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Modeling and Simulation of A48-Bus, 330 kV Power System Using PSAT

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ABSTRACT

This paper presents the modelling and simulation of the Nigerian 330 kV 48-bus power system using the Power System Analysis Toolbox (PSAT) in the MATLAB/Simulink environment. The Nigerian transmission network was represented as a 48-bus interconnected system comprising 16 generator buses, 32 load buses, one slack bus, and 59 transmission lines. Published network bus and line data were used in developing the model, while generator stations, load buses, and transmission lines were appropriately configured within the PSAT platform. Steady-state load flow analysis was carried out using the Newton-Raphson iterative technique to evaluate the voltage performance of the network. The developed model was validated by comparing simulated bus voltage magnitudes with reported experimental values. The results showed close agreement between both datasets, with an average percentage deviation of 2.146%, confirming the reliability and accuracy of the developed model. Most generator buses maintained voltage magnitudes close to the nominal value of 1.0 pu, while some load buses such as Jos, Makurdi, Ikot Ekpene, Ugwuaji, and New Haven recorded relatively low voltage levels, indicating weak bus conditions and the need for voltage support. The study demonstrates that PSAT is an effective tool for modelling and simulation of large-scale transmission systems. The developed Nigerian 48-bus model provides a dependable platform for further studies involving voltage stability analysis, continuation load flow, contingency analysis, optimal power flow, and integration of Flexible AC Transmission System (FACTS) devices for improved grid performance.

KEYWORDS

Nigerian power system, PSAT, power flow analysis, 48-bus network, voltage profile, MATLAB/Simulink, transmission system modelling

I. INTRODUCTION

Electric power systems are among the most important infrastructures for national development because they support industrial production, commercial activities, healthcare services, transportation, communication, and domestic living standards. The reliability and efficiency of a nation’s power network depend largely on the ability of the transmission system to transfer generated power from power stations to load centres with acceptable voltage levels and minimum losses. As electrical demand continues to increase, modern transmission networks require continuous analysis, planning, and operational improvement to ensure stable and secure power delivery. The Nigerian electric power system is one of the largest interconnected networks in Africa and is primarily structured around a 330 kV. Transmission grid that serves as the backbone for bulk power transfer across the country. This grid links major hydro and thermal generating stations with substations and regional load centres through long transmission corridors. However, like many developing power systems, the Nigerian grid is challenged by issues such as inadequate transmission capacity, voltage instability, network congestion, reactive power deficiency, and frequent disturbances. According to recent industry assessments, these grid vulnerabilities severely constrain economic output and grid reliability. These challenges make detailed system modelling and simulation essential for planning future expansion and improving operational reliability.

Power system modelling involves representing generators, transmission lines, transformers, loads, and buses in a mathematical form that can be analysed using computer-based simulation tools. Through simulation studies, engineers are able to predict system behaviour under different operating conditions, identify weak buses, estimate losses, analyse contingencies, and evaluate stability margins. Load flow studies are particularly important because they provide the steady-state operating condition of the network in terms of bus voltages, phase angles, active power flow, and reactive power flow. Several software tools have been developed for power system studies, including PSS/E, Dig SILENT Power Factory, ETAP, Power World, and MATLAB-based packages. Among these, the Power System Analysis Toolbox (PSAT) has gained wide acceptance in academic and research environments because it is open-source,

Flexible, and capable of performing load flow, continuation power flow, optimal power flow, small-signal stability, and dynamic simulations within the MATLAB/Simulink environment. PSAT provides an efficient platform for modelling large-scale transmission networks and testing different operational scenarios. The Nigerian 330 kV network has previously been represented in various simplified forms for research purposes, with the 48-bus equivalent model being one of the widely adopted representations. This model captures the major generating stations, substations, and transmission links necessary for realistic steady-state analysis. Developing an accurate PSAT model of the 48-bus Nigerian grid is therefore valuable for studying network performance and providing a foundation for future enhancement studies.

The aim of this study is to model and simulate the Nigerian 330 kV 48-bus power system using PSAT. The specific objectives are to develop the network model based on available bus and line data, perform steady-state load flow analysis using the Newton-Rap son method, validate the simulated results using available voltage data, and identify buses with weak voltage profiles. The outcome of the study is expected to provide a reliable simulation platform for further investigations involving voltage stability, contingency assessment, optimal power flow, and the integrated deployment of Flexible AC Transmission System (FACTS) devices—such as Static Var Compensators (SVC) or Static Synchronous Compensators (STATCOM)—for improved system performance and structural capacity.

II. MATERIALS AND METHODS

A. Study Area and Network Description

This study considered the Nigerian 330 kV national transmission grid represented as a 48-bus interconnected power system. The network consists of major generating stations, transmission substations, load centres, and long-distance transmission corridors linking different geopolitical regions of the country. The 330 kV grid serves as the backbone of bulk power transfer from generation plants to regional substations.

The modelled system comprises:

- 48 buses
- 16 generator buses (PV buses)
- 59 transmission lines
- 1 Slack/reference bus

The single-line diagram of the network served as the basis for the simulation model.

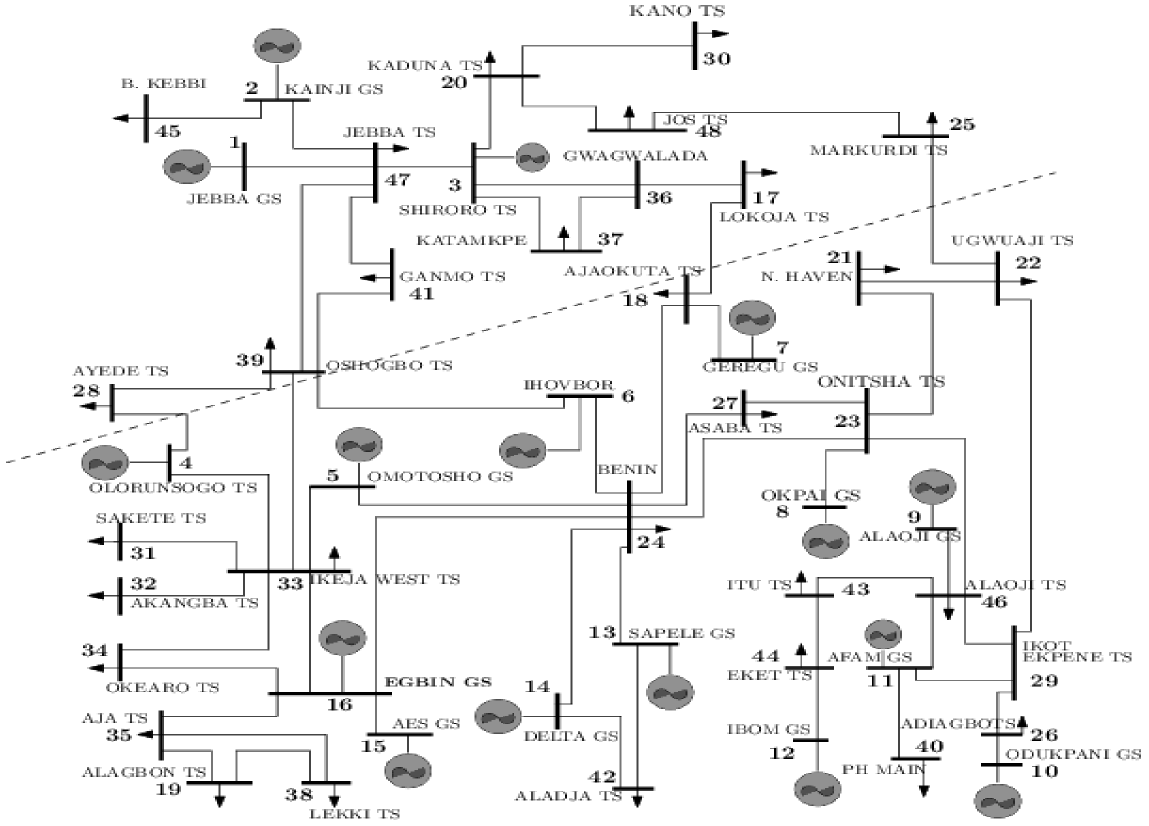


Figure 1. Single-line diagram of the Nigerian 330 kV 48-bus transmission network

Table 1. Summary of Nigerian 48-bus system data used for simulation.

Parameter	Description	Quantity/Value
Total Number of Buses	Total buses in the Nigerian 330 kV network model	48
Generator Buses (PV)	Buses representing generating stations	16
Load Buses (PQ)	Buses representing load demand centres	32
Slack Bus	Reference bus used for power balance	1

Transmission Lines	Total interconnected transmission lines	59
System Voltage Level	Nominal transmission voltage	330 kV
Base Power	Selected system base power for per unit analysis	100 MVA
System Frequency	Operating frequency of the grid	50 Hz
Simulation Software	Power System Analysis Toolbox	PSAT
Simulation Platform	Computational environment used	MATLAB/Simulink
Load Flow Method	Numerical solution technique adopted	Newton-Raphson
Stability Assessment Method	Technique used for load ability study	Continuation Load Flow (CLF)

B. Research Design

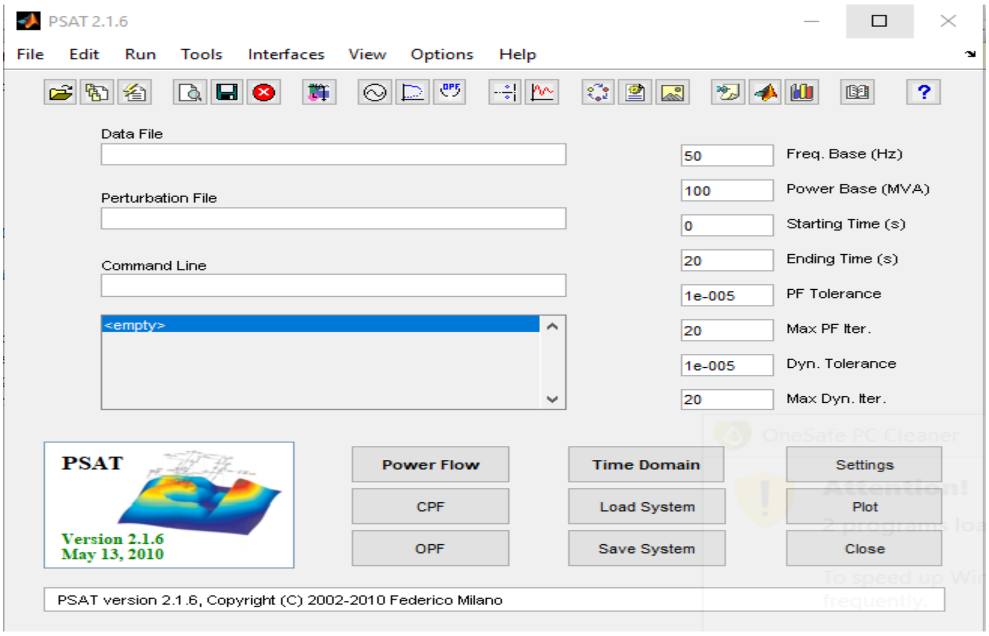
The research adopted a simulation-based methodology using the Power System Analysis Toolbox (PSAT) implemented in the MATLAB/Simulink environment. The study commenced with the collection of bus and transmission line data required for the network representation. Thereafter, the 48-bus Nigerian transmission grid was developed in PSAT, followed by the modelling of generator buses, load buses, and transmission lines based on the available system parameters. Steady-state power flow studies were then carried out to determine the operating condition of the network under normal loading conditions. Continuation Load Flow (CLF) analysis was subsequently performed to assess the load ability and voltage stability characteristics of the system. Finally, the developed model was validated through the evaluation of voltage profiles and loading performance across the network.

C. Data Collection and Network Parameters

The bus and transmission line parameters used in this work were adopted from previously published Nigerian transmission network datasets (Nkan, Okpo, & Okoro, 2o21). The extracted bus data comprised the bus number, bus name, bus type (Slack, PV, and or PQ), voltage magnitude, voltage angle, generated active power, reactive power limits, and load demand. Similarly, the transmission line data included the sending bus, receiving bus, line resistance, and line reactance, line charging sus acceptance, line length, and MVA rating.

D. Development of the 48-Bus Power System Model in PSAT

The Nigerian 330 kV network model was developed in PSAT using MATLAB/Simulink. The PSAT library blocks for buses, generators, loads, and transmission lines were interconnected according to the network single-line diagram



50 Freq. Base (Hz)
100 Power Base (MVA)
0 Starting Time (s)
20 Ending Time (s)
1e-005 PF Tolerance
20 Max PF Iter.
1e-005 Dyn. Tolerance
20 Max Dyn. Iter.

PSAT version 2.1.6, Copyright (C) 2002-2010 Federico Milano

Figure 2. Loading of the PSAT environment in MATLAB.

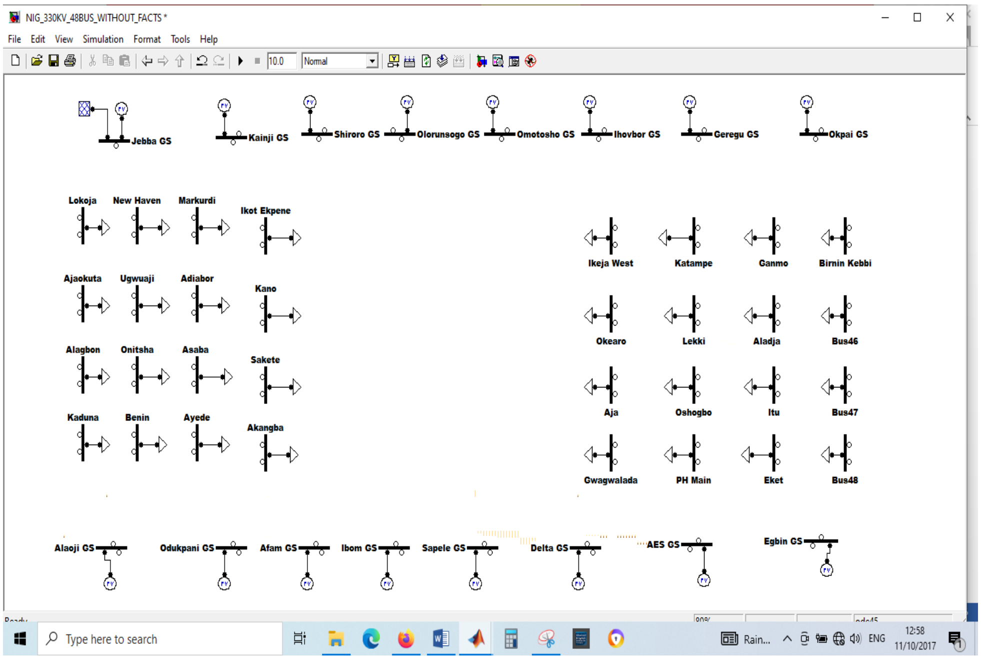


Figure 3. Initial modelling of generator and load buses.

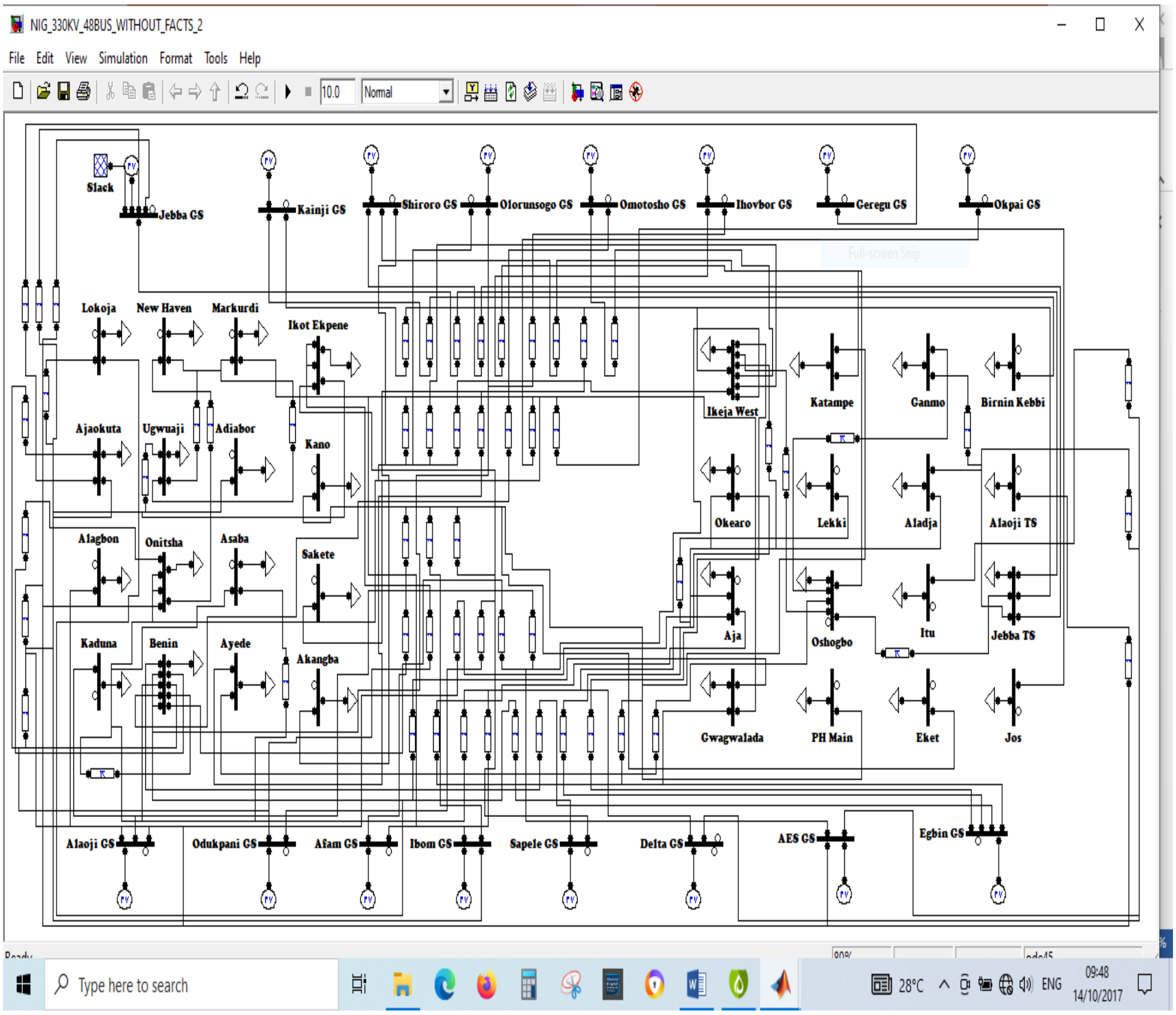


Figure 4. Complete developed model of the Nigerian 330 kV 48-bus power system

The modelling procedure followed the sequence:

Creation of bus bars.

1. Addition of generator buses.
2. Addition of load buses.
3. Interconnection using transmission line blocks.
4. Parameter initialization.
5. Solver configuration.

E. *Generator Bus Modelling*

The 16 generating stations were modelled as PV buses, where active power output and voltage magnitude were specified while reactive power output was allowed to vary within limits.

For a typical generating station:

1. Rated voltage = 330 kV
2. Frequency = 50 Hz

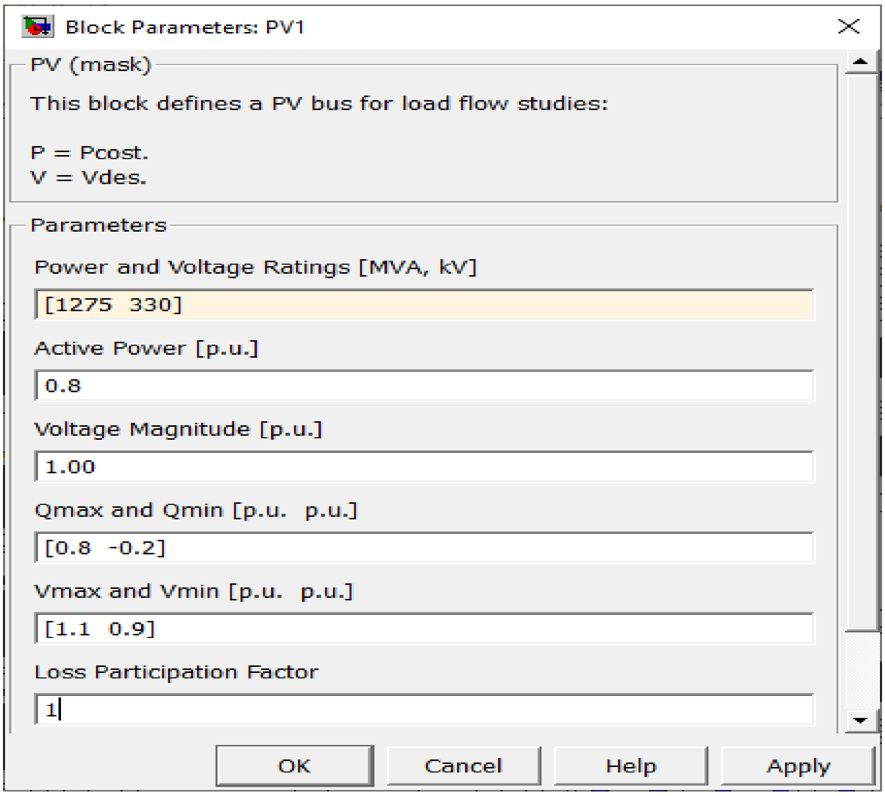
3. Voltage magnitude = 1.0 pu
4. Active power = specified from generator data
5. Reactive limits = Q_min to Q_max

For example, Egbin generating station was modelled with:

1. Rating = 1275 MVA
2. Voltage = 300 kV
3. Active power = 0.8 pu
4. Voltage magnitude = 1.0 pu
5. Reactive limits = -0.2 pu to 0.8 pu

F. Slack Bus Selection

Bus 1 (Jebba Generating Station) was selected as the reference or slack bus. The slack bus balances system active and reactive power mismatch while maintaining reference angle.



Block Parameters: PV1

PV (mask)

This block defines a PV bus for load flow studies:

P = Pcost.
V = Vdes.

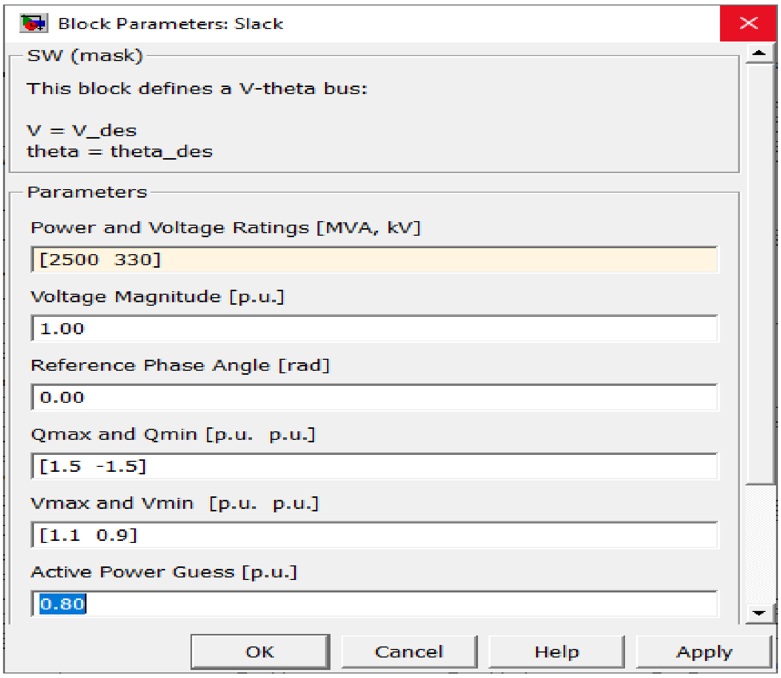
Parameters

Power and Voltage Ratings [MVA, kV]: [1275 330]
Active Power [p.u.]: 0.8
Voltage Magnitude [p.u.]: 1.00
Qmax and Qmin [p.u. p.u.]: [0.8 -0.2]
Vmax and Vmin [p.u. p.u.]: [1.1 0.9]
Loss Participation Factor: 1

Figure 5. Configuration of a generator (PV) bus in PSAT.

Slack bus settings*:*

1. Voltage magnitude = 1.0 pu
2. Voltage angle = 0 rad
3. Generator rating = 2500 MVA
4. Voltage base = 330 Kv



SW (mask)

This block defines a V-theta bus:

V = V_des
theta = theta_des

Parameters

Power and Voltage Ratings [MVA, kV]
[2500 330]

Voltage Magnitude [p.u.]
1.00

Reference Phase Angle [rad]
0.00

Qmax and Qmin [p.u. p.u.]
[1.5 -1.5]

Vmax and Vmin [p.u. p.u.]
[1.1 0.9]

Active Power Guess [p.u.]
0.80

Figure 6. Configuration of the slack bus

G. Load Bus Modelling

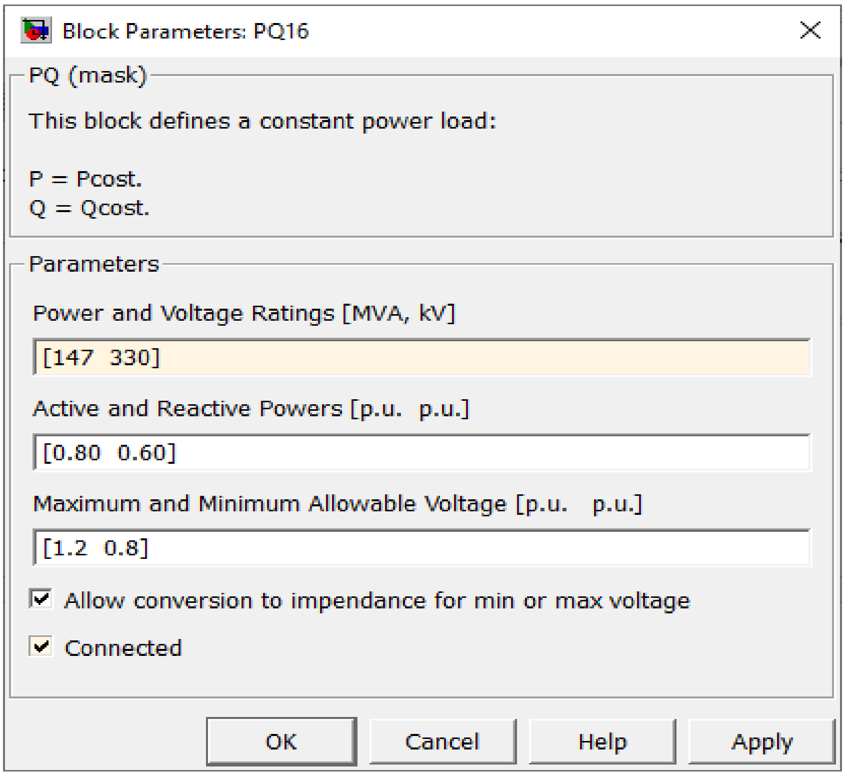
The 32 load buses were modelled as PQ buses, where active and reactive power demands were specified.

For each load bus:

1. Rated voltage = 330 kV
2. Active load demand = specified value
3. Reactive load demand = specified value
4. Voltage limits = 0.8 pu to 1.2 pu

For example, New Haven load bus was modelled with:

1. Load rating = 147 MVA
2. Active power = 0.80 pu
3. Reactive power = 0.60 pu



Block Parameters: PQ16

PQ (mask)

This block defines a constant power load:

P = Pcost.
Q = Qcost.

Parameters

Power and Voltage Ratings [MVA, kV]: [147 330]

Active and Reactive Powers [p.u. p.u.]: [0.80 0.60]

Maximum and Minimum Allowable Voltage [p.u. p.u.]: [1.2 0.8]

☑ Allow conversion to impendance for min or max voltage

☑ Connected

Figure 7. Input parameter configuration of a PQ load bus

H. Transmission Line Modelling

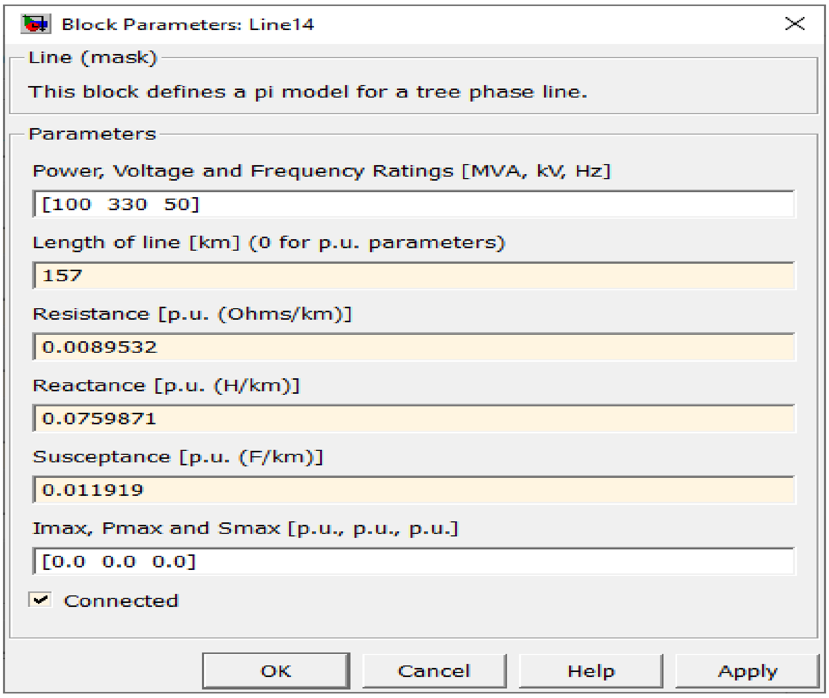
The 59 transmission lines were represented using the distributed parameter line model available in PSAT. All lines were based on:

1. Voltage rating = 330 kV
2. Power base = 100 MVA
3. Frequency = 50 Hz

Each line was parameterized by resistance R, reactance X, and charging susceptance B.

For example, the Ugwuaji–Makurdi transmission line was modelled with:

1. Length = 157 km
2. Resistance = 0.0089532 pu
3. Reactance = 0.0759871 pu
4. Susceptance = 0.011919 pu



Block Parameters: Line14

Line (mask)

This block defines a pi model for a tree phase line.

Parameters

Power, Voltage and Frequency Ratings [MVA, kV, Hz]: [100 330 50]

Length of line [km] (0 for p.u. parameters): 157

Resistance [p.u. (Ohms/km)]: 0.0089532

Reactance [p.u. (H/km)]: 0.0759871

Susceptance [p.u. (F/km)]: 0.011919

Imax, Pmax and Smax [p.u., p.u., p.u.]: [0.0 0.0 0.0]

☑ Connected

Figure 8. Transmission line parameter configuration in PSAT

I. Power Flow Formulation

The steady-state power flow equations used are:

Active Power Injection

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i)$$

Reactive Power Injection

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i)$$

Where:

1. $\mathrm{P_i} =$ active power at bus i
2. $\mathrm{Q_i} =$ reactive power at bus i
3. $\mathrm{V_i, V_j} =$ bus voltages
4. $\mathrm{Y_{ij}} =$ admittance between buses
5. $\delta_i, \delta_j = \mathit{voltage\ angles}$

J. Newton-Raphson Load Flow Solution

The power flow problem was solved using the Newton-Raphson iterative method embedded in PSAT because of its fast convergence and suitability for large-scale systems.

The iterative equation is:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix}$$

Where:

1. $J = Jacobian\ matrix$
2. $\varDelta P, \varDelta Q = power\ mismatches$
3. $\varDelta\delta, \varDelta \mid V \mid = state\ variable\ corrections$

Convergence tolerance was set within PSAT default limits.

K. Continuation Load Flow (CLF)

Continuation Load Flow was carried out to determine the maximum loading margin and voltage stability condition of the network.

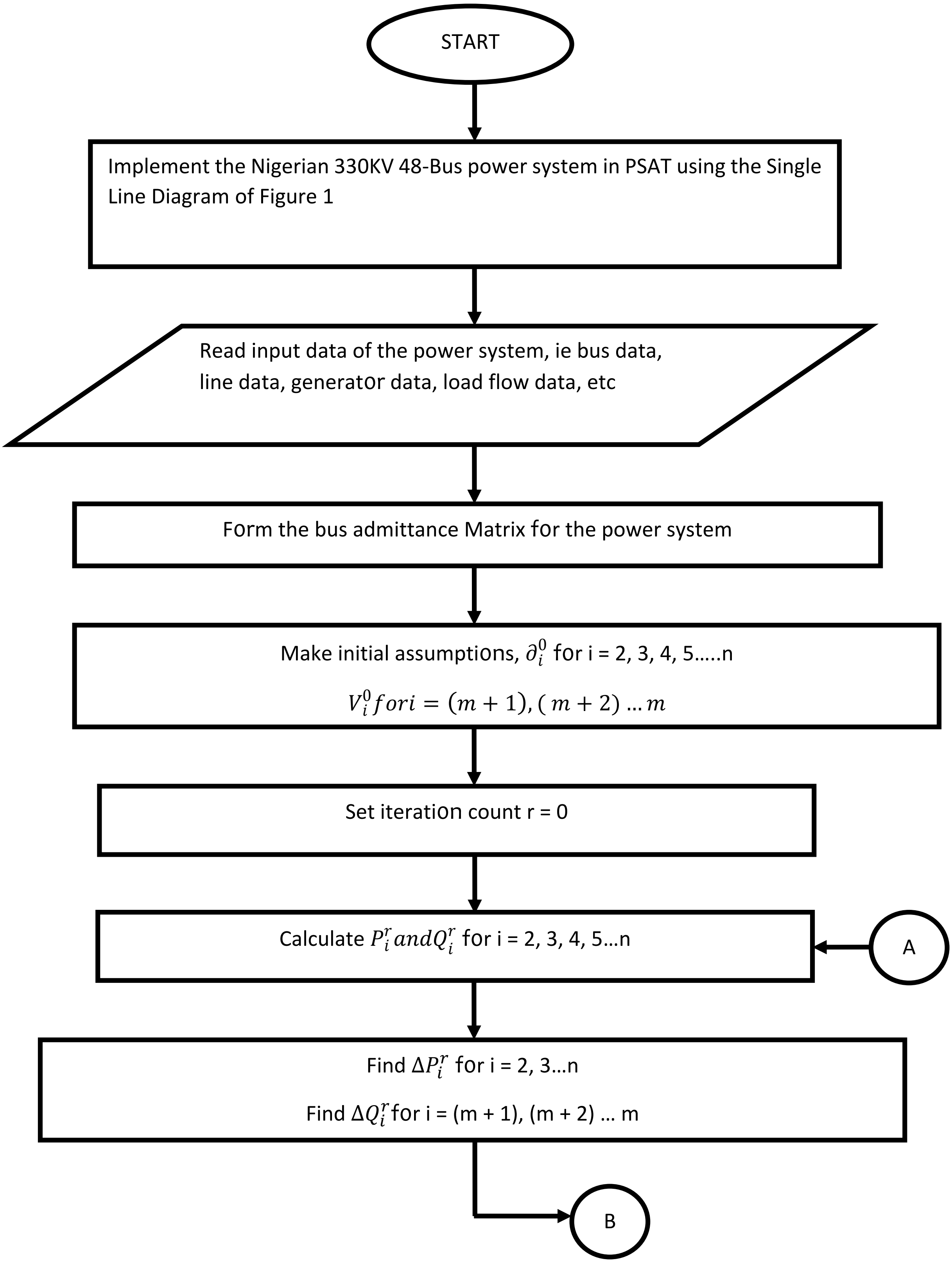
The system loading factor λ was progressively increased as:

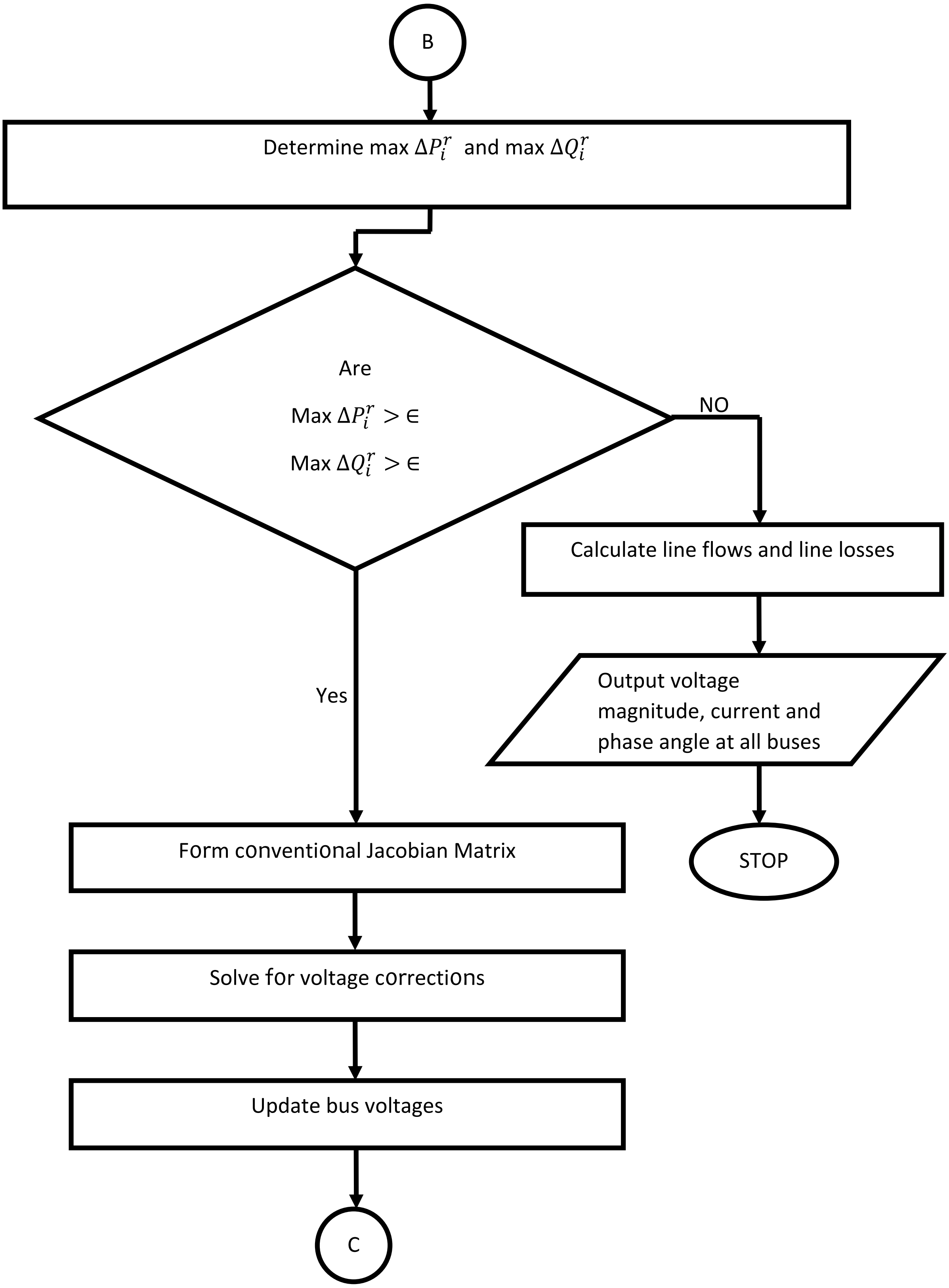
$$P_L = P_{Lo}(1+\lambda), Q_L = Q_{Lo}(1+\lambda)$$

Where:

1. $P_{(Lo)}, Q_{Lo} = base\ load\ demand$
2. $\lambda = loading\ parameter$

The continuation process continued until voltage collapse point was reached


START
Implement the Nigerian 330KV 48-Bus power system in PSAT using the Single Line Diagram of Figure 1
Read input data of the power system, ie bus data, line data, generator data, load flow data, etc
Form the bus admittance Matrix for the power system
Make initial assumptions, ∂_i^0 for i = 2, 3, 4, 5.....n
$V_i^0 for i = (m+1), (m+2) \dots m$
Set iteration count r = 0
Calculate $P_i^r and Q_i^r$ for i = 2, 3, 4, 5...n
A
Find ΔP_i^r for i = 2, 3...n
Find ΔQ_i^r for i = (m + 1), (m + 2) ... m
B


B
Determine max ΔP_i^r and max ΔQ_i^r
Are
Max $\Delta P_i^r > \in$
Max $\Delta Q_i^r > \in$
NO
Calculate line flows and line losses
Output voltage magnitude, current and phase angle at all buses
STOP
Yes
Form conventional Jacobian Matrix
Solve for voltage corrections
Update bus voltages
C

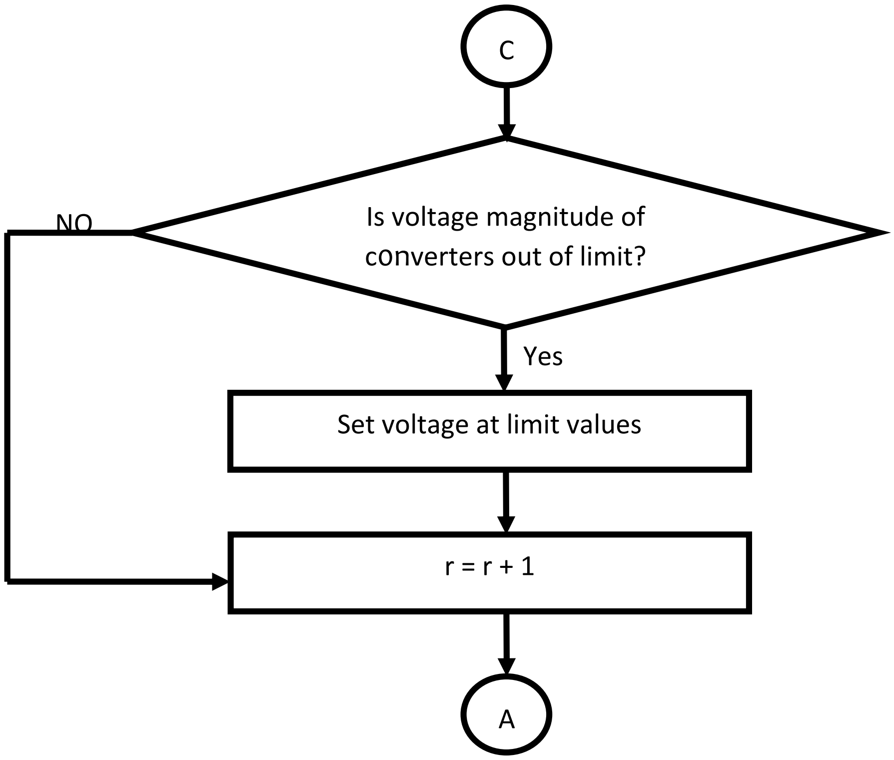


Figure 9. Flowchart for Continuation Load Flow (CLF) analysis.

L. Simulation Environment

All simulations were carried out using the MATLAB environment with the Power System Analysis Toolbox (PSAT) installed on a Windows-based workstation. The network was modelled using a system operating frequency of 50 Hz and a selected base power of 100 MVA for per unit analysis.

M. Performance Indices Evaluated

The outputs extracted from the simulation included bus voltage magnitudes, voltage deviations, real and reactive power losses, line loading levels, maximum load ability point, weak bus identification, and convergence characteristics of the load flow solution.

N. Validation of Model

The developed model was validated by ensuring successful convergence of the load flow solution and realistic voltage magnitudes within acceptable operational limits, with a preferred range of 0.95 to 1.05 pu. Validation also considered consistency with known operating characteristics of the Nigerian transmission grid as well as reasonable active and reactive power balance across the network.

III. RESULTS AND DISCUSSIONS

A. Bus Voltage Magnitude Validation of the Developed PSAT Model

The developed Nigerian 330 kV 48-bus power system model was validated by comparing the simulated bus voltage magnitudes obtained from PSAT with previously reported experimental bus voltage results. The comparison is presented in Table 2. The purpose of this validation was to determine the accuracy and reliability of the developed model in representing the actual steady-state behaviour of the Nigerian transmission network. The results show that the simulated voltage magnitudes closely follow the experimental values across most buses. Several generator buses such as Jebba GS, Kainji GS, Shiroro GS, Olorunsogo GS, Omotosho GS, Ihovbor GS, Geregu GS, Okpai GS, Alaoji GS, Odukpani GS, Ibom GS, Sapele GS, Delta GS, AES GS, and Egbin GS recorded zero percentage deviation, indicating exact correspondence between the developed PSAT model and the referenced operational data. This confirms the correctness of generator bus modelling and voltage-controlled bus representation. The overall average percentage deviation for the 48 buses was 2.146%, which is sufficiently low for large-scale transmission system simulation studies. This indicates that the developed PSAT model is an acceptable representation of the Nigerian 330 kV network and can be confidently used for further load flow, stability, and optimization studies

Table 2. Comparison of Experimental and Simulated Bus Voltage Magnitudes

Bus N0.	Bus Name	Experimental Voltage (pu)	Simulated Voltage (pu)	% Deviation
1	Jebba GS	1.000	1.000	0.000
2	Kainji GS	1.000	1.000	0.000
3	Shiroro GS	1.000	1.000	0.000
4	Olorunsogo GS	1.000	1.000	0.000
5	Omotosho GS	1.000	1.000	0.000
6	Ihovbor GS	1.000	1.000	0.000
7	Geregu GS	1.000	1.000	0.000
8	Okpai GS	1.000	1.000	0.000
9	Alaoji GS	1.000	1.000	0.000
1o	Odukpani GS	1.000	1.000	0.000
11	Afam GS	0.973	1.000	2.775
12	Ibom GS	1.000	1.000	0.000
13	Sapele GS	1.000	1.000	0.000
14	Delta GS	1.000	1.000	0.000
15	AES GS	1.000	1.000	0.000
16	Egbin GS	1.000	1.000	0.000
17	Lokoja	0.970	0.998	2.896
18	Ajaokuta	0.970	0.997	2.769
19	Alagbon	0.970	1.000	3.124
2o	Kaduna	0.955	1.000	4.717
21	New Haven	0.988	0.940	4.809
22	Ugwuaji	0.994	0.927	6.730

23	Onitsha	0.982	0.960	2.247
24	Benin	0.994	0.992	0.161
25	Makurdi	0.939	0.924	1.579
26	Adiabor	0.970	1.000	3.098
27	Asaba	0.924	0.976	5.645
28	Ayede	0.970	1.000	3.073
29	Ikot Ekpene	0.948	0.926	2.350
3o	Kano	0.909	1.000	10.017
31	Sakete	0.909	0.999	9.864
32	Akangba	1.000	0.999	0.134
33	Ikeja West	1.000	0.999	0.139
34	Okearo	1.000	0.999	0.065
35	Aja	1.000	1.000	0.025
36	Gwagwalada	0.955	0.999	4.638
37	Katampe	1.000	1.000	0.031
38	Lekki	0.909	1.000	10.044
39	Oshogbo	1.000	1.000	0.047
4o	PH Main	0.909	1.000	10.017
41	Ganmo	0.994	1.000	0.566
42	Aladja	0.985	1.000	1.528
43	Itu	1.000	1.000	0.005
44	Eket	0.994	1.000	0.609
45	Birnin Kebbi	0.988	1.000	1.220
46	Alaoji TS	0.970	1.000	3.098
47	Jebba TS	0.988	1.000	1.185
48	Jos	0.939	0.903	3.812

Average Percentage Deviation = 2.146%

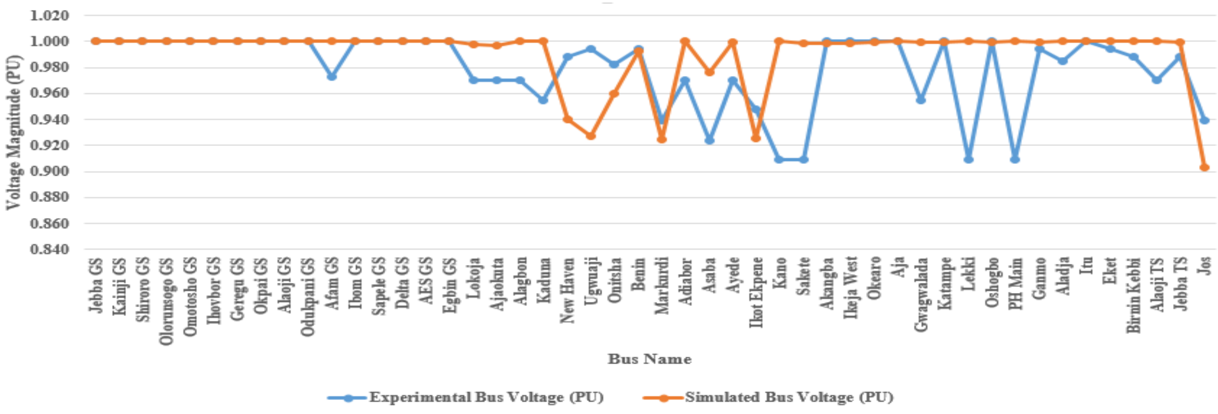


Figure 9. Comparison of Experimental and Simulated Bus Voltage Magnitude

B. *Analysis of Weak Voltage Buses*

The simulation results revealed that a number of buses experienced lower voltage magnitudes compared to the ideal 1.o pu operating level. The most critical buses in the simulated network were

Table 3. Buses with Poor Voltage Magnitude

Rank	**Bus Name**	**Simulated Voltage (pu)**
1	Jos	0.903
2	Makurdi	0.924
3	Ikot Ekpene	0.926
4	Ugwuaji	0.927
5	New Haven	0.940

These buses may be considered weak buses due to their relatively depressed voltages. The low voltage levels can be attributed to heavy load demand, long transmission distances from generation sources, reactive power deficiency, and line impedance effects. The weakest bus in the system was Jos Bus with a simulated voltage magnitude of 0.9o3 pu, which falls below the commonly acceptable minimum limit of 0.95 pu. This indicates the need for voltage support measures such as reactive compensation, transformer tap adjustment, or FACTS device integration in future studies.

C. Voltage Regulated and Stable Buses

Several buses maintained voltages close to 1.o pu, especially generator buses and buses located close to major generating stations. These buses included

- Shiroro GS
- Egbin GS
- Delta GS
- Olorunsogo GS
- AES GS
- Lekki
- PH Main
- Jebba GS
- Kainji GS

This demonstrates effective voltage regulation at generation buses due to excitation control and reactive power support.

D. Voltage Deviation Pattern across the Network

The percentage deviation between experimental and simulated results remained below 5% for most buses, showing strong agreement between both datasets. Only a few buses such as Kano, Sakete, Lekki, and PH Main exhibited deviations above 9%, mainly due to assumptions in the simulation model, simplified generator controls, updated network operating conditions, or differences in real-time load demand during data acquisition.

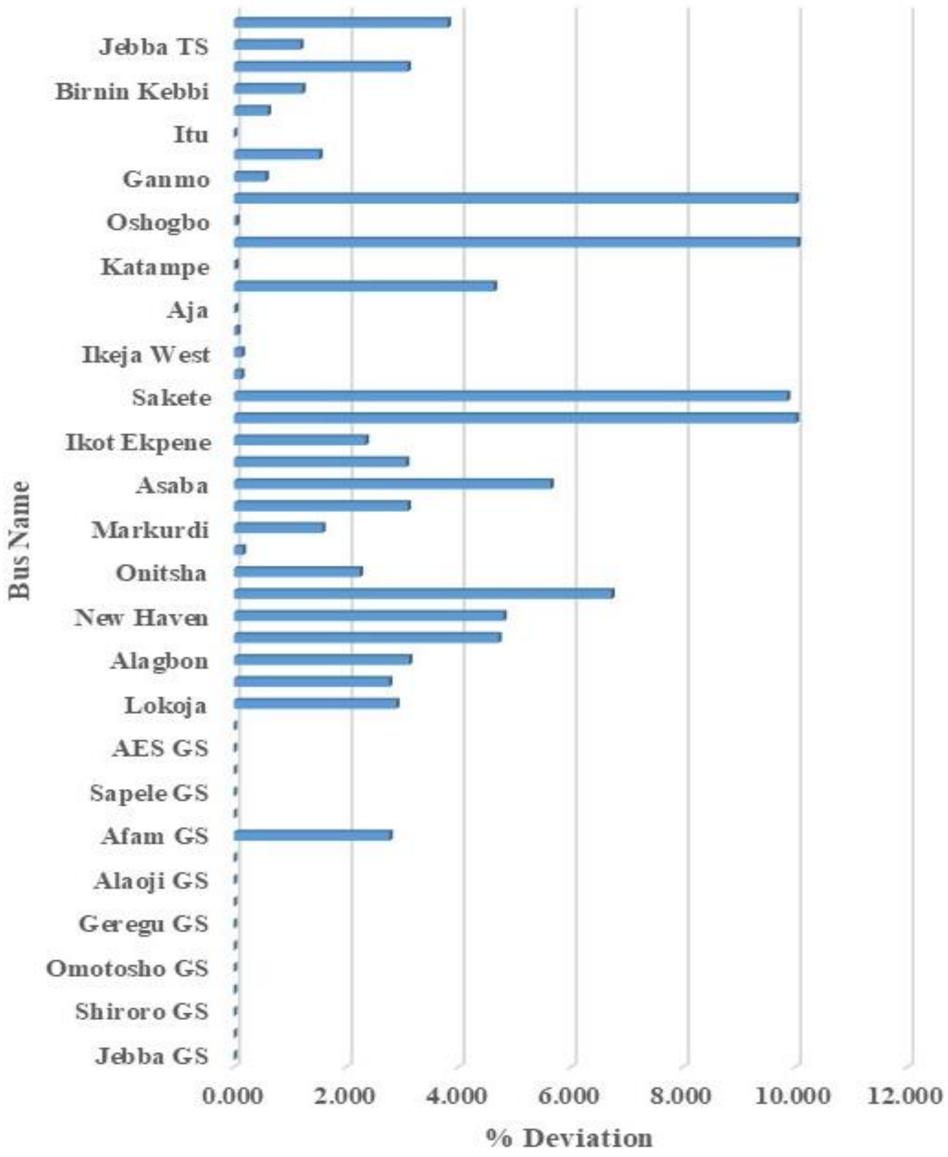


Figure 10. Percentage Deviation per Bus

Table 4. Voltage Performance Classification of Simulated Buses

Voltage Range (pu)	Condition	Number of Buses
≥ 0.98	Excellent	31
0.95 – 0.979	Acceptable	6
0.9o – 0.949	Critical	11
< 0.9o	Severe	o

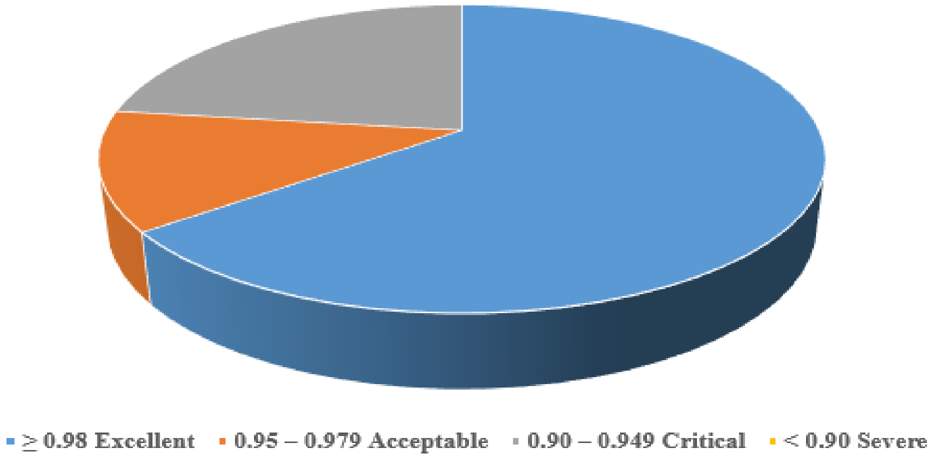


Figure 11. Pie Chart showing the Performance Classification of the Simulated Buses

The table shows that most buses operated within acceptable voltage limits, while a smaller number of buses require corrective attention.

E. Implication of Results

The low average deviation of 2.146% confirms that the PSAT-developed model accurately represents the Nigerian 330 kV 48-bus transmission network. Hence, the model is suitable for advanced studies such as

- Continuation Load Flow (CLF)
- Voltage stability analysis
- Load ability enhancement studies
- FACTS device placement
- Optimal power flow studies
- Contingency analysis

F. General Discussion

The results demonstrate that the Nigerian 330 kV network contains a combination of well-regulated buses and weak buses requiring reactive support. While generation buses maintained strong voltages, some distant load buses suffered voltage drops due to transmission constraints. This validates practical grid behavior where remote buses typically experience reduced voltage magnitude. The developed PSAT model therefore provides a realistic platform for future network reinforcement and stability improvement studies.

IV. CONCLUSION

This study successfully developed and simulated a model of the Nigerian 330 kV 48-bus power system using the Power System Analysis Toolbox (PSAT) in the MATLAB/Simulink environment. The model incorporated 48 buses, 16 generator buses, 32 load buses, and 59 transmission lines based on published network data, thereby providing a representative framework of the Nigerian transmission grid for steady-state analysis. The validation of the developed model through comparison of simulated and experimental bus voltage magnitudes showed strong agreement, with an average percentage deviation of 2.146%. This low deviation confirms the accuracy and reliability of the developed PSAT model for power system studies. Most generator buses maintained voltage magnitudes close to the nominal value of 1.o pu, demonstrating effective voltage regulation at generation points.

The results also revealed the presence of several weak buses with depressed voltage profiles, particularly Jos, Makurdi, Ikot Ekpene, Ugwuaji, and New Haven buses. These buses are likely affected by transmission distance, loading conditions, and reactive power limitations, indicating the need for corrective measures such as reactive power compensation and network reinforcement. Overall, the developed model provides a realistic and dependable platform for further investigation of the Nigerian transmission system. It can be effectively utilized for continuation load flow studies, voltage stability assessment, contingency analysis, optimal power flow, and future integration of FACTS devices for enhanced system performance. The study therefore establishes PSAT as a suitable tool for modelling and simulation of large-scale interconnected power networks such as the Nigerian 330 kV grid.

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