

HARMONIC ANALYSIS AND EVALUATION OF 52 BUS IN NIGERIA TRANSMISSION NETWORK

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Abstract: The 330kV grid in Nigeria, consisting of 52 buses, is confronted with significant challenges, including voltage instability, extended transmission lines, inherent transmission line characteristics, and substantial power losses, which adversely impact both power generation and distribution systems. This study focuses on the harmonic analysis of the Nigerian 52-bus grid, comprising 52 buses, 18 generating stations, and 65 transmission lines. Utilizing ETAP 16.0 as the analytical tool, the research investigates harmonic orders on the 330kV line network in Nigeria. Simulations were conducted using the ETAP 16.0 software package, with input parameters encompassing relative amplitudes and phase angles for both current and voltage source models. Data for the study were sourced from the Transmission Company of Nigeria (TCN). The obtained results reveal that some bus voltages exceed the prescribed standard limits. Consequently, it can be deduced from the findings that the existing Nigerian 52-bus grid grapples with considerable line losses, necessitating compensation through the implementation of reactive power support mechanisms, such as Flexible Alternating Current Transmission Systems (FACTS) devices, to optimize line utilization effectively.

Keywords: Load flow, Harmonic Order, Transmission Line, Voltage instability, Power Quality.

1 Introduction

The Electrical Power sector plays an important role in the socioeconomic development of a nation. However, in the case of Nigeria, the power network is facing multifaceted challenges that demand intervention. The power system is overloaded, supplying beyond nominal capacity. With a growing population, the demand for electrical energy has surged exponentially, outpacing the capacity of the existing infrastructure. Generation stations situated far from load centres transmit their electrical energy via long, radial and not up-to-standard transmission lines [1]. This noticeable demand-supply gap has resulted in a strain on the power system, giving rise to voltage fluctuations, equipment overheating and diminished power quality, ultimately compromising the overall reliability of the grid [2]. However, the urgency for a comprehensive system analysis of the electrical network in Nigeria cannot be overstated as she's at

an all-time peak of industrial production and thus ensuring a stable power supply is crucial to sustain this growth.

Incorporated in the existing 330kV Nigeria grid network are complex equipment such as transmission lines, transformer tapings, various alternators, reactors, compensators, phase shifters, synchronous condensers, static capacitors, etc, and Power quality meters which serve as the medium for data collection. With the availability of the data comes the avenue for system status and operation assessment, analysis by network designers, and network system forecast [3]. This work used the harmonic analysis method of analysing power systems to evaluate the improved 52-bus Nigeria 330kV power network.

The harmonic analysis offers a granular perspective on the power system in the frequency domain as opposed to the time domain, pinpointing sources of distortion and hence enabling the development of mitigation strategies that enhance power

quality [4]. Using Electrical transient and analysis program (ETAP), one of the best tools to study harmonics in the power system, this work navigated the complexities of the 52-Bus Nigeria Transmission Network evaluating the network performance, effectiveness and alternative plans for network reconfiguration. The level of harmonic distortion in the system is indicated by the Total Harmonic Distortion (THD) index, which is used to measure current and voltage dimensions.

THD is defined as the root mean square (rms) value of the h th harmonic component divided by the respective rms value of the fundamental component, multiplied by 100% [5]. The THD of current can vary from 5% to 100%, while THDs of voltage less than 5% are generally considered acceptable. Values exceeding 5% may indicate problematic equipment, devices, or arrangements [6].

Harmonic modelling in power networks is a crucial aspect of electrical engineering that involves the analysis and understanding of harmonic distortions within an electrical system. These harmonic distortions emerge from the operation of various equipment and inductive and capacitive loads in the system causing problems such as voltage distortion, overheating and power quality issues. To address these problems, we use harmonic modelling to identify possible sources of harmonics in a particular system. Key steps needed to conduct a harmonics study come from research experience and practical insights. However, these steps encompass the acquisition of a single-line diagram of the network, pinpointing the point of common coupling, identifying harmonic sources, conducting harmonic measurements, and modelling network components using simulation software like ETAP. After, there is a comparison of the results with national standards.

In order to create a reliable harmonic model for any network, it is imperative to accurately represent all the network components. To conduct comprehensive harmonic modelling and simulation of a given system, two critical considerations have been identified and reviewed to bridge the gap and yield more dependable results. ETAP is employed, and on-site measurements of harmonic currents are used to fine-tune computer-based harmonic current models to match and validate the measured data. The Power System Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) software is utilized to build simulation models based on laboratory-measured waveforms. A generalised model for distribution systems has been successfully implemented for practical case studies, using verified simulation models for a range of industrial and household electrical equipment and appliances. Similarly, DigSilent/PowerFactory serves as the simulation software used to assess future levels of harmonic distortion in the power grid, based on the present harmonic current source model developed from measured data [7].

2. Methodology

$F(t)$ = periodic function of Fourier Series $f(t)$
=

$$C_0 + \sum_{h=1}^{\infty} C_h \cos(h\omega t + \theta_h) \quad (1)$$

$$C_o = \frac{1}{T} \int_0^T f(t) dt, \quad C_h = \sqrt{A_h^2 + B_h^2} \quad (2)$$

$$A_h = \frac{2}{T} \int_0^T f(t) \cos(h\omega t) dt \quad (3)$$

$$B_h = \frac{2}{T} \int_0^T f(t) \sin(h\omega t) dt \quad (4)$$

where:

h : order of the harmonic

C_o : coefficient of the n th harmonic

ω : natural frequency

A_h, B_h : sine and cosine coefficients of the n th harmonic

Total Harmonic Distortion(THD) in Voltage(Percent):

$$THD_v \% = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_i} \times 100 \quad (5)$$

Total Harmonic Distortion(THD) in Current(Percent):

$$THD_i \% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_i} \times 100 \quad (6)$$

where:

V_h, I_h : h^{th} Harmonic component of the voltage and current,

V_i, I_i : fundamental component

$$\tilde{V}_H = \sqrt{\sum_{h=2}^{\infty} \tilde{V}_h^2} \quad (7)$$

$$\tilde{I}_H = \sqrt{\sum_{h=2}^{\infty} \tilde{I}_h^2} \quad (8)$$

$$\tilde{I} = \sqrt{\sum_{h=1}^{\infty} \tilde{I}_h^2} \quad (9)$$

$$\tilde{V} = \sqrt{\sum_{h=1}^{\infty} \tilde{V}_h^2} \quad (10)$$

$$THD_o \% = HF \times \frac{\text{Drive kVA}}{\text{SC kVA}} \times 100 \quad (11)$$

$$HF = \sqrt{\sum_{h=5}^{\infty} \frac{h^2 \tilde{I}_h^2}{\tilde{I}_1^2}}, \text{ Harmonic Factor} \quad (12)$$

$$P = \tilde{V} \tilde{I}_{i,1} \cos \phi_1 \quad (13)$$

$$Q = \tilde{V} \tilde{I}_{i,1} \sin \phi_1, S = \tilde{V} \tilde{I} \quad (14, 15)$$

$$VA = \sqrt{S^2 - P^2 - Q^2} \quad (16)$$

$D = \text{Distortion}$

$$D^2 = S^2 - (\tilde{V}^2 \tilde{I}_{i,1}^2) = \tilde{V}^2 \sum_{h=2}^{\infty} \tilde{I}_{i,h}^2$$

$$\lambda = \text{True Power Factor} = \frac{P}{S} = \left(\frac{\tilde{I}_{i,1}}{\tilde{I}} \right) \cos \phi_1$$

$= \text{Distortion Factor} \times \text{Displacement Factor}$ (17)

Nonsine wave voltage and current

$$P = \sum_{h=1}^{\infty} \tilde{V}_h \tilde{I}_h \cos \phi_h, Q = \sum_{h=1}^{\infty} \tilde{V}_h \tilde{I}_h \sin \phi_h \quad (18)$$

$D = \text{Distortion Power}$

$$= \sum_{n,m} S_{nm} S_{nm}^* - \sum_{n,m} S_n S_m^* \quad (19)$$

$$S^2 = P^2 + Q^2 + D^2 \quad (20)$$

$$S = \sqrt{\sum_{h=1}^{\infty} \tilde{V}_h^2 \tilde{I}_h^2} = (\tilde{V}_1 \tilde{I}_1)^2 + (\tilde{V}_1 \tilde{I}_H)^2 + (\tilde{V}_H \tilde{I}_1)^2 + (\tilde{V}_H \tilde{I}_H)^2 = S_1^2 + S_N^2 \quad (21)$$

$$S_1 = \text{Fundamental Apparent Power} = \tilde{V}_1 \tilde{I}_1$$

$S_N = \text{Non fundamental Apparent Power}$

$$S_N^2 = (\tilde{V}_1 \tilde{I}_H)^2 + (\tilde{V}_H \tilde{I}_1)^2 + (\tilde{V}_H \tilde{I}_H)^2 \quad (22)$$

$$\tilde{V}_1 \tilde{I}_H = \text{Current Distortion Power}$$

$$\tilde{V}_H \tilde{I}_1 = \text{Voltage Distortion Power}$$

$$\tilde{V}_H \tilde{I}_H = \text{Harmonic Apparent Power}$$

$$S_H^2 = P_H^2 + N_H^2$$

$= \text{Total Harmonic Active Power} + \text{Total Harmonic Non Active Power}$ (23)

$$X_c = \text{Reactance of the capacitor} = \frac{(V_{L-L})^2}{\text{VAR}_{3-phase}} \quad (24)$$

METHODOLOGY FOR COMPUTING DISTORTION

$$I_b = \text{Base current in Amps} = \frac{\text{MVA}_b \times 10^3}{\sqrt{3} kV_b} \text{ Amps} \quad (25),$$

$$Z_s (\text{System impedance}) = \frac{\text{MVA}_b}{\text{MVA}_{sc}} p.u. \quad (26)$$

$$THD_i\% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_i} \times 100 \quad (29)$$

$$I_H (\text{Percent individual harmonic distortion}) = \frac{I_h}{I_L} \times 100$$
$$\text{Short circuit Ratio} = \frac{I_{sc}}{I_L} = \frac{MVA_{sc}}{MVA_D} \quad (30)$$

The data used for this study were obtained from Transmission Company of Nigeria (TCN) and are presented in Table 1, Table 2 and Table 3. The ETAP 16.0 electrical software was used in conducting the simulation.

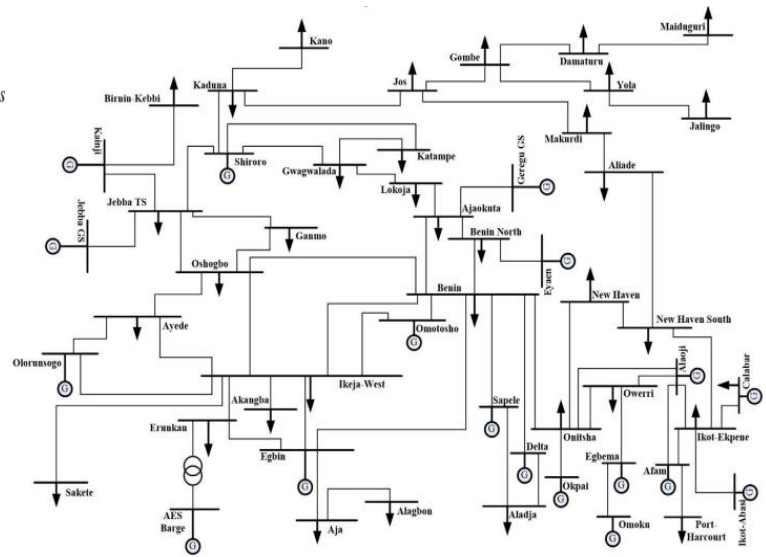


Table 1

Line data, for the 52-bus 330 kV Nigeria Power Grid

S/N	Line	Name	L(km)
1	01-02	Egbin-Benin	218
2	01-03	Egbin-Ikeja-West	62
3	01-31	Egbin-Aja	14
4	01-51	Egbin-Erunkan	30
5	02-03	Benin-Ikeja West	280
6	02-08	Benin-Omotoso	51
7	02-09	Benin-Osogbo	251
8	02-22	Benin-Ajaokuta	195
9	02-24	Benin-Onitsha	137
10	02-27	Benin-Sapele	50
11	02-28	Benin-Delta	41
12	02-48	Benin-Benin North	20
13	03-04	Ikeja West-Akangba	17

14	03-05	Ikeja West-Sakete	70
15	03-06	Ikeja West-Ayede	137
16	03-07	Ikeja West-Papalanto	30
17	03-08	Ikeja West-Omotoso	200
18	03-09	Ikeja West-Osogbo	250
19	03-51	Ikeja West-ErunKan	32
20	06-07	Ayede-Papalanto	60
21	06-09	Ayede-Osogbo	115
22	09-10	Osogbo-Ganmo	75
23	09-12	Osogbo-Jebba TS	157
24	10-12	Ganmo-Jebba TS	80
25	11-12	Shiroro-Jebba TS	244
26	11-17	Shiroro-Kaduna	96
27	11-21	Shiroro-Katampe	144
28	11-50	Shiroro-Gwagwalada	114
29	12-13	Jebba GS-Jebba TS	8
30	12-15	Kainji-Jebba TS	81
31	14-15	Birnin Kebbi-Kainji	310
32	16-17	Kaduna-Kano	230
33	17-18	Kaduna-Jos	196
34	18-19	Jos-Gombe	264
35	18-36	Makurdi-Jos	230
36	19-20	Gombe-Yola	240

37	19-33	Gombe-Damaturu	135
38	20-35	Yola-Jalingo	132
39	21-50	Gwagwalada-Katampe	30
40	22-23	Ajaokuta-Geregu	1
41	22-48	Benin North-Ajaokuta	195
42	22-49	Ajaokuta-Lokoja	38
43	24-25	Alaoji-Onitsha	138
44	24-26	New Haven-Onitsha	96
45	24-29	Onitsha-Okpai	60
46	24-38	Owerri-Onitsha	137
47	25-30	Alaoji-Afam	25
48	25-38	Owerri-Alaoji	60
49	25-40	Alaoji	38
50	26-39	New Haven-New Haven South	5
51	27-32	Sapele-Aladja	63
52	28-32	Delta-Aladja	32
53	30-40	Afam-Ikot Ekpene	90
54	30-41	Afam-Port Harcourt	45
55	31-52	Aja-Alagbon	26
56	33-34	Damaturu-Maiduguri	140
57	36-46	Aliade-Makurdi	50
58	38-45	Owerri-Egbema	30
59	39-40	Ikot Ekpene-New Haven South	153
60	39-46	New Haven South-Aliade	150

61	40-42	Ikot Ekpene-Calabar	72
62	40-43	Ikot Abasi- Ikot Ekpene	75
63	44-45	Omoku-Egbema	30
64	47-48	Eyaen-Benin North	5
65	49-50	Lokoja-Gwagwalada	140

Table 2

Load data of the 52-bus 330 kV Nigeria Power Grid

Lo ad	M W	MV AR	Lo ad	M W	MV AR	Lo ad	M W	MV AR
Lo ad 02	18 8	91	Lo ad 19	11 3	55	Lo ad 36	60	30
Lo ad 03	32 1	155	Lo ad 20	71	34	Lo ad 38	12	6
Lo ad 04	29 7	144	Lo ad 21	18 9	62	Lo ad 39	60	30
Lo ad 05	91	44	Lo ad 22	60	29	Lo ad 40	15	7
Lo ad 06	17 0	82	Lo ad 24	10 2	48	Lo ad 41	10	6
Lo ad 09	14 8	72	Lo ad 25	16 7	78	Lo ad 46	50	20
Lo ad 10	17 0	82	Lo ad 26	14 0	64	Lo ad 48	18	8
Lo ad 12	26 0	125	Lo ad 31	13 9	65	Lo ad 49	16	7
Lo ad 14	71	34	Lo ad 32	10 5	51	Lo ad 50	10	4

Lo ad 16	15 7	76	Lo ad 33	60	40	Lo ad 51	14	6
Lo ad 17	17 3	84	Lo ad 34	50	30	Lo ad 52	17	8
Lo ad 18	89	43	Lo ad 35	45	25			

Table 3

Generator data of the 52-bus 330kV Nigeria Power Grid

Generators	Plant type	Active Power Limit (MW)
Gen 01_Egbin	Steam and Gas	1320
Gen 07_Papalanto	Gas	335
Gen 08_Omotosho	Gase	335
Gen 11_Shiroro	Hydro	600
Gen 13_Jebba	Hydro	607
Gen 15_Kainji	Hydro	760
Gen 23_Geregu	Gas	444
Gen 25_Alaoji	Gas	480.25
Gen 27_Sapele	Gas	1080
Gen 28_Delta	Gas	960
Gen 29_Okpai	Gas	450
Gen 30_Afam	Gas	727
Gen 37_AES Barge	Gas	280
Gen 42_Calabar	Gas	562
Gen 43_Ikot-Abasi	Gas	196
Gen 44_Omoku	Gas	150

Gen 45_Egbema	Gas	340
Gen 47_Eyaen	Gas	452

3. Results and Discussion

The simulation results obtained are presented in Table 5 below. Table 5 presents the result of alert of the harmonic load flow obtained from Etap.

Harmonic Load Flow Analysis Alert View - Output Report: Untitled

Study Case: HA
Configuration: Normal

Date Revision: Base
Date: 15-06-2022

Filter
☐ Zone

Critical						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
AFAM GS	Bus IHD	Exceeds Limit	2	3.45	172.64	5.00
AFAM GS	Bus IHD	Exceeds Limit	2	2.41	120.68	7.00
AFAM GS	Bus IHD	Exceeds Limit	1.5	1.54	102.35	11.00
AFAM GS	Bus IHD	Exceeds Limit	0.5	0.51	101.99	41.00
AFAM GS	Bus IHD	Exceeds Limit	0.47	0.51	106.94	43.00
AFAM GS	Bus THD	Exceeds Limit	3	4.9	163.49	Total
ALAQUI GS	Bus IHD	Exceeds Limit	1	2.96	296.49	5.00
ALAQUI GS	Bus IHD	Exceeds Limit	1	1.94	193.59	7.00
ALAQUI GS	Bus IHD	Exceeds Limit	1	1.84	183.81	11.00
ALAQUI GS	Bus IHD	Exceeds Limit	1	1.63	163.2	13.00
ALAQUI GS	Bus THD	Exceeds Limit	1.5	4.38	291.91	Total
ALAQUI TS	Bus IHD	Exceeds Limit	1	3.04	304.12	5.00
ALAQUI TS	Bus IHD	Exceeds Limit	1	1.98	198.46	7.00
ALAQUI TS	Bus IHD	Exceeds Limit	1	1.88	188.2	11.00
ALAQUI TS	Bus IHD	Exceeds Limit	1	1.67	166.97	13.00
ALAQUI TS	Bus THD	Exceeds Limit	1.5	4.49	299.16	Total
ASABA	Bus THD	Exceeds Limit	3	3.02	100.78	Total
BENIN	Bus IHD	Exceeds Limit	1	1.13	113.12	7.00
IKOT EKPENE	Bus IHD	Exceeds Limit	1	2.33	233.13	5.00
IKOT EKPENE	Bus IHD	Exceeds Limit	1	1.24	123.6	7.00
IKOT EKPENE	Bus THD	Exceeds Limit	1.5	2.76	183.98	Total
MAKURDI	Bus IHD	Exceeds Limit	2	2.09	104.56	5.00
MAKURDI	Bus IHD	Exceeds Limit	2	2.58	128.84	7.00
MAKURDI	Bus THD	Exceeds Limit	3	3.44	114.64	Total
N HAVEN	Bus IHD	Exceeds Limit	2	2.16	108.1	5.00
ONITSHA	Bus IHD	Exceeds Limit	1	2.12	211.63	5.00
ONITSHA	Bus IHD	Exceeds Limit	1	1.66	165.78	7.00
ONITSHA	Bus IHD	Exceeds Limit	1	1.36	136.3	11.00
ONITSHA	Bus THD	Exceeds Limit	1.5	3.08	205.27	Total
UGWUJAI	Bus IHD	Exceeds Limit	2	2.19	109.72	5.00

Figure 2: Alert Values of the Harmonic Load Flow Simulation of Nigeria 52-bus 330kV Grid

Conclusion

In this paper, the harmonic modelling and simulation for the Nigerian 52-bus 330kV grid network was done using the ETAP 16.0 electrical simulation software. The findings indicate that the 330kV grid network in Nigeria is plagued by several issues, including voltage instability (manifested as voltage profile violations), challenges associated with lengthy transmission lines, the inherent characteristics of these transmission lines, and subpar power quality. This is particularly pronounced in the Northern regions of the examined network. To address

these issues effectively, it is recommended to incorporate more substations and additional transmission lines into the existing 330kV grid. Introducing these enhancements will create additional loops within the network, significantly improving its overall profile and performance.

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