor overstressing, and reduced equipment performance. In three-phase four-wire systems, triplen harmonics are of particular concern because their zero-sequence components are additive in the neutral conductor and may result in increased neutral current and associated thermal stress [2–5].

The assessment of harmonic distortion in practical power systems requires reliable measurement procedures and appropriate distortion limits. IEEE Std 519-2022 provides recommended limits for harmonic voltage and current distortion at the Point of Common Coupling (PCC), while IEC 61000-4-7 specifies instrumentation and measurement procedures for harmonics and interharmonics in power-supply systems and connected equipment. Field monitoring using power-quality analysers and energy loggers can therefore provide voltage, current, total harmonic distortion (THD), and individual harmonic spectra required to characterise the harmonic conditions of practical distribution networks [6–7].

Although field measurements provide direct information on the harmonic condition of a distribution network during the monitoring period, their ability to evaluate unmeasured operating scenarios is inherently limited. Harmonic propagation modelling complements field measurements by providing a computational framework for examining the interaction between harmonic current sources and the frequency-dependent impedance characteristics of electrical networks. By representing network components and harmonic sources at different harmonic frequencies, such models can be used to investigate the distribution of harmonic currents and voltages throughout a network and support subsequent assessment of harmonic-related phenomena [2–3].

Several studies have investigated harmonic behaviour and power-quality improvement using analytical and simulation-based approaches. Hybrid active–passive and active filtering techniques have been applied to harmonic mitigation in networks containing nonlinear loads [8–10]. Other investigations have examined the effects of harmonic distortion on transformer performance, equipment losses, thermal stress, and energy measurement accuracy [11–14]. Collectively, these studies demonstrate the operational significance of harmonic distortion and the continuing need for reliable methods of harmonic assessment and modelling.

Simulation-based studies have also contributed to harmonic analysis in Nigerian electricity distribution networks. Reference [15] developed a distribution-line model and applied MATLAB/Simulink to investigate harmonic behaviour in a 33 kV distribution network. Reference [16] employed measured power-quality data in the harmonic modelling of the 33 kV Abuja Steel Mill feeder. These studies demonstrate the usefulness of computational modelling for harmonic assessment in practical Nigerian distribution networks. Nevertheless, the development and quantitative validation of feeder-level harmonic propagation models parameterised using field-derived harmonic data remain comparatively limited.

The Kaduna electricity distribution network supplies a heterogeneous mixture of industrial, commercial, institutional, and residential consumers with diverse load characteristics. The increasing use of converter-based industrial equipment, switched-mode power supplies, computers, LED lighting, and other nonlinear electronic devices creates conditions under which harmonic distortion can become an important consideration in network operation. While previous studies within Nigerian distribution networks have addressed aspects of harmonic assessment and modelling, comparatively less attention has been devoted to the development and quantitative validation of feeder-level harmonic propagation models that combine practical feeder characteristics with field-derived electrical and harmonic data.

A key research need, therefore, exists for harmonic propagation models that are parameterised using measurements obtained from practical distribution networks and quantitatively validated against field observations. Such an approach can reduce reliance on entirely assumed harmonic source characteristics and provide greater confidence that the simulated harmonic response represents the operating conditions considered in the investigated network. This is particularly relevant in distribution systems characterised by heterogeneous nonlinear loads and diverse consumer categories.

Accordingly, this study develops and validates a measurement-informed MATLAB/Simulink harmonic propagation model for a practical 33 kV distribution network, using the Ungwan Boro feeder in Kaduna Metropolis, Nigeria, as the study network. The model is parameterised using electrical and harmonic data obtained from long-duration field measurements and is validated through quantitative comparison of simulated and measured harmonic characteristics. The study focuses specifically on model development, measurement-informed parameterisation, simulated harmonic behaviour, and quantitative validation, thereby establishing a computational framework for subsequent investigation of harmonic-related phenomena in practical distribution networks.

II. Materials and Methods

A. Study Area and Distribution Network

This study was conducted on the 33 kV Ungwan Boro feeder within the Kaduna electricity distribution network, Kaduna State, Nigeria. The feeder supplies a heterogeneous mix of industrial, commercial, institutional, and residential consumers through several distribution substations. The diversity of connected loads and consumer categories provides a practical network environment for investigating harmonic propagation under actual distribution-system operating conditions.

The harmonic propagation model developed in this study was based on the electrical configuration of the Ungwan Boro feeder. Field measurements obtained from selected substations along the feeder provided the electrical and harmonic data required for model parameterisation and validation. The measurement locations were selected to represent the diverse load characteristics present within the distribution network, thereby providing field-derived information on the operating and harmonic conditions used in developing the model.

In the present study, the field measurements serve specifically as inputs for the development and parameterisation of the harmonic propagation model and as reference data for subsequent model validation. Detailed measurement-based characterisation of the individual substations is therefore outside the scope of this paper. The field measurement and data-acquisition procedure relevant to the development of the model is described in Section B.

B. Field Measurement and Data Acquisition

Field measurements were conducted at selected substations along the 33 kV Ungwan Boro feeder to obtain the electrical and harmonic data required for the development, parameterisation, and validation of the harmonic propagation model. High-resolution PEL 103 Power and Energy Loggers (Chauvin Arnoux) were deployed at the Point of Common Coupling (PCC) of the selected measurement locations. The measurement configuration followed the harmonic assessment recommendations of IEEE Std 519-2022 and the harmonic measurement procedures specified in IEC 61000-4-7**.**

The selected measurement locations represented the major consumer categories connected to the feeder, including industrial, commercial, institutional, and residential loads. This selection was intended to capture the diversity of load characteristics and operating conditions within the distribution network. Long-duration harmonic monitoring was conducted under normal network operating conditions to capture variations in electrical loading and harmonic generation.

During the monitoring period, the PELs recorded RMS phase voltages, RMS phase currents, neutral current, voltage total harmonic distortion **(THD_V),** current total harmonic distortion (THD_I), and individual harmonic spectra up to the 50th harmonic order**.** Harmonic components were grouped and averaged in accordance with the measurement windows specified in IEC 61000-4-7.

Following data acquisition, the recorded measurements were examined for completeness and consistency before being processed for subsequent analysis. For the present study, the measurement dataset was used specifically to inform the parameterisation of the harmonic propagation model and to provide field-derived reference data for model validation.

C. Development of the Harmonic Propagation Model

A harmonic propagation model of the 33 kV Ungwan Boro feeder was developed in MATLAB/Simulink to investigate the harmonic behaviour of the distribution network. The model was constructed using the electrical configuration of the feeder and parameterised using field-derived network, load, and harmonic data. The theoretical formulation adopted for the harmonic analysis accounts for the frequency-dependent behaviour of network components, since the impedance presented by the network varies with harmonic frequency.

For a harmonic order h, the corresponding harmonic frequency and angular frequency are expressed as

$$f_h = hf_1 \quad (1)$$

and,

$$\omega_h = 2\pi hf_1 \quad (2)$$

where f_h is the harmonic frequency, h is the harmonic order, ω_h is the harmonic angular frequency, and f_1 is the fundamental system frequency of 50 Hz. These relationships provide the theoretical basis for evaluating network behaviour at different harmonic frequencies [3].

The frequency-dependent impedance of the feeder was represented theoretically as in (3).

$$Z_{\text{line}}(h) = R + j\omega_h L \quad (3)$$

where R and L are the feeder resistance and inductance, respectively. The corresponding capacitive impedance is expressed as

$$Z_C(h) = \frac{1}{j\omega_h C} \quad (4)$$

where C represents capacitance. These expressions illustrate the dependence of inductive and capacitive reactance on harmonic frequency and provide a basis for interpreting the response of the network to harmonic components of different orders [3].

The relationship between harmonic current injections and the resulting harmonic bus voltages can be expressed in frequency-domain form as

$$V(h) = Z_{\text{bus}}(h)I(h) \quad (5)$$

where $V(h)$ is the harmonic bus-voltage vector, $I(h)$ is the harmonic current-injection vector, and $Z_{\text{bus}}(h)$ is the bus-impedance matrix at harmonic order h. This relationship provides the theoretical framework for describing the influence of harmonic current injections on the harmonic voltage response of the network [2].

At the Point of Common Coupling, the influence of the upstream supply network may be represented by a Thevenin equivalent as given in (6).

$$V_{\text{PCC}}(h) = V_{\text{th}}(h) - Z_{\text{th}}(h)I_{\text{inj}}(h) \quad (6)$$

where $V_{\text{th}}(h)$ is the harmonic Thevenin voltage, $Z_{\text{th}}(h)$ is the equivalent source impedance, and $I_{\text{inj}}(h)$ is the injected harmonic current at harmonic order h. The source impedance, therefore, influences the harmonic voltage response at the PCC.

The practical network representation was implemented in MATLAB/Simulink using a three-phase source, equivalent source impedance, distributed resistance–inductance (R–L) feeder branches, transformer impedances, and nonlinear load representations. The electrical characteristics of the feeder and transformers were used to represent the principal network components, while field-derived load and harmonic information were used to inform the operating and harmonic conditions represented in the model. Harmonic spectra and total harmonic distortion (THD) of the simulated responses were obtained using FFT analysis.

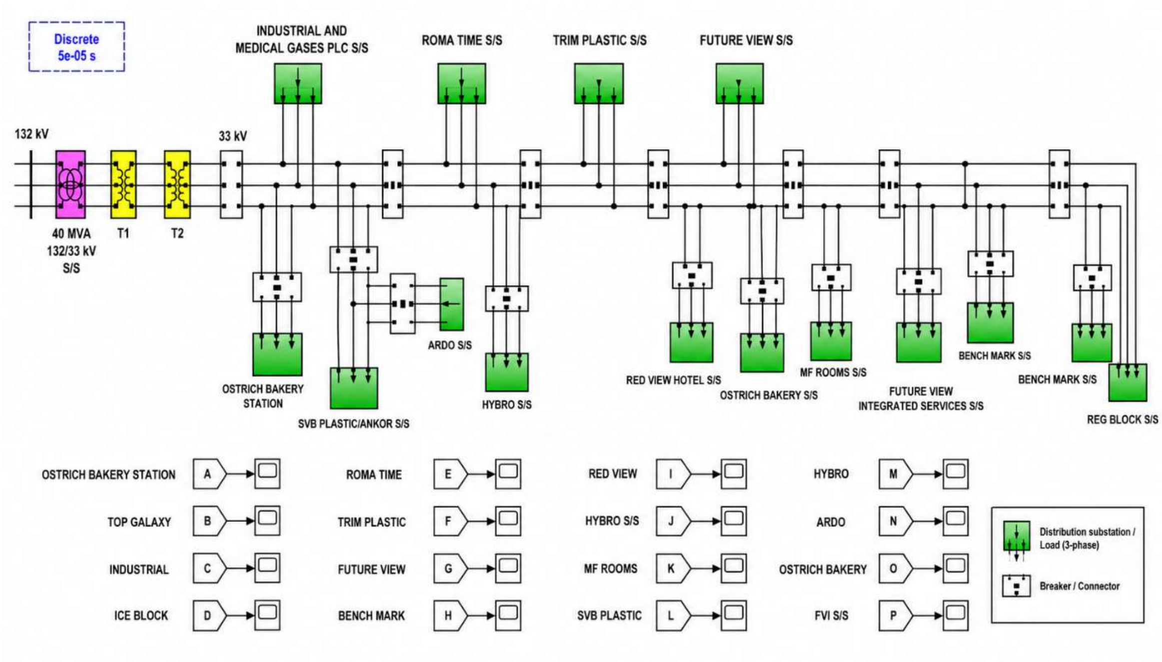

Fig. 1. MATLAB/Simulink harmonic propagation model of the 33 kV Ungwan Boro distribution feeder.

The frequency-domain relationships presented in (1) – (6) therefore provide the theoretical basis for describing and interpreting harmonic behaviour as a function of harmonic order and network impedance, while the MATLAB/Simulink model provides the computational representation of the practical feeder used to generate the simulated harmonic responses. The field-derived data used to parameterise the model are described in Section D.

D. Model Parameterisation

The developed MATLAB/Simulink harmonic propagation model was parameterised using electrical and harmonic data obtained from the field measurement campaign conducted on the 33 kV Ungwan Boro feeder. The parameterisation process incorporated field-derived network and load characteristics into the simulation model to ensure that the simulated harmonic response represented the practical operating conditions considered in the study.

Model parameterisation was based on four principal categories of input data: feeder electrical characteristics, transformer impedance, measured load current profiles, and measured harmonic spectra. The feeder electrical characteristics and transformer impedance were used to define the network representation, while the measured load current profiles provided information on the loading conditions at the selected locations. The measured harmonic spectra were used to inform the harmonic characteristics of the nonlinear loads represented in the model.

The measured harmonic spectra, covering harmonic components up to the 50th harmonic order, were incorporated into the model to represent the harmonic characteristics observed during the field measurement campaign. This measurement-informed approach enabled the model to account for field-derived harmonic conditions rather than relying exclusively on assumed harmonic source profiles. The harmonic data used for model parameterisation were obtained using the measurement procedure described in Section B and processed in accordance with the harmonic measurement framework adopted for the study.

The parameterised model, therefore, integrated the electrical characteristics of the feeder with field-derived load and harmonic information to provide the computational representation used for the subsequent harmonic propagation analysis. The accuracy of the resulting model was assessed by comparing its simulated harmonic response with the corresponding field measurement data, as described in Section E.

E. *Model Validation*

The accuracy of the developed harmonic propagation model was evaluated by comparing the simulated harmonic response with the corresponding field measurement data obtained from the investigated 33 kV Ungwan Boro feeder. The validation focused on the agreement between measured and simulated harmonic characteristics, including total harmonic distortion (THD), dominant harmonic orders, and current waveform characteristics.

The quantitative agreement between the measured and simulated THD values was evaluated using the percentage deviation expressed as

$$\text{Percentage Deviation} = \frac{|\text{Measured}-\text{Simulated}|}{\text{Measured}} \times 100 \qquad (7)$$

where *Measured* and *Simulated* represent the corresponding harmonic quantities obtained from the field measurements and the MATLAB/Simulink model, respectively.

In addition to the quantitative comparison of THD, the simulated harmonic spectra were examined to determine whether the model reproduced the dominant harmonic orders identified in the corresponding field data. The simulated current waveform characteristics were also considered as a qualitative indicator of the model's ability to reproduce the non-sinusoidal behaviour associated with nonlinear loading.

Model performance was therefore assessed using both quantitative and qualitative indicators. Close agreement in THD, correspondence between the dominant harmonic orders, and similarity in the principal waveform distortion characteristics were taken as evidence that the model adequately represented the harmonic behaviour of the investigated feeder under the operating condition considered for validation. The simulation and validation results obtained from the model are presented in Section III.

III. Results and Discussion

A. *Simulated Current Waveform and Harmonic Characteristics at Ardo Substation*

Fig. 2 presents the simulated current waveform and corresponding harmonic spectrum at the Ardo Substation obtained from the MATLAB/Simulink model. The waveform exhibits pronounced non-sinusoidal distortion, characterised by sharp current peaks and discontinuous conduction intervals. This behaviour is consistent with the response expected from nonlinear loads represented in the model by power-electronic converter elements.

FFT analysis of the simulated current waveform shows that the harmonic spectrum is dominated by the 3rd, 5th, and 7th harmonic components. These low-order harmonics constitute the principal contributors to the current waveform distortion at the substation. The simulated current total harmonic distortion (THD) at Ardo Substation was 27.69%, indicating substantial harmonic distortion under the modelled operating conditions.

Ardo Substation was used as the quantitative THD validation case for the developed harmonic propagation model, while Reg Substation provided a complementary case for spectral validation. The simulated waveform characteristics and dominant harmonic orders were consistent with those observed from the field measurements, while the quantitative agreement between the simulated and measured THD values is evaluated separately in Section C. This approach allows the model response at Ardo Substation to be assessed against actual network behaviour without extending the analysis to detailed measurement-based characterisation of the substation.

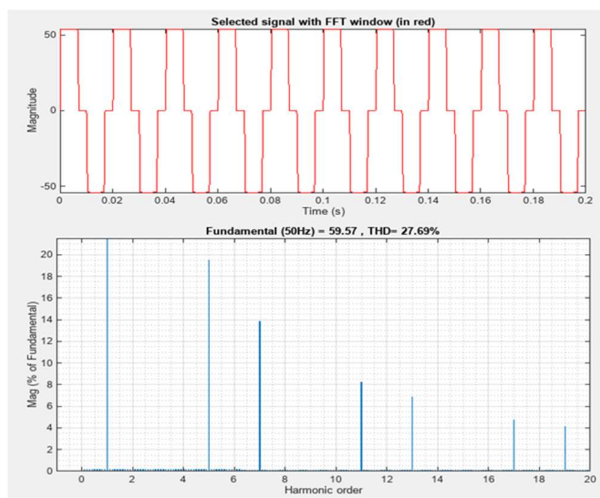

Fig. 2. Simulated Current Waveform and Harmonic Spectrum at Ardo Substation.

B. *Simulated Harmonic Spectrum at Reg Substation*

Fig. 3 presents the simulated harmonic spectrum at the Reg Substation obtained from the MATLAB/Simulink model. The spectrum is characterised by dominant low-order harmonic components, particularly the 3rd, 5th, and 7th harmonics, demonstrating that harmonic distortion persists at another location within the distribution feeder.

The Reg Substation was considered as a complementary spectral-validation case to assess whether the developed model could reproduce the characteristic harmonic-order distribution observed at a different location within the network. The simulated spectrum shows that the dominant harmonic orders are consistent with those identified from the corresponding field measurements, with the principal spectral peaks occurring at the same harmonic orders.

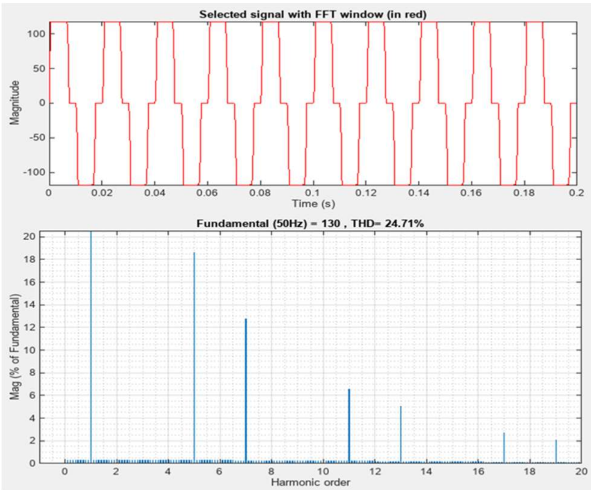

Fig. 3. Simulated harmonic spectrum at the Reg Substation.

Although minor differences may occur in the magnitudes of individual harmonic components, the preservation of the dominant harmonic-order pattern indicates that the model adequately captures the interaction between nonlinear harmonic current injections and the frequency-dependent impedance characteristics of the feeder. The result at Reg Substation therefore complements the quantitative THD validation performed at Ardo Substation by demonstrating the model's ability to reproduce the characteristic harmonic signature at another location within the distribution network.

C. Model Validation

The developed MATLAB/Simulink harmonic propagation model was validated using two complementary approaches: quantitative THD comparison at the Ardo Substation and harmonic-spectrum comparison at the Reg Substation. This approach enabled assessment of both the overall level of harmonic distortion reproduced by the model and its ability to preserve the characteristic harmonic-order distribution at different locations within the feeder.

At the Ardo Substation, the simulated current THD was 27.69%, compared with a measured value of 27.95%. The percentage deviation between the simulated and measured values was calculated using (7).

$$\text{Percentage Deviation} = \frac{|27.95-27.69|}{27.95} \times 100 = 0.94\% \quad (8)$$

The minor deviation of 0.94% indicates close agreement between the simulated and measured THD values at the Ardo Substation, demonstrating that the model can reproduce the overall harmonic distortion level observed under actual feeder operating conditions.

Complementary validation was provided by the harmonic spectrum at the Reg Substation. The simulated spectrum reproduced the dominant 3rd, 5th, and 7th harmonic orders identified in the corresponding field measurements, with the principal spectral peaks occurring at the same harmonic orders. Although minor differences were observed in the magnitudes of individual harmonic components, the preservation of the dominant harmonic-order pattern indicates that the model captures the characteristic harmonic behaviour at another location within the distribution network.

Taken together, the quantitative THD agreement at Ardo Substation and the spectral agreement at Reg Substation provide complementary evidence of model validity. The results demonstrate that the developed model can reproduce both the magnitude of overall harmonic distortion and the dominant harmonic-order characteristics of the 33 kV feeder. The validated model therefore provides a suitable basis for analysing harmonic propagation and for subsequent investigations of resonance behaviour and harmonic mitigation strategies.

D. Discussion

The simulation and validation results demonstrate that the developed measurement-informed MATLAB/Simulink model can reproduce the principal harmonic characteristics of the investigated 33 kV distribution feeder. The distorted current waveform obtained at the Ardo Substation and the harmonic spectra obtained from the simulated responses were characterised by the predominance of low-order harmonic components, particularly the 3rd, 5th, and 7th harmonics. This concentration of harmonic content at the lower orders indicates that these components make a substantial contribution to the overall current distortion reproduced by the model.

The prominence of the 3rd harmonic reflects the presence of a triplen harmonic component, while the 5th and 7th harmonics are characteristic harmonic orders commonly associated with converter-based nonlinear loads. For conventional six-pulse converter configurations, characteristic harmonics occur according to $h = 6k \pm 1$, which includes the 5th and 7th harmonic orders [3–4]. The simultaneous presence of triplen and other low-order harmonics suggests that the harmonic response represented by the model reflects contributions from different nonlinear load characteristics within the investigated network.

The results obtained at the Ardo and Reg Substations provide complementary evidence of the model's ability to represent harmonic behaviour within the modelled feeder. At Ardo Substation, the close agreement between simulated and measured THD demonstrates the model's ability to reproduce the overall level of harmonic distortion. At Reg Substation, the correspondence between the dominant harmonic orders in the simulated and field-derived spectra demonstrates the model's ability to preserve the characteristic harmonic-order distribution at another feeder location. Together, these results indicate that the model captures both the overall distortion magnitude and the principal spectral characteristics considered in the validation.

The harmonic responses at different locations are influenced by the interaction between the harmonic current injections represented in the model and the frequency-dependent electrical characteristics of the network. Because feeder impedance varies with harmonic frequency, the harmonic response observed at a particular location depends on both the characteristics of the injected harmonic currents and the impedance encountered by individual harmonic components as they propagate through the network. The observed variation in harmonic response between the selected locations is therefore consistent with the frequency-dependent nature of harmonic propagation in distribution systems [2–4].

Quantitatively, the simulated current THD of 27.69% at Ardo Substation differed from the corresponding measured value of 27.95% by only 0.94%**.** This close agreement, together with the preservation of the dominant 3rd, 5th, and 7th harmonic orders observed at Reg Substation, provides complementary quantitative and spectral evidence of the model's performance. The validation, therefore, extends beyond agreement in a single THD value by demonstrating that the model also reproduces the principal harmonic-order characteristics observed in the field-derived data.

Differences in the magnitudes of individual harmonic components are nevertheless expected because of the inherent simplifications associated with modelling a practical distribution network. The developed model assumes balanced and steady-state operating conditions, whereas actual network conditions may vary with changes in load composition, consumer demand, equipment switching, and the time-dependent operation of nonlinear devices. These factors may contribute to variations in individual harmonic magnitudes that are not fully reproduced under the simulation conditions considered.

Despite these limitations, the close quantitative agreement obtained at Ardo Substation and the spectral correspondence observed at Reg Substation indicate that the measurement-informed parameterisation provides an effective representation of the harmonic behaviour of the investigated feeder under the validation conditions considered. The approach demonstrates the value of integrating field-derived network and harmonic information with MATLAB/Simulink modelling, thereby reducing reliance on entirely assumed harmonic source and network conditions.

Overall, the results support the use of the developed model as a computational framework for investigating harmonic propagation within the modelled 33 kV distribution network. The validated framework also provides a basis for subsequent investigations into other harmonic-related phenomena, including network resonance and the evaluation of harmonic mitigation strategies, without extending those analyses into the scope of the present study.

IV. CONCLUSION

This study developed and validated a measurement-informed MATLAB/Simulink harmonic propagation model for a practical 33 kV distribution network, using the Ungwan Boro feeder in Kaduna Metropolis, Nigeria, as the study network. The model integrated feeder electrical characteristics, transformer impedance, measured load current profiles, and field-derived harmonic information to represent the harmonic behaviour of the network under the operating conditions considered.

The simulation results revealed pronounced current waveform distortion, with the harmonic response dominated by the 3rd, 5th, and 7th harmonic components. Results obtained at the Ardo and Reg Substations demonstrated the ability of the model to reproduce principal low-order harmonic characteristics at different locations within the modelled feeder.

Model validation was established through two complementary approaches. At Ardo Substation, the simulated current THD of 27.69% compared closely with the measured value of 27.95%, corresponding to a percentage deviation of 0.94%. At Reg Substation, the simulated harmonic spectrum reproduced the dominant 3rd, 5th, and 7th harmonic orders identified in the corresponding field-derived data. The combined quantitative and spectral validation indicates that the developed model can reproduce both the overall level of harmonic distortion and the principal harmonic-order characteristics of the investigated feeder under the validation conditions considered.

The developed modelling framework demonstrates the applicability of integrating field-derived electrical and harmonic data with MATLAB/Simulink for harmonic studies in practical distribution networks. However, the model assumes balanced and steady-state operating conditions, whereas practical networks are subject to variations in load composition, switching conditions, and time-varying operating characteristics. Future studies could therefore extend the framework to incorporate unbalanced and time-varying load conditions and evaluate its performance across a wider range of network operating scenarios.

Overall, the validated measurement-informed model provides a computational framework for investigating harmonic propagation in practical distribution networks while reducing reliance on entirely assumed network and harmonic-source conditions. The model also establishes a basis for subsequent investigations of harmonic-related phenomena, including network resonance and the development and evaluation of appropriate harmonic mitigation strategies.

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DATA AVAILABILITY STATEMENT

The field-derived electrical and harmonic data used for model parameterisation and validation in this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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