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Decoupling of Nigeria Grid System through Regionalization for Efficient Power System Operations and Stability

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Abstract: - The Nigerian electricity grid operates a single interconnected 330kV network that remains unstable, inefficient, and prone to cascading failures. Localized faults often escalate into nationwide blackouts, restricting industrial and economic activity. The 2023 Electricity Act provides a legal foundation for decentralization by empowering regional entities to manage generation, transmission, and distribution assets. This study develops a technical model for implementing decentralization using the Power System Analysis Toolbox (PSAT) in MATLAB. The grid was divided into four regional zones based on the former PHCN structure, and Area 1 (Kainji–Gombe) was selected for detailed simulation. Steady-state load flow analysis, conducted using the Newton-Raphson method, verified that the decoupled region maintained nominal voltage and angular stability. Convergence was achieved smoothly, with voltages within 0.95-1.05 p.u., confirming operational feasibility. The results demonstrate that regionalization facilitates stable and localized grid management, offering a viable engineering pathway for implementing the 2023 Electricity Act.

Keywords: Power Systems, Voltage stability, Grid Regionalization, Distributed Transmission, Power System Reliability, Optimized Grid System, Economic Dispatch

1.0 Introduction

The Nigerian electricity grid is characterized by a centralized 330/132 kV architecture that suffers from chronic challenges, including insufficient transmission capacity and high system losses[1–3]. Critically, this structure is highly susceptible to cascading failures, where localized disturbances rapidly trigger widespread national blackouts, severely constraining economic stability [4,5]. Addressing this requires a fundamental paradigm shift from centralized to decentralized operation. The Nigerian Electricity Act of 2023 provides the necessary legal mandate for this transition, enabling regional entities to manage power assets [2,6,7]. This study proposes the technical blueprint for implementation by regionally decoupling the transmission grid into four control zones, based on the former PHCN control structure [1,6]. The framework was modeled using the Power System Analysis Toolbox (PSAT), with a focus on Area 1 (Kainji to Gombe), to confirm its technical feasibility. The primary contribution of this work is the validation of enhanced system stability and feasibility. Through comprehensive power flow analysis, the study demonstrates that the regionalized structure maintains nominal voltage stability and angular coherence under steady-state conditions. This confirmed viability establishes regionalization as the most effective.

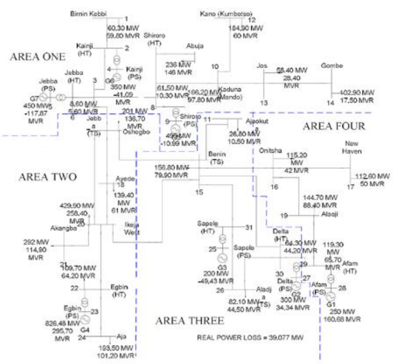

Figure 1: Centralized structure of the Nigerian 330kV grid network, divided into four areas

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1.1 Problem Context and Policy Framework

I. Centralized Grid Structural Weaknesses

The primary challenge facing the Nigerian electricity grid is its centralized nature [3,8]. The national grid operates as a single interconnected system, which means that any fault in a critical section can trigger a series of cascading failures that result in widespread power outages [9]. This lack of operational segregation significantly reduces the grid's resilience. Additionally, the system suffers from limited transmission capacity; despite an installed capacity of over 12,000 MW, the network can only evacuate approximately 5,000 MW, leading to severe congestion and load rejection [10].

II. Policy Mandate: The Electricity Act of 2023 and Proposed Grid Regionalization

Nigeria's chronic grid unreliability, marked by repeated nationwide and partial collapses, has imposed large economic losses and exposed structural weaknesses in transmission and system operations [7,9–11]. Recent reporting notes multiple nationwide outages in 2024 alone and persistent constraints that keep delivering power near 4–5 GW despite far higher installed capacity, owing to aging infrastructure, vandalism, gas supply issues, and high technical losses In response, the Electricity Act 2023 repeals the 2005 reform law and decentralizes electricity governance, enabling state electricity markets and empowering states to license generation, transmission, and distribution within their jurisdictions; a legal foundation for moving decision-making closer to load centers and investors [6]. This dovetails with Nigeria's existing transmission footprint, which already operates through multiple regional transmission areas under the Transmission Company of Nigeria (TCN), offering a practical framework for a regionalized grid model; planning, protection, and operations are aligned by region while maintaining national interconnection. Analysts similarly view the Act as a path to state-level utilities, successor companies, and investment vehicles that can accelerate localized reliability upgrades and new capacity additions, including renewables and storage [12–16]

Proposed regionalization model aligned with the Act

Regulatory alignment: Establish state/regional system operators under state laws while maintaining NERC/TCN coordination for intertie reliability, protection settings, and market settlement rules, which avoids regulatory fragmentation while capturing local accountability.

Operational segmentation: Partition the grid into interconnected regional control areas, building on TCN regions with N–1 security, defined under-frequency/under-voltage load shedding schemes, and islanding/re-synchronization playbooks for disturbance containment.

Targeted investments: Prioritize regional bottlenecks (132/330 kV lines, substations, STATCOM/SVC for voltage support), SCADA/EMS and WAMS/PMU coverage for wide-area visibility, and grid-forming BESS at urban nodes to arrest frequency dips and black-start critical corridors.

Distributed resources integration: Use the Act's state-market provisions to procure regional renewables, storage, and industrial self-generation behind the meter, governed by uniform grid codes and interconnection standards coordinated with TCN/NERC.

Why this satisfies the Act: A regionalized, interconnected grid improves contingency containment, aligns planning and operation and maintenance with local realities, and meets the Electricity Act's decentralization intent without sacrificing national synchronism or market coherence. It also creates clearer lanes for state-level financing and PPPs while preserving federal oversight of interstate power flows and reliability standards.

2.0 Methodology

2.1 Power Flow Analysis

Evaluating the proposed regionalization requires robust computational analysis. This study utilizes Newton-Raphson power flow analysis to determine the steady-state operating condition of the grid. The power flow equations are generally solved using the Newton-Raphson (NR) load flow method, which is known to be more sophisticated and converges faster than all other methods. For an *n*-bus system, the nodal current equation describing the performance of a power system network is:

The iterative NR method yields the unknown voltage magnitudes and angles necessary to confirm the steady-state technical feasibility of the decoupled regional grid.

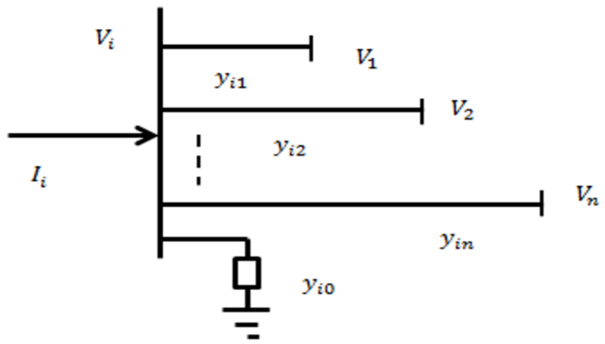

Figure 2: Bus-loading representation used for the power flow formulation

$$\mathbf{I_{bus} = Y_{bus} V_{bus}} \quad (1)$$

$$S_i = P_i + jQ_i = V_i I_i^* \quad (2)$$

2.2 Data Sources

All network data, including bus, line, and generator parameters, were obtained from previous studies. [7]. Parameters were converted to the per-unit system on a 100 MVA base.

Table 1: Existing Generation Stations in Nigeria

S/NO	Power Station Name	Location/State	Type of Fuel Used	Capacity (MW)
1	Egbin Thermal Power Station	Lagos	Gas	1320
2	Afam Thermal Power Station	Rivers	Thermal	969.6
3	Sapele Thermal Power Station	Delta	Thermal	1020
4	Ijora Thermal Power Station	Lagos	Thermal	40
5	Delta Thermal Power Station	Delta	Thermal	912
6	Kainji Hydro Power Station	Niger	Hydro	760
7	Jebba Hydro Power Station	Niger	Hydro	578
8	Shiroro Hydro Power Station	Niger	Hydro	600
9	AES Thermal Power Station	Lagos	Thermal	300

Table 2: Bus Data for 330kV lines

S/N	Bus Name	Generation P(MW)	Generation P(MVar)	Load P(MW)	Load P(MVar)	Voltage (V)	Angle (Degrees)	Type of Bus
1	Egbin	-	-	0.000	0.000	1.020	0.000	Slack
2	Delta Ps	55.000	28.160	-	-	1.000	0.000	PV Bus
3	Okpai	220.000	112.700	-	-	1.000	0.000	PV Bus
4	Sapele	75.000	38.420	-	-	1.000	0.000	PV Bus
5	Afam	479.000	245.390	-	-	1.000	0.000	PV Bus
6	Jebba	322.000	164.960	-	-	1.000	0.000	PV Bus
7	Kainji	323.000	165.490	-	-	1.000	0.000	PV Bus
8	Shiroro	280.000	143.440	-	-	1.000	0.000	PV Bus
9	Geregu	200.000	102.440	-	-	1.000	0.000	PV Bus
10	Oshogbo	-	-	120.370	61.650	1.000	0.000	Load Bus
11	Benin	-	-	160.560	82.240	1.000	0.000	Load Bus
12	Ikeja West	-	-	334.000	171.110	1.000	0.000	Load Bus
13	Ayede	-	-	176.650	90.490	1.000	0.000	Load Bus
14	Jos	-	-	82.320	42.130	1.000	0.000	Load Bus
15	Onitsha	-	-	130.510	66.860	1.000	0.000	Load Bus
16	Akangba	-	-	233.370	119.560	1.000	0.000	Load Bus
17	Gombe	-	-	74.480	38.140	1.000	0.000	Load Bus
18	Abuja (Katampe)	-	-	200.000	102.440	1.000	0.000	Load Bus
19	Maiduguri	-	-	10.000	5.110	1.000	0.000	Load Bus
20	Egbin-Ts	-	-	0.000	0.000	1.000	0.000	Load Bus

21	Aladja	-	-	48.000	24.580	1.000	0.000	Load Bus
22	Kano	-	-	252.450	129.330	1.000	0.000	Load Bus
23	Aja	-	-	120.000	61.480	1.000	0.000	Load Bus
24	Ajaokuta	-	-	63.220	32.380	1.000	0.000	Load Bus
25	New Haven	-	-	113.050	57.910	1.000	0.000	Load Bus
26	Alaoji	-	-	163.950	83.900	1.000	0.000	Load Bus
27	Jebba-Ts	-	-	7.440	3.790	1.000	0.000	Load Bus
28	Birnin-Kebbi	-	-	70.000	35.850	1.000	0.000	Load Bus
29	Kaduna	-	-	149.770	76.720	1.000	0.000	Load Bus
30	Makurdi	-	-	73.070	37.430	1.000	0.000	Load Bus

Base value = 100MVA

Base voltage = 330kV

Per Unit Value = MVA/(Base Value)

Table 3: Bus Data in Per Unit

S/N	Bus Name	Generation		Load	
		P (p.u)	Q (p.u)	P (p.u)	Q (p.u)
1	Egbin	-	-	0.0000	0.0000
2	Delta	0.55	0.2816	-	-
3	Okpai	2.20	1.1270	-	-
4	Sapele	0.75	0.3842	-	-
5	Afam	4.79	2.4539	-	-
6	Jebba	3.22	1.6496	-	-
7	Kainji	3.23	1.6549	-	-
8	Shiroro	2.80	1.4344	-	-
9	Geregu	2.00	1.0244	-	-
10	Oshogbo	-	-	1.2037	0.6165
11	Benin	-	-	1.6056	0.8224
12	Ikeja West	-	-	3.3400	1.7111

13	Ayede	-	-	1.7665	0.9049
14	Jos	-	-	0.8223	0.4213
15	Onitsha	-	-	1.3051	0.6686
16	Akangba	-	-	2.3337	1.1956
17	Gombe	-	-	0.7448	0.3814
18	Abuja(Katampe)	-	-	2.0000	1.0244
19	Maiduguri	-	-	0.1000	0.0511
20	Egbin-Ts	-	-	0.0000	0.000
21	Aladja	-	-	0.4800	0.2458
22	Kano	-	-	2.5245	1.2933
23	Aja	-	-	1.2000	0.6148
24	Ajaokuta	-	-	0.6322	0.3238
25	New Haven	-	-	1.1305	0.5791
26	Alaoji	-	-	1.6395	0.8390
27	Jebba-Ts	-	-	0.0744	0.0379
28	Birnin Kebbi	-	-	0.7000	0.3585
29	Kaduna	-	-	1.4977	0.7672
30	Makurdi	-	-	0.7307	0.3743

Table 4: Transmission Line Data of the Centralized Nigeria Electricity Grid

Line No	Location Description (I)	Location Description (J)	PU Value	Thermal Rating (A)	Thermal Rating (MVA)
1	Kainji (HT)	Birnin Kebbi	1.0269	1360	777.4
2	Kainji (HT)	Jebba (TS)	0.5366	1360	777.4
3	Kainji (PS)	Kainji (HT)	0.0000	-	860
4	Jebba (HT)	Jebba (TS)	0.0530	1360	777.4
5	Jebba (TS)	Oshogbo	1.5600	1360	777.4
6	Shiroro (HT)	Jebba (TS)	0.6165	1360	777.4
7	Jebba (PS)	Jebba (HT)	0.0000	-	714
8	Oshogbo	Benin (TS)	0.8315	1360	777.4
9	Oshogbo	Ayede	0.3472	1360	777.4
10	Oshogbo	Ikeja West	0.9805	1360	777.4
11	Shiroro (PS)	Shiroro (HT)	0.0000	-	800
12	Shiroro (HT)	Kaduna (Mando)	0.6360	1360	777.4
13	Kaduna (Mando)	Kano (Mando)	0.7619	1360	777.4

14	Kaduna (Mando)	Jos	0.6526	1360	777.4
15	Benin (TS)	Ajaokuta	0.6460	1360	777.4
16	Jos	Gombe	0.8778	1360	777.4
17	Ayede	Ikeja West	0.4538	1360	777.4
18	Ikeja West	Benin (TS)	1.8850	1360	777.4
19	Delta (HT)	Benin (TS)	0.2418	1360	777.4
20	Sapele (HT)	Benin (TS)	0.3313	1360	777.4
21	Onitsha	New Haven	0.3180	1360	777.4
22	Alaoji	Onitsha	0.5101	1360	777.4
23	Benin (TS)	Onitsha	0.4540	1360	777.4
24	Afam (HT)	Alaoji	0.1656	1360	777.4
25	Ikeja West	Akangba	0.1190	1360	777.4
26	Egbin (HT)	Ikeja West	0.4108	1360	777.4
27	Egbin (PS)	Egbin (HT)	0.0000	-	1620
28	Egbin (HT)	Aja	0.0928	1360	777.4
29	Sapele (PS)	Sapele (HT)	0.0000	-	1177
30	Delta (HT)	Aladja	0.0861	1360	777.4
31	Sapele (HT)	Aladja	0.2087	1360	777.4
32	Delta (PS)	Delta (HT)	0.0000	-	720
33	Afam (PS)	Afam (HT)	0.0000	-	504
34	Shiroro	Abuja (Katampe)	0.4130	1360	777.4

2.3 Implementation and Dynamic Modeling

All simulations were executed using the PSAT environment. The steady-state calculations employed the Newton-Raphson iterative method for its rapid convergence properties. The dynamic components were accurately modeled, with loads treated as constant impedance (Z-type), and the dynamic equations were solved using the fourth-order Runge-Kutta integration method. The centralized network was divided into four major regions, designated as Area 1, Area 2, Area 3, and Area 4. In this paper, Area 1 was considered, and the simulations for the other regions are still ongoing.

2.4 Regionalization Scheme and Decoupling

I. Case Study: Area 1 (Kainji to Gombe) was selected for detailed simulation.
II. Decoupling Strategy: Regionalization was achieved by setting all lines crossing the Area 1 boundary to open circuits in the model, retaining only essential tie-lines.
III. Local Slack Bus: The Kainji Generation Bus was designated as the new local Slack Bus for the decoupled Area 1, ensuring a localized power balance and angular reference.

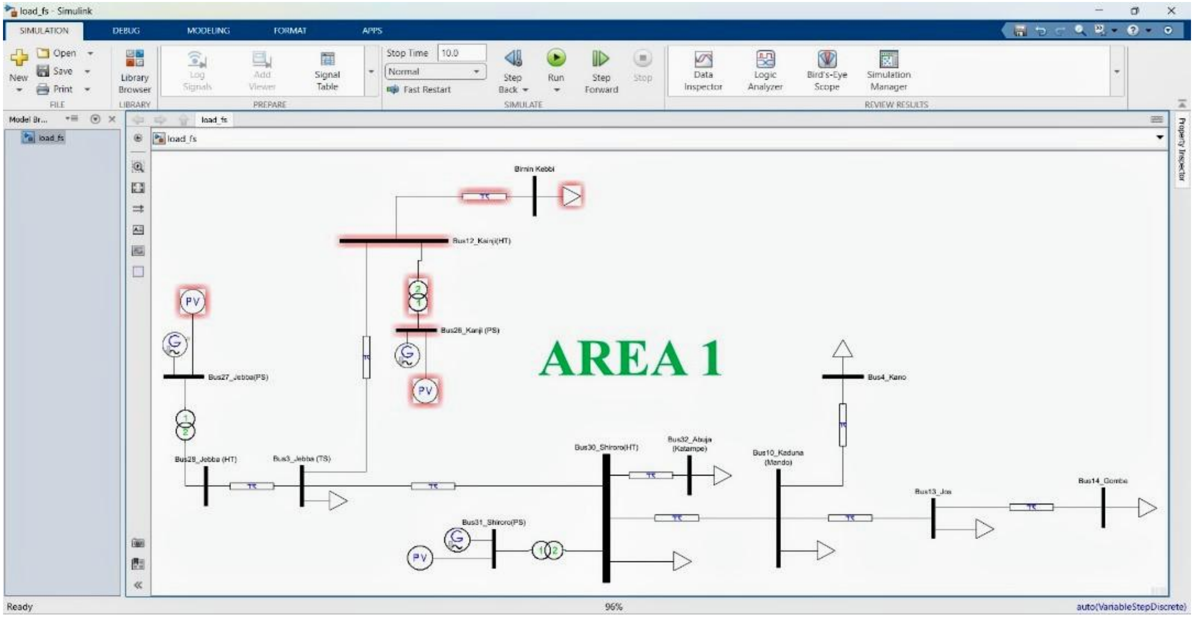

Figure 3: Simulation model of Area 1 (Birnin Kebbi–Gombe) in PSAT.

3.0 Result And Discussion

3.1 MATLAB SIMULINK Data

The per-unit data from the buses connected to AREA 1, from Kainji to Gombe, were selected, along with illustrated bus identifiers, from Birnin Kebbi to Jebba Bus 3. Voltage lines and Power at minimal consumption were selected and included for the analysis. Overall, the central grid variables were only added since the current operation of the grid remains at the central location. The regionalized nature of AREA 1 means that fault occurrence and control duties will be carried out by respective personnel, and any regional schemes to be implemented will be done no longer at the center but by regional centers per the provisions of the Nigerian Electricity Act of 2023.

This analysis considers the current power system protection schemes in operation across the 330kV transmission lines. Protection schemes in these regions include SCADA systems and Relays. All data included are the per-unit data of the primary transmission lines.

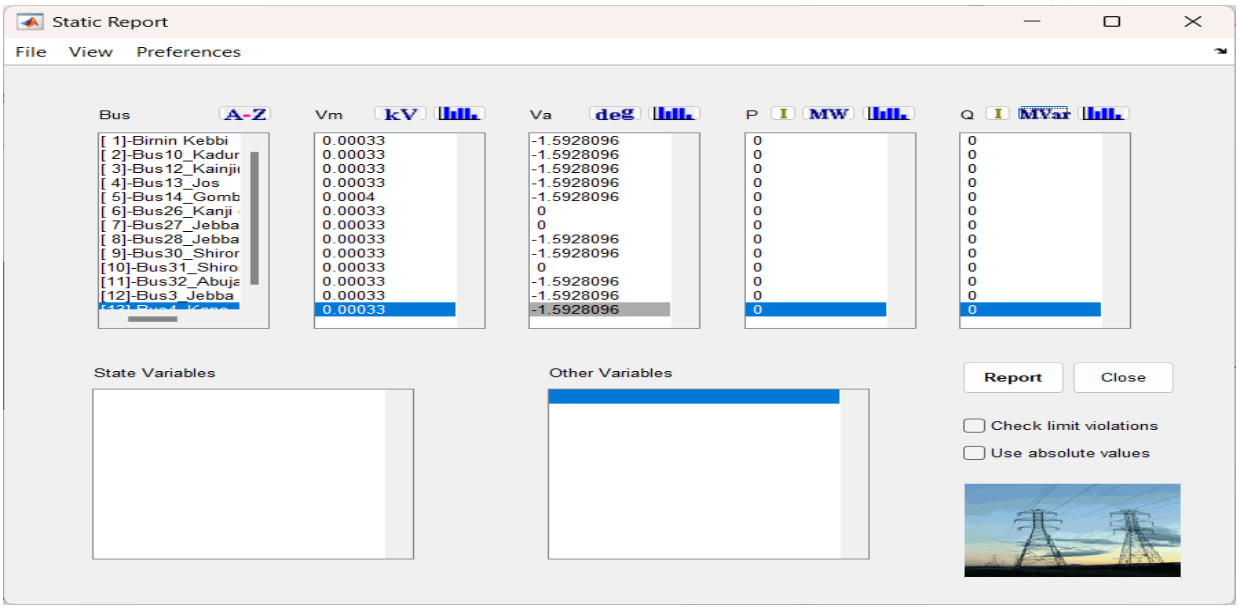

Figure 4. Input data for the regionalization of the Nigerian Power System using AREA 1 as a Case Study

3.2 Voltage Phase and Magnitude Profile

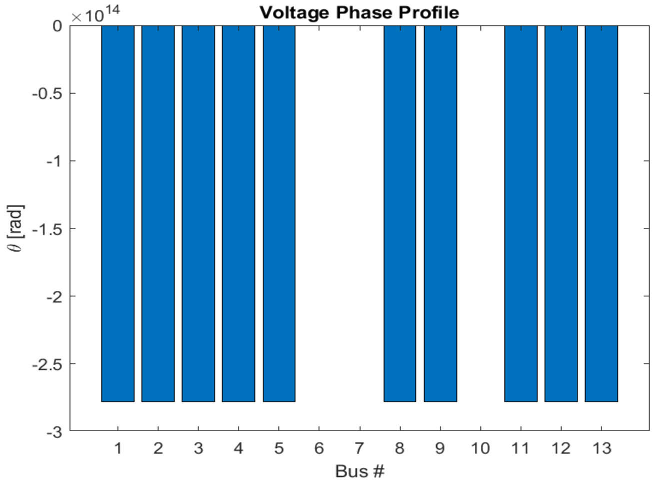

Figure 5: Voltage phase profile of Area 1 sector of the Regionalized Grid

The voltage phase profile has been used as a tool for deciphering the behaviour of the power system infrastructure. The analysis assessed the stability of AREA 1 of the proposed decentralization to understand the feasibility of the power system and its operation. In Fig. 5, the result showed that the decoupling of the AREA 1 region, comprising the gen bus and the PV bus from Kainji to Gombe, still reflected the same voltage phase profile of 0.86 as the existing centralized grid. In Fig. 6, the voltage magnitude profile of the AREA 1 region was also consistent with that of the existing centralized grid. This tentatively suggests that after decoupling the power system infrastructure, the resulting regional energy system will be more responsible for the affairs of its region, with similar parameters to those of other areas, facilitating consistent integration across the regions in accordance with the Nigerian Electricity Act of 2023.

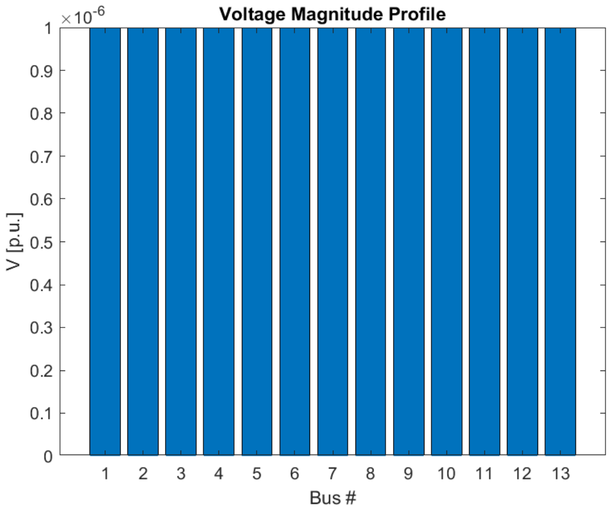

Figure 6: Voltage magnitude profile of Area 1 sector of the Regionalized Grid

Beyond stability, the voltage phase and magnitude profile unveil transient events, those fleeting disturbances that disrupt the current flow. Voltage sags, surges, and interruptions, manifested as abrupt deviations from the norm, leave indelible marks on the profile. These transient events, born of lightning strikes, equipment faults, or operational maneuvers, serve as breadcrumbs guiding engineers towards the root causes of disturbances, empowering them to fortify defenses against future disruptions.

3.3 Power System Profile

Using the pu data, the 330kV power profile of the central grid was identified and the result of the simulation showed a variation in the power profile of the regionalized AREA 1 power system network compared to the central grid. From the result shown, the regionalization of Nigeria's power system introduces a new paradigm, dividing the grid into distinct zones. Real power generation capacity varies across regions, reflecting resource endowments and demand patterns.

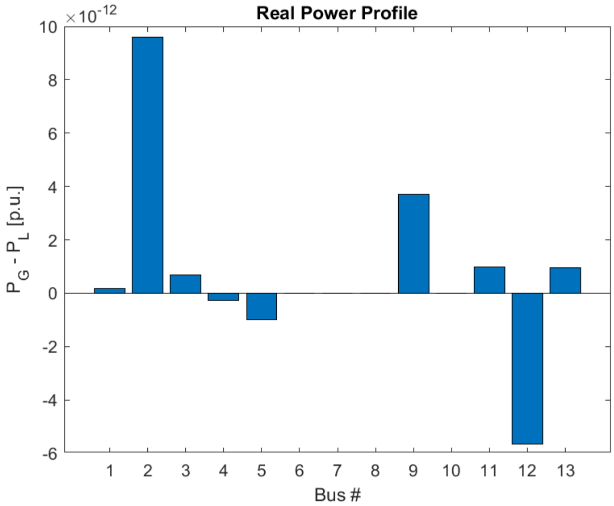

Figure 7: Real power profile of AREA 1 after decoupling from the existing grid

Urban centers demand high electricity consumption, while rural areas require reliable access. Interconnectors facilitate power exchange between regions, yet transmission constraints must be addressed. Reactive power dynamics play a vital role in voltage regulation, with capacitive and inductive loads influencing demand. Harnessing distributed energy resources can enhance voltage stability. Effective management of reactive power resources is crucial for grid resilience. As Nigeria navigates this transition, collaboration and innovation are key to unlocking the full potential of regionalization, ensuring sustainable energy access, and driving economic growth.

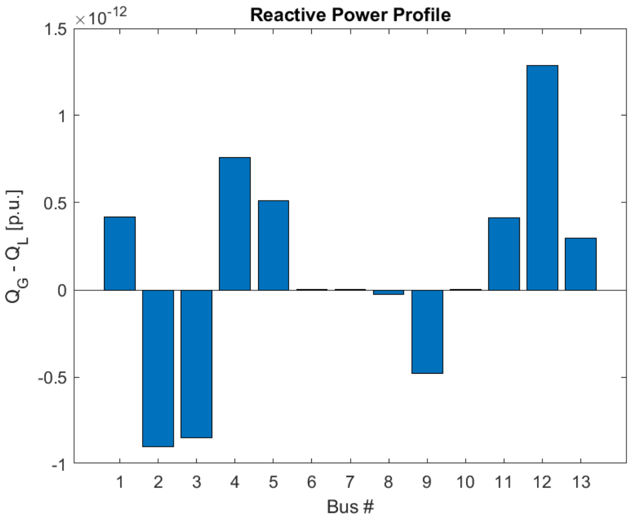

Figure 8: Reactive power profile of Area 1 after decoupling from the existing grid

3.4 Network Visualization

The network visualization of AREA 1 provides insight into the behavior of the power system, especially in regionalized centers. Data was collected and assessed to depict the behavior of the resulting AREA 1 energy system and compare it with the power system of the existing centralized grid. The analyses were conducted and presented in this paper, including line flow diagrams, voltage angles, and voltage magnitudes.

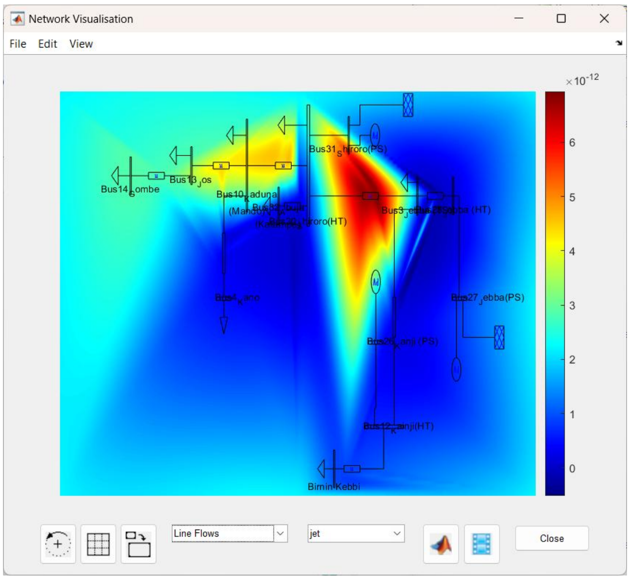

Figure 9: Line flow visualization of Area 1 after decoupling

The line flow diagram shows that at each bus in the respective substations along AREA 1 the decoupling process will not in any way alter the flow of energy across the grid including an assurance that the stability of the emerging sectors will be enhanced alongside the operation and observability.

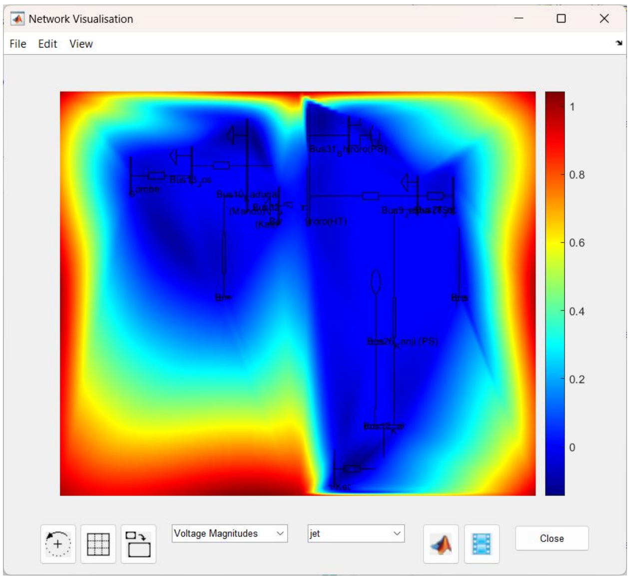

Figure 10: Voltage magnitude result of Area 1 after decoupling

In the case where load increase occurs, thereby threatening the overall operation of the grid, the regionalized layout can effectively conduct load shedding activities and observe the system for any eventual fault that may occur on the system. Consequently, the line stability means that the Nigerian Electricity Act 2023 once in practice can increase the observability and control of the power system network. Together with the results shown in Fig. 10 and Fig. 11, the decoupled AREAs are expected to still have the infrastructural ability to cooperate and function appropriately as a unit should any situation require it.

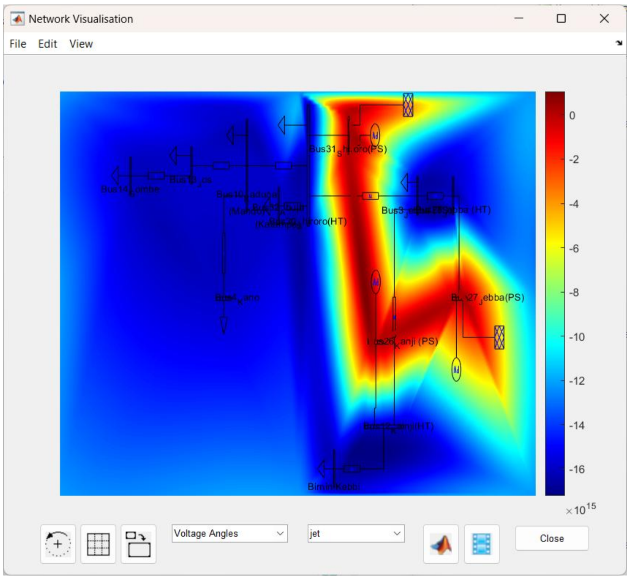

Figure 11: Voltage angle of Area 1 after decoupling

In Fig. 11, the PSAT result identified key areas where voltage angles were distorted due to decoupling but showed a consistent stability from the line diagram and the active station. At Bus 2, voltage angle results were within the 0.005 degree of the Nigerian power system without any effect on the stability. The results shown in Fig. 9, Fig. 10, and Fig. 11 lead to the conclusion that deregulation and decoupling of the Nigerian power system are required for more efficiency in energy delivery. The Nigerian Electricity Act of 2023, with its provisions, will surely guarantee the overall efficiency of the energy system and help address the endemic faults in the Nigerian power system infrastructure.

4.0 Conclusion

The study validated that regionalizing the Nigerian electricity grid, structured according to the former PHCN control zones, provides a technically sound path to implementing the 2023 Electricity Act. The analysis, focusing on Area 1 (Kainji to Gombe) in PSAT, demonstrated that the decoupled regional grid maintains robust voltage stability and power flow efficiency under normal operating conditions. Critically, the regionalized model significantly enhances system resilience, offering a mechanism for localized load management and, most importantly, fault isolation. By preventing the propagation of a major fault beyond the regional boundary, this framework directly addresses the issue of widespread national grid collapse. Implementing this model will foster a more efficient, resilient, and observable power system, ultimately driving sustainable energy delivery and economic growth.

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