European Journal of
Engineering & Environmental Sciences

RESEARCH ARTICLE

Harmonic Analysis and Challenges in Developing Country Power Grids

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ABSTRACT

Nonlinear and electronically switched loads cause harmonic pollution, distort current and voltage waveforms, and increase losses in the power system. Studies in harmonics have become prevalent with the increasing use of capacitors and power-electronic converters in power systems to improve voltage, power factor, and system reliability. Moreover, the International Electrotechnical Commission (IEC) has set the standard limit of harmonic current injected by nonlinear loads in public distribution. In this study, the focus was on modelling a power grid, harmonic analysis, and reporting of harmonic sources and distortion limit violations. The harmonic load flow examines the effect of harmonic current on the system using the Electrical Transient Analyzer Program (ETAP), version 19. The result shows violations of the IEC standard limit of voltage and current harmonic distortions. Voltage distortions were notably higher in the distribution lines compared to sub-transmission lines, with an average of 23.61% at 33kV, 21.13% at 11kV, and 7.29% at 132kV. Equally, current distortions (THDi%) were significantly higher in the distribution lines, with an average of 70.56% at 11kV, 77.39% at 33kV, and 75.28% at 132kV. In addition, the individual harmonic distortion analysis reveals 3rd, 5th, 7th, and 9th harmonic orders, measured at 14.76%, 14.09%, 5.14%, and 2.10% for the 11kV feeders, and 19.92%, 11.08%, 5.40%, and 3.26% for the 33kV feeders, respectively. The 132kV feeder primarily experienced significant distortion from the 5th harmonic order, measuring at 6.73%. The combination of high 5th, 7th, and 3rd harmonics causes critical issues to power systems' quality. In developing countries like Nigeria, higher harmonic distortions are common due to factors including aging infrastructure, rapid industrial growth, limited regulatory standards, inadequate investment in power quality solutions, low awareness, financial constraints, and fragile electrical grids.

***Keywords**: Harmonic Analysis; Radial Distribution Network; International Electrotechnical Commission (IEC); Developing Country Power Grids*

Introduction

Harmonics have become a significant concern due to their adverse effects on the performance and stability of electrical networks. They are unwanted sinusoidal voltages or currents that occur at integer multiples of the fundamental frequency (50/60 Hz), typically caused by non-linear loads like rectifiers, battery chargers, variable frequency drives, discharge lamps, saturated electric machinery, etc. by consuming current in rapid short pulses, instead of a smooth sinusoidal manner, Mahiwal et. al. (2019). Nonlinear and electronically switched loads cause harmonic pollution, distort current and voltage waveforms, generate resonances, increase system losses, and shorten the useful life of electrical equipment (Bhuiyan, 2017; Younis and Al-Yousif, 2022).

Harmonics are often divided into two categories based on the signal type (voltage or current) and the harmonic order (even, odd, triplen, or non-triplen odd); and in a three-phase system, based on the phase sequence, positive, negative, zero (Jain, 2018). Studies in harmonics have become quite popular with the increasing use of capacitors in power systems to improve voltage and power factor, as well as power-electronic converters to enhance system reliability and efficiency. Harmonics can be reduced using filters (Aswal and Pal, 2018); the filters can be a single or a combination of several elements, and they can be placed at a single node or be distributed across several nodes to perform actively or passively (Ala'a, 2018).

Power system harmonics are a global engineering problem, although most peculiar in developing countries like Nigeria. Regrettably, the attempts by distribution companies to deliver improved power quality to end users in the form of pure sinusoidal voltage and current waveforms are constrained by distortions due to harmonics. This distortion leads to several problems including increased power losses, equipment and conductor heating, the flow of extra current through power capacitors, variable speed drives to misfire, and produce torque pulsations in motors and generators (Hameed, et. al., 2016); in addition, harmonics cause thermal tripping of protective devices and logic

Citation: Ilo, F. C. & Eke, J. (2023). Harmonic Analysis and Challenges in Developing Country Power Grids. *European Journal of Engineering and Environmental Sciences, 7(4), 1-11. DOI: https://doi.org/10.5281/zenodo.8416470*

faults of digital devices, such as errors in meter readings, and forced outages, grid collapse, poor frequency profile (Daniel and Carnovale, 2006). Moreover, due to obvious technical limitations, harmonic analysis of the distribution lines 11kV and 33kV, are presumably more crucial than in sub-transmission lines 132kV, and transmission lines 330kV due to the prevalence of non-linear loads from the network receiving end 'the consumers'.

Literature Review

Conceptual Knowledge

The electricity supply is represented in the form of voltage and current with an RMS value. The voltage/current waveforms should be sinusoidal with the same frequency as the linear load (50Hz or 60Hz). This is however not the same with non-linear loads, hence harmonic distortions are generated. The International Electrotechnical Commission (IEC) Standards 61000-3-2 and 61000-2-2 defined the limits on harmonic current injected into a public distribution network by nonlinear appliances with an input current less than or equal to 16 A (Das, 2015).

The distorted or non-sinusoidal waveforms with periodic characteristics can be composed of the sum of various sinusoids, and each sinusoid component can be considered as harmonics, compared to the original waveform. Fourier series (FS) is most common for non-sinusoidal waveform analysis. The sum of an infinite number of sinusoidal or cosinusoidal components can be used to represent any continuous signal with a repeated interval T. Fourier series takes a periodic signal x(t) and describes it as a sum of sine and cosine waves.

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(2\pi \frac{nt}{T}\right) + b_n \sin\left(2\pi \frac{nt}{T}\right) \quad (1)$$

where a_n and b_n are the coefficients of the Fourier series, and calculated thus,

$$a_n = \frac{2}{T} + \int_0^T x(t) \cos\left(2\pi \frac{nt}{T}\right) dt \quad (2)$$

$$b_n = \frac{2}{T} + \int_0^T x(t) \sin\left(2\pi \frac{nt}{T}\right) dt \quad (3)$$

Harmonic Analysis

Total harmonic distortion (THD or THDi), a measurement of the harmonic distortions in a signal, is the ratio of the sum of all harmonic components' powers to the fundamental frequency's power. Reduced THD translates into reduced peak currents, heating, electromagnetic emissions, and core loss in motors (Generator Jungle, 2023).

$$THD_F = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots}}{V_1} \quad (4)$$

where V_n is the RMS value of the *n*th harmonic voltage and V_1 is the RMS value of the fundamental component.

For a pure sine wave with only 50 Hz, the THD value = 0. The current THD in loads usually ranges from a few percent to 100 %. While the voltage THD is often less than 5%. The voltage THD if exceeds the normal levels, causes problems for the network.

$$THD_R = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots}}{\sqrt{V_1^2 + V_2^2 + V_3^2 + \dots}} = \frac{THD_F}{\sqrt{1 + THD_F^2}} \quad (5)$$

These can be distinguished as THD_F (for "fundamental"), and THD_R (for "root mean square").

The relationship between V_{RMS} value and THD_V is stated below.

$$THD_v = \sqrt{\left(\frac{V_{RMS}}{V_{1RMS}}\right)^2 - 1} \quad \text{where } V_{RMS} = V_{1RMS}\sqrt{1 + THD_v{}^2} \quad (6)$$

The individual harmonics distortion (IHD) measured by a similar index is:

$$\%\, IHD_v = \frac{V_{RMS}}{V_{1RMS}}\, 100\% \quad (7)$$

This index helps us to plot the harmonics magnitude spectrum for the complex (distorted) wave of several loads. Harmonics magnitude spectrum data also indicates the most harmonics orders which contribute to distortion.

Vol. 7, No. 4 | 2023 | 1-11 | DOI: https://doi.org/10.5281/zenodo.8416470
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Review of Related Works

Scholars have proven that harmonic currents increase the r.m.s. current in electrical systems and deteriorate the supply voltage quality. It stresses the electrical network with increased operating temperatures, damages equipment, and causes increased operating costs to the utilities. Recent harmonic analysis studies integrate real-life data from a utility grid and analyzed it in ETAP. Similarly, Hariharan (2020) modelled a 33kV bus system, connected to a utility grid via incoming feeder and VFDs, with motors connected to a bus. The study was analyzed using ETAP and recommended that single-tuned filters should be installed for worst-case conditions to mitigate harmonics injected by VFD. Braide, (2022), analyzed the 330kV transmission lines in Nigeria and reported that total harmonic distortion (THD) violates the IEC 61000-3-6:2008 standards. Moreover, due to harmonics, capacitive reactance decreases as the frequency increases; this means that a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit, hence the need for filters to reduce power losses (Eke, et al., 2021). Harmonic filters reduce distortion levels and also improve the power factor (Riaz et al., 2021).

Methodology

Modelling of the Distribution Grid

The parameters for modelling include the power grid data (132kV, operating in swing mode), bus data in nominal kV (33kV and 11kV busses), and branch data, i.e., transformers (MVA), transmission lines (km), peak load (MW), etc. This study considered current harmonic source from the Typical IEEE XFMR Magnet, with lumped loads 5% motor and 95% static.

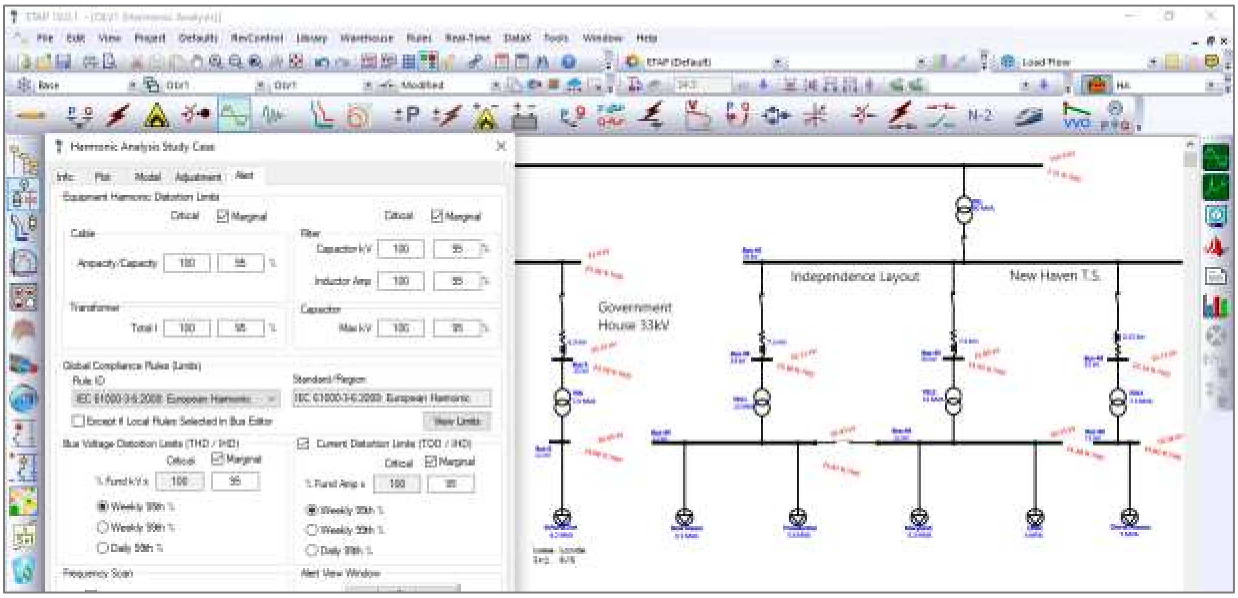

Figure 1: Harmonic Analysis Study in ETAP

It has 40 buses, 43 branches, and 26 loads of 82.201 MW and 27.018 Mvar, with 2 x 60 MVA 132/33kV power transformers at the substations, 5 x 15, 8 x 7.5, 2 x 5, and 2 x 2.5 (MVA) step-down transformers at the distribution feeders, 29 x 11kV feeders with a combined peak load of 102.8 MW and total route length of 599.7 km from the source. It was modelled using the Electrical Transient Analyzer Program (ETAP), version 19. ETAP's harmonic analysis module can detect harmonic issues, minimize nuisance trips, design and test filters, report distortion limit violations, etc. See Appendix 1 for details.

Calculation of Total Harmonic Distortions

The total harmonic distortion, or THD, of a quantity is the ratio of all harmonic components to the fundamental component, given as:

$$THD_Y = \sqrt{\frac{\sum_{h=2}^{\infty} Y_h^2}{Y_1}} \qquad (8)$$

Where Y_1 is the rms value of fundamental, Y_h is the rms value of h^{th} harmonic

The ratio of the harmonic currents' root-mean-square value to the fundamental current is known as the current THD.

$$I_{THD} = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1}} \quad (9)$$

Where I_1 is the rms value of fundamental and I_h is the rms value of h^{th} harmonic

Results and Discussion

The Findings

Table 1: Average of Harmonic Voltage and Current Distortions %

Harmonic voltage distortions (Bus Information)			
kV	Avg. Fund. %	Avg. RMS %	Avg. THD %
11.00	92.33	94.38	21.13
33.00	94.70	97.30	23.61
132.00	100.00	100.27	7.29
Average			22.15
Harmonic current distortions (Branch Information)			
kV	Avg. Fund. %	Avg. RMS %	Avg. THD %
11.00	85.45	86.36	19.63
33.00	174.54	220.24	77.39
132.00	723.63	901.23	75.28
Average			52.79

Table 1 above analyses the effects of harmonic voltage and current distortions (percentage of fundamental) the distribution network. It shows that voltage distortions THD*v* % are significantly higher in distribution lines than in the sub-transmission line, with an average of 23.61% in 33kV, 21.13% in 11kV, and 7.29% in 132kV. The proximity to non-linear loads allows harmonic currents generated by these loads to directly influence the voltage within the low voltage network.

The average of current distortions THD*i*% are significantly higher in 33kV lines at 77.39%, followed by the 132kV line at 75.28%, and lastly the 11kV lines at 19.63%. Harmonic current distortions are typically higher in high voltage (HV) and medium voltage (MV) distribution networks due to a broader range of industrial and commercial loads, larger transformers with higher impedance, and longer transmission distances that can accumulate and propagate harmonics, compared to low voltage systems with shorter distances. The details are shown in Appendix 2.

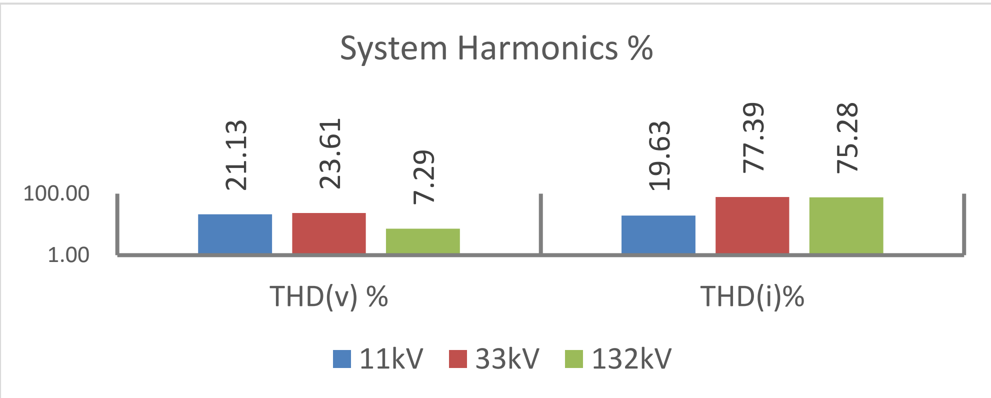

Figure 2: System harmonics average

Figure 2 is a graphical representation of the harmonic voltage and current distortions (percentage of fundamental) as shown in Table 1 above. The buses/lines with more non-linear loads have higher harmonic current distortions. The current harmonics (distorted waveform) flow through system impedance (sources and line impedances) and cause a harmonic voltage drop across the impedance. This will distort the supply voltage waveform, creating voltage harmonics, which do not originate directly from non-linear loads.

The sum of the fundamental frequency's current waveform and its multiples (harmonics) can be used to represent the distorted current waveforms:

$$f(t) = \sum_{h=1}^{\infty}(C_h\, Sin(h\omega_0 t + \varphi h)) \quad (10)$$

Where C_h is the magnitude of n^{th} order harmonics, φh is the phase angle of n^{th} order harmonics.

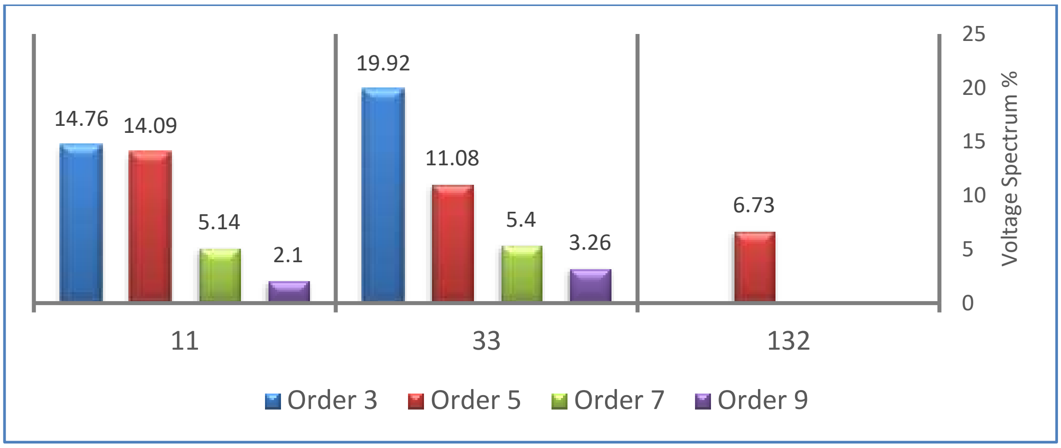

Figure 3: Individual harmonic voltage per harmonic orders

Figure 3 above is a graphical representation of the individual harmonic voltage distortions, with an average of 21.13% at the 11kV feeders, distributed at 14.76%, 14.09%, 5.14%, and 2.10% for the 3rd, 5th, 7th, and 9th orders. The 33kV feeders had an average of 23.61%, distributed at 19.92%, 11.08%, 5.40%, and 3.26% for the 3rd, 5th, 7th, and 9th orders, while the 132kV feeder had an average of 7.29%, with 6.73% from the 5th order. See Appendix 3 for details.

Table 2: IEEE (519-2014) current distortion limits for systems rated 120V – 69kV

	Maximum harmonic current distortion in percent of I_L					
	Individual harmonic order (Odd harmonics)[a, b]					
I_{SC}/I_L	3≤ h <11	11≤ h<17	17≤ h<23	23≤ h<35	35≤ h	TDD
<20c	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are restricted to a quarter (25%) of the limits defined for odd harmonics. Regardless of the actual I_{SC}/I_L current distortion, power generation equipment is limited above. I_{SC} represents the maximum short circuit current at the point of common coupling (PCC), and I_L represents the maximum demand load current at the PCC in normal operating conditions.

Table 3: IEEE 519 – 2014 Voltage Distortion Limits

Bus voltage V at PCC	*Individual harmonic (%)*	*Total harmonic distortion THD (%)*
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

In high-voltage systems, a maximum total harmonic distortion (THD) of 2.0% is permissible when attributed to an HVDC terminal, provided that its impact diminishes as the network extends to potential future user connection points.

Table 3 provides the individual and total voltage distortion limitations for different voltage levels, including 69kV and below, 69.001 to 16 kV, and 161kV and higher. According to IEC, the limits should be considered as the worst case of system design values for normal operation.

Conclusion

Based on the IEEE (519-2014) standard for systems rated 120V to 69kV, the research findings indicate notable violations in voltage and current distortion limits across various voltage levels within the distribution network. The harmonic orders were the 3rd, 5th, 7th, and 9th orders, with substantial distortion levels of 14.76%, 14.09%, 5.14%, and 2.10% for the 11kV feeders, and 19.92%, 11.08%, 5.40%, and 3.26% for the 33kV feeders, respectively. Most significant was the 3rd harmonic distortions, which can lead to increased heating in transformers and motors, interference with sensitive electronic equipment, and reduced energy efficiency, reduced power factor, increased energy losses, and decreased overall power quality, potentially causing operational issues and equipment damage.

In addition, the findings revealed that harmonics are higher in the distribution lines 11kV and 33kV than in transmission lines 330kV due to the prevalence of non-linear loads from the end users. Consequently, with higher harmonics in the distribution grid, technical losses are bound to increase, which will invariably affect the power system quality.

Higher harmonic distortions are more prevalent in developing countries like Nigeria due to factors such as aging infrastructure, rapid industrialization, limited regulation and standards, insufficient investment in power quality solutions, lack of awareness, financial constraints, and weak electrical grids. Voltage and current distortions in the distribution network not only compromise the quality of electricity supply to customers but also result in increased losses and higher costs per tariff due to reduced operational efficiency and equipment damage.

Thus, mitigating high harmonic distortions requires investments in infrastructure modernization, robust power quality standards enforcement, awareness campaigns, and the implementation of effective harmonic filtering and compensation solutions.

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European Journal of Engineering and Environmental Sciences | EJEES
Vol. 7, No. 4 | 2023 | 1-11 | DOI: https://doi.org/10.5281/zenodo.8416470
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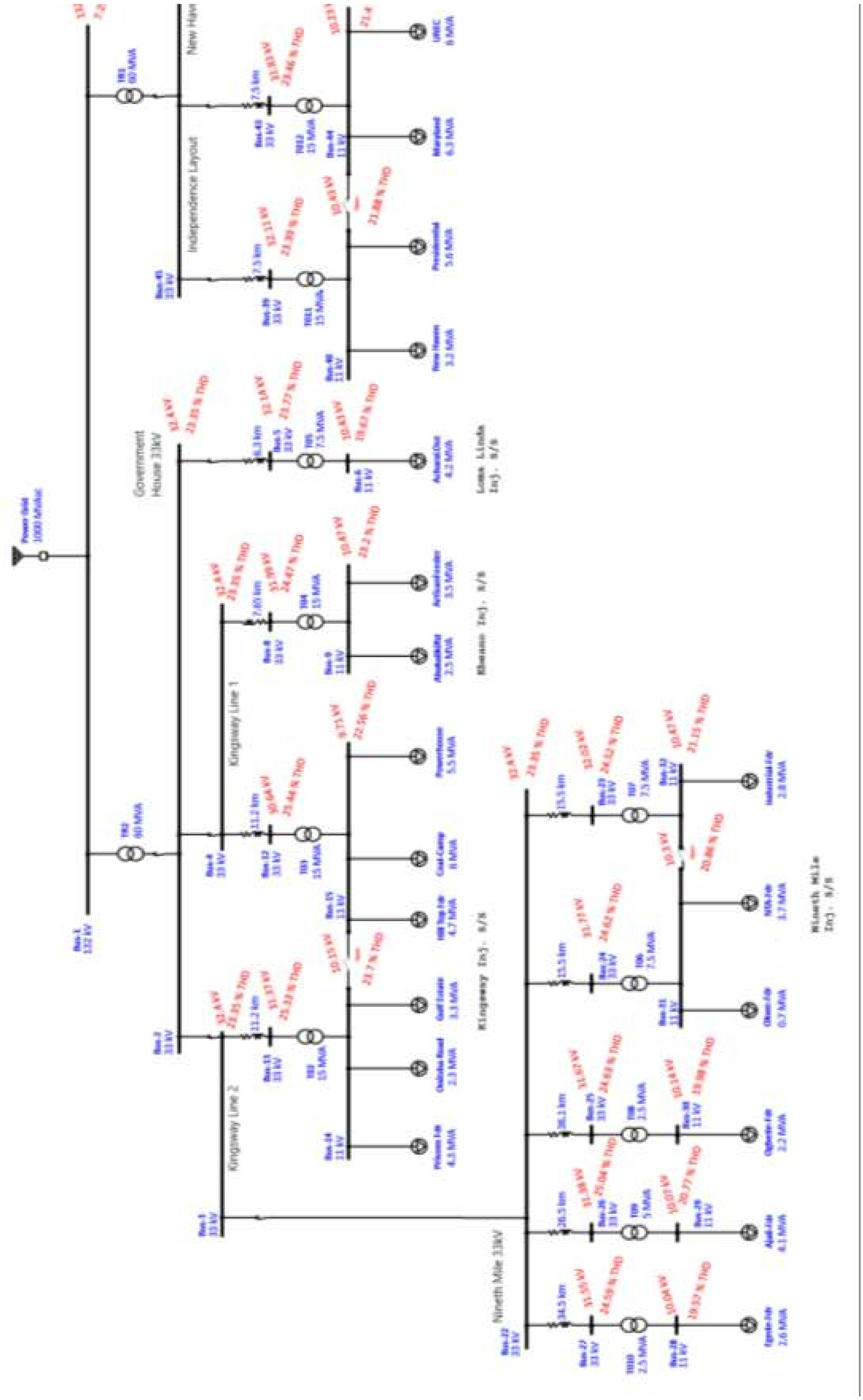
Appendix 1a: New Haven 132KV distribution grid (modelled)



European Journal of Engineering and Environmental Sciences | EJEES
Vol. 7, No. 4 | 2023 | 1-11 | DOI: https://doi.org/10.5281/zenodo.8416470
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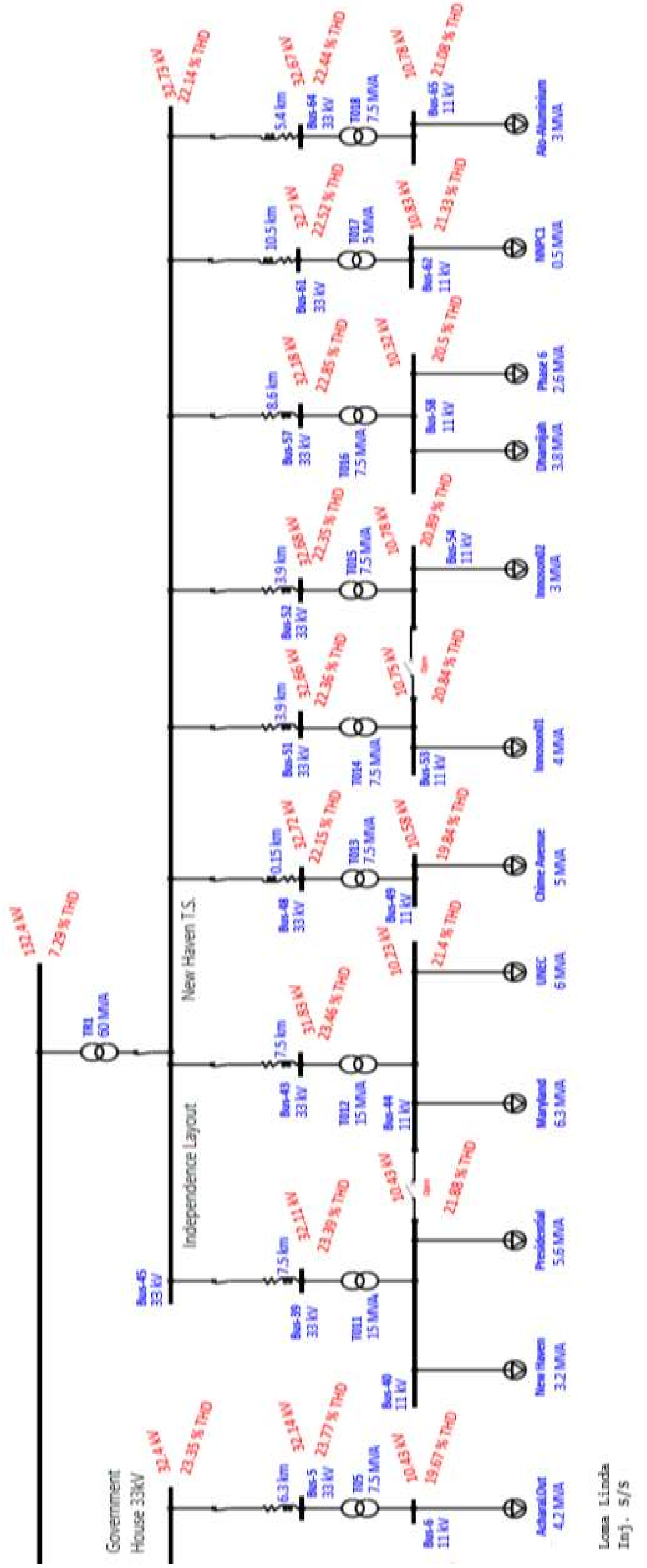
Appendix 1b: New Haven 132KV distribution grid (modelled)



Vol. 7, No. 4 | 2023 | 1-11 | DOI: https://doi.org/10.5281/zenodo.8416470
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Appendix 2: Harmonic Voltage and Current Distortions Per Buses

Bus		*Voltage Distortion*			*Current Distortion*		
ID	kV	Fund(v) %	RMS(v) %	THD(v) %	Fund(i) %	RMS(i) %	THD(i) %
Bus-1	132	100.00	100.27	7.29	724	901.23	75.28
Bus-2	33	95.61	98.18	23.35	259	326.48	45.01
Bus-3	33	95.61	98.18	23.35	275	366.11	56.20
Bus-4	33	95.61	98.18	23.35	231	234.79	20.42
Bus-5	33	94.77	97.41	23.77	138	176.76	59.09
Bus-6	11	93.00	94.78	19.67	69	69.18	9.43
Bus-8	33	94.16	96.94	24.47	196	296.65	85.56
Bus-9	11	92.75	95.21	23.20	98	99.55	16.92
Bus-12	33	89.98	92.85	25.44	497	539.61	28.00
Bus-13	33	92.14	95.05	25.33	315	383.24	49.45
Bus-14	11	89.81	92.30	23.70	157	158.02	8.70
Bus-15	11	86.15	88.31	22.56	248	248.87	6.12
Bus-22	33	95.61	98.18	23.35	86	87.78	19.58
Bus-23	33	94.25	97.04	24.52	92	144.59	92.72
Bus-24	33	93.47	96.26	24.62	142	180.23	56.60
Bus-25	33	93.17	95.95	24.63	70	78.79	36.50
Bus-26	33	92.24	95.09	25.04	130	148.89	39.11
Bus-27	33	92.84	95.60	24.59	82	89.54	29.92
Bus-28	11	89.53	91.23	19.57	41	41.28	5.03
Bus-29	11	89.67	91.59	20.77	65	65.25	6.55
Bus-30	11	90.38	92.17	19.98	35	35.23	5.47
Bus-31	11	91.64	93.61	20.86	71	71.54	9.52
Bus-32	11	93.09	95.15	21.15	46	46.76	18.78
Bus-39	33	94.74	97.29	23.39	288	362.45	56.27
Bus-40	11	92.63	94.82	21.88	144	144.62	10.71
Bus-43	33	93.90	96.45	23.46	395	450.75	38.55
Bus-44	11	90.93	92.99	21.40	198	198.20	6.90
Bus-45	33	96.84	99.19	22.14	86	91.15	58.49
Bus-48	33	96.82	99.17	22.15	166	199.07	48.17
Bus-49	11	94.37	96.20	19.84	83	83.30	7.66
Bus-51	33	96.59	98.98	22.36	67	130.84	130.82
Bus-52	33	96.66	99.04	22.35	51	123.25	176.65
Bus-53	11	95.64	97.70	20.84	34	35.19	30.86
Bus-54	11	95.95	98.02	20.89	25	27.63	44.05
Bus-57	33	95.08	97.53	22.85	208	234.02	36.59
Bus-58	11	91.94	93.85	20.50	104	104.07	5.85
Bus-61	33	96.68	99.10	22.52	17	77.02	362.14
Bus-62	11	96.33	98.50	21.33	8	11.79	97.09
Bus-64	33	96.59	98.99	22.44	50	123.22	176.80
Bus-65	11	95.88	97.98	21.08	25	27.62	44.09
AVG.		93.83	96.13	22.15	150.41	180.36	52.79

Appendix 2 above shows the harmonic voltage and current distortions per bus, with the details of kV, Fund %, RMS %, and THD %. The candidate buses are key locations for the installation of active harmonic filters in parallel to the loads.

Appendix 3: Individual Harmonic Distortion (VIHD) Report

kV	ID	Harmonic Orders				AVG.
		3.00	**5.00**	**7.00**	**9.00**	
11	Bus-14	16.03	16.40	5.53	2.23	10.05
	Bus-15	16.06	14.97		1.95	10.99
	Bus-28	13.14	13.60		1.71	9.48
	Bus-29	13.34	14.93	5.22	1.84	8.83
	Bus-30	13.17	14.05		1.79	9.67
	Bus-31	13.26	15.05	5.39	1.93	8.91
	Bus-32	13.21	15.41	5.62	2.00	9.06
	Bus-40	15.63	14.36		2.22	10.74
	Bus-44	15.61	13.76		2.06	10.48
	Bus-49	15.25	11.83		2.11	9.73
	Bus-53	15.47	12.96		2.36	10.27
	Bus-54	15.48	13.02		2.38	10.30
	Bus-58	15.39	12.71		2.01	10.04
	Bus-6	13.09	13.67	5.02	1.92	8.42
	Bus-62	15.49	13.63		2.41	10.51
	Bus-65	15.49	13.28		2.39	10.39
	Bus-9	15.83	15.85	5.56	2.35	9.90
11 AVG.		14.76	14.09	5.39	2.10	9.80
33	Bus-12	20.98	12.80	5.58	3.47	10.71
	Bus-13	20.49	13.30	5.78	3.39	10.74
	Bus-2	19.73	10.85	5.26	3.24	9.77
	Bus-22	19.73	10.85	5.26	3.24	9.77
	Bus-23	20.04	12.51	5.63	3.33	10.38
	Bus-24	20.21	12.46	5.60	3.36	10.41
	Bus-25	20.43	12.07	5.57	3.60	10.42
	Bus-26	20.55	12.67	5.65	3.50	10.59
	Bus-27	20.48	11.91	5.50	3.59	10.37
	Bus-3	19.73	10.85	5.26	3.24	9.77
	Bus-39	19.83	10.94		3.15	11.31
	Bus-4	19.73	10.85	5.26	3.24	9.77
	Bus-43	20.01	10.80		3.17	11.33
	Bus-45	19.39	9.17		3.07	10.54
	Bus-48	19.40	9.18		3.07	10.55
	Bus-5	19.91	11.37	5.34	3.28	9.97
	Bus-51	19.44	9.56		3.08	10.69
	Bus-52	19.43	9.55		3.08	10.69
	Bus-57	19.76	10.00		3.14	10.97
	Bus-61	19.44	9.90		3.09	10.81
	Bus-64	19.45	9.72		3.08	10.75
	Bus-8	20.04	12.45	5.60	3.30	10.35
33 AVG		19.92	11.08	5.48	3.26	10.44
132	Bus-1		6.73			6.73
132 AVG			6.73			6.73
AVG.		17.67	12.25	5.45	2.75	10.15