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Power Transient Stability Assessment of the Benin-Onitsha-Alaoji 330 kV Transmission Line as a Case Study Using a Matlab/Simulink Model

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Abstract
Voltage collapse has become a recurring challenge in the Nigerian National Grid (NNG), primarily due to island formation caused by the switching out of critical buses. This paper evaluates the stability of the NNG with a focus on a critical transmission line that could lead to islanding following a fault occurrence. A MATLAB/SIMULINK model is developed to analyze both the steady-state and dynamic behavior of a critical bus within the network with the use of power systems stabilizer (Multiband precisely) designed by [6]. Simulations are conducted under various fault conditions, and the results are analyzed. Findings reveal that faults along transmission lines result in high reactive power flow and excessive current, which contribute to system instability. Additionally, the simulation results show non-sinusoidal waveforms, indicating the need for a significant level of compensation at the studied bus. The study specifically examines the Benin bus within the Benin–Onitsha–Alaoji 330 kV transmission corridor, given its strategic role in grid stability. The insights from this research highlight the importance of improving system protection, enhancing compensation strategies, and reinforcing critical transmission corridors to mitigate voltage collapse risks in the NNG.

Keywords: Nigerian National Grid, Voltage Collapse, Corridor, Critical Buses, Simulink Model

1. Introduction

Electricity is a fundamental pillar of economic growth, industrialization, and societal development, with stable supply driving productivity, investment, and quality of life, while unreliable supply hinders progress [1]. Despite vast energy resources, Nigeria continues to face inconsistent power supply due to inefficiencies in its aging and fragile grid, which suffers frequent collapses caused by systemic instability, poor automation, and inadequate redundancy. Since a complete grid overhaul is economically unfeasible, optimization through computational modeling and smart grid technologies offers a practical path forward.

2. Related Works

Over the years, several researchers have worked on the assessment of the power system especially the Nigerian National Grid (NNG), proposing various methods as well as possible improvements with the results they got. In response to the persistent fragility of Nigeria's power transmission network, largely due to inadequate investment in expansion programs, developed a transient stability model using ETAP to analyze fault scenarios on the Ikeja-West sub-network, demonstrating how dynamic stability studies can mitigate cascading outages and enhance the resilience and operational security of Nigeria's power grid [2]. It is worthy of note that conducted a transient stability assessment of Nigeria's 330 kV grid within the Benin regional control center, focusing on the impact of a three-phase fault along the Delta–Benin transmission line [3]. Using Artificial Neural Network (ANN) techniques, the study determined the critical clearing angle and circuit breaker clearing time. The results indicated significant impacts on Sapele, Delta, and Ihovbor generating stations, with post-fault bus voltages of 182.2 kV, 170.5 kV, and 173.1 kV, respectively. The authors emphasized the importance of transient stability studies in guiding effective planning and strengthening of the national grid by the Transmission Company of Nigeria (TCN) [4]. On the economic perspective, highlighted the critical role of electricity in national development, identifying grid instability as a major barrier to Nigeria's growth. Between 2000 and 2022, the national grid suffered 564 partial or total collapses, averaging 28 annually in the last 12 years, resulting in significant economic losses, including an estimated 1.97 million naira per minute in 2018. The study linked a 1% rise in outages in sub-Saharan Africa to a 2.86% GDP decline, underscoring losses of about US$28 billion, while Nigeria's heavy reliance on petrol generators further imposed US$23 billion in fuel costs annually alongside environmental and health risks. Specific incidents of multiple collapses in 2017, 2018, 2021, and 2022 were documented, with 2018 recording the highest load loss (2,138.55 MW). The authors attributed voltage collapse to systemic weaknesses and proposed remedial measures for improving grid reliability.

In the last 3 years, new methods have been proposed for transient stability assessment especially on the Benin bus. Adopted Newton-Raphson load flow and impedance matrix methods in Power World Simulator to assess loadability and contingencies in the Nigerian 330 kV grid [5]. By modeling key transmission routes and reinforcing overloaded lines, it identifies and mitigates line overloads to improve voltage stability, power quality, and prevent network congestion. In addition to this, study analyzed the stability of Nigeria's 330 kV grid network under the Benin Regional Control Centre, which oversees the South-South and South-East regions. Using the swing equation, equal area criterion, and modified Euler's method in ETAP 12.6, a three-phase fault was simulated 96 km along the Onitsha– Benin line [6]. Results showed system frequency remained within acceptable limits before the fault but deviated during the disturbance, causing voltage violations across major buses. The system regained stability when the fault was cleared at 1.210 s, but failure to clear it beyond this point would lead to loss of synchronism and system instability.

Finally, applied a Voltage Source Converter–High Voltage Direct Current (VSC-HVDC) system controlled by a proportional-integral (PI) method to improve the transient stability of Nigeria's 330 kV transmission network. Using MATLAB/PSAT for modeling and load flow analysis, critical buses such as Benin and the Ikeja West–Benin line were identified through eigenvalue and damping ratio assessments [7]. Simulations showed that the network loses synchronism under a balanced three-phase fault, confirming its instability. Installing VSC-HVDC on these critical lines significantly improved transient stability compared to the conventional system configuration.

By enabling detailed analyses of vulnerabilities, and assessing both transient and steady-state stability, this research aims to propose targeted improvements that enhance grid resilience, providing policymakers, engineers, and operators with data-driven strategies for ensuring a more reliable and sustainable Nigerian power supply.

3. Problem Statement

Despite decades of investment, Nigeria's power grid remains plagued by frequent collapses due to outdated frameworks, inadequate real-time control, and weak resilience against rising demand, renewable integration, and disturbances; traditional transient stability methods are too slow for real-time use, while limited adoption of advanced computational tools and poor public awareness further hinder effective fault detection, predictive analysis, and policy response.

4. Research Methodology

This research modeled the Benin–Onitsha–Alaoji 330 kV transmission line (which runs from Edo state, through Anambra state, to Abia State) in SIMULINK, with results displayed in MATLAB, and after completing the model, steady-state and dynamic state simulations were conducted to assess system responses; however, before presenting results, the underlying theoretical principles of the model are first explained.

A. Mathematical Modelling

- The Swing Equation [5]

Consider a generating unit consisting of a three-phase synchronous generator and its prime mover. The rotor motion is determined by Newton's second law, given by

$$\mathrm{J}\alpha_{\mathrm{m}}(\mathrm{t}) = \mathrm{T_m}(\mathrm{t}) - \mathrm{T_e}(\mathrm{t}) = \mathrm{T_a}(\mathrm{t}) \tag{1}$$

Where

- J = total moment of inertia of the rotating masses, kg•m^2
- α_m = mechanical torque supplied by the prime mover minus the retarding torque due to mechanical losses, N-m
- T_e = electrical torque that accounts for the total three-phase electrical power output of the generator, plus electrical losses, N-m
- T_a = net accelerating torque, N-m
- T_m and T_e are positive for generator operation. In steady state (as will be considered in the simulation), $T_m = T_e$, the accelerating torque, Ta = 0. Increasing rotor speed implies $T_m > T_e$ and hence $T_a > 0$ while for decreasing rotor speed, $T_m < T_e$ and hence $T_a < 0$.

The per-unit swing equation eventually yields the following equation:

$$\frac{2H}{\omega_{syn}}\omega_{p.u.}(t)\frac{d^2\delta(t)}{dt^2} = p_{mp.u.}(t) - p_{sp.u.}(t) - \frac{D}{\omega_{syn}\frac{d\delta(t)}{dt}} = P_{ap.u.}(t) \tag{2}$$

Where
- H = normalized inertia constant
- $\delta(t)$ = power angle
- $p_{mp.u.}$ = mechanical power supplied by the prime mover minus mechanical losses, per unit

– $p_{ep.u.}$ = electrical power output of the generator plus electrical losses, per unit.

It is important to note that when transient stability studies involving large-scale power systems with many generating units (which in this case was initially 4) are performed with a digital computer, computation time can be reduced by combining the swing equations of those units that swing together. Such units, which are called coherent machines, are usually connected to the same bus or are electrically close, and are usually remote from the disturbances of the network under study [8].

Since we have two synchronous machines, the swing equation, given that D = 0, is given as follows:

$$\frac{2(H_1+H_2)}{\omega_{syn}}\omega_{p.u.}(t)\frac{d^2\delta(t)}{dt^2} = p_{mp.u.}(t) - p_{ep.u.}(t) - D/\omega_{syn}\frac{d\delta(t)}{dt} = P_{ap.u.}(t) \tag{3}$$

For the two synchronous generators, $H_1 = H_2 = 3.7$, $D = 0$, $\omega_{p.u.}(t) = 1$ and $\omega_{syn} = 2\pi f = 2\pi \times 50 = 100\pi rads^{-1}$

The unique swing equation is thus given as:

$$\frac{37}{250\pi}\frac{d^2\delta(t)}{dt^2} = p_{mp.u.}(t) - p_{ep.u.}(t) = P_{ap.u.}(t) \tag{4}$$

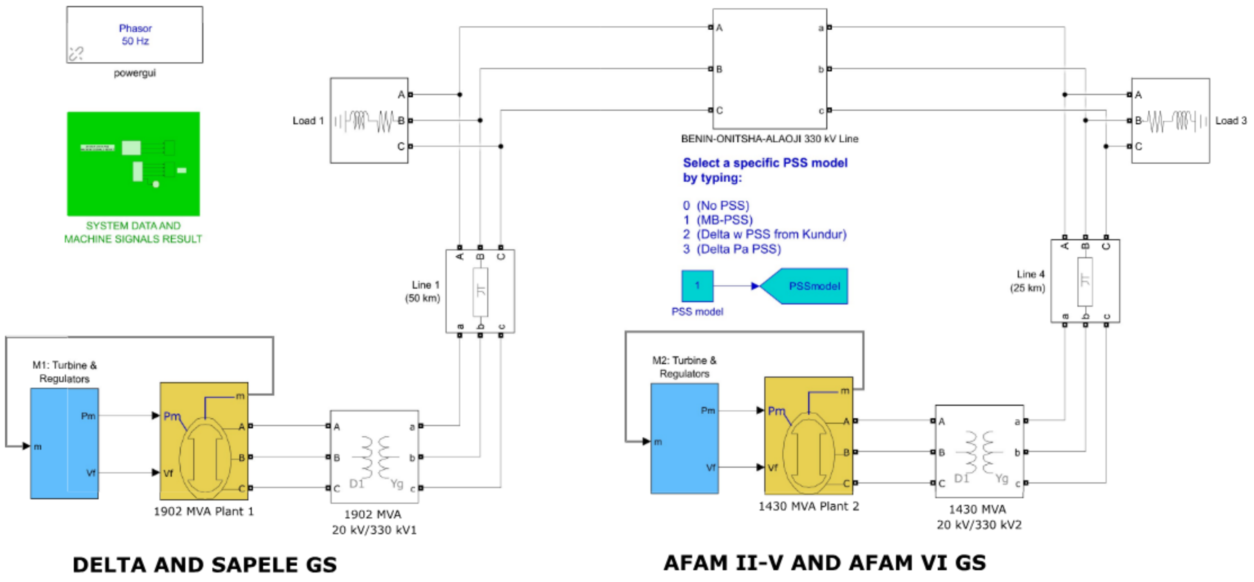


Figure 1: Matlab/Simulink model of Benin Onitsha-Alaoji 330-kV transmission line power system

- **The Equal-Area Criterion [5]**

Solving the derived equation eventually leads to:

$$\int_{\delta_0}^{\delta_1} \underbrace{(p_{m\text{p.u.}} - p_{e\text{p.u.}})d\delta}_{A_1} = \int_{\delta_1}^{\delta_2} \underbrace{(p_{e\text{p.u.}} - p_{m\text{p.u.}})d\delta}_{A_2} \tag{5}$$

B. System Modelling

The Benin–Onitsha–Alaoji 330 kV line, being a single-circuit corridor, lacks redundancy and is highly susceptible to faults that can disrupt power flow and endanger grid stability, unlike double-circuit lines that offer backup paths. The Benin bus, a key interconnection point linking all regions of the Nigerian grid, is especially sensitive to disturbances, making it a vulnerable node for fault propagation and voltage instability. Hence, this research carries out a transient stability assessment focused on the Benin bus, using generator, transformer, bus, and line data extracted from to build the equivalent network model in MATLAB/Simulink as shown below [8].

The model in fig 1 consists of two generating plants, one of 1902 MW and the second of 1430 MW operating at 12 kV line-to-line rating voltage. Plant 1 represents Delta and Sapele generating stations with installed capacity of 1902 MW and plant 2 represents Afam II-V and Afam VI generating stations with installed capacity of 1430 MW. Plant 1 is connected to Benin transmission station and plant 2 is connected to Alaoji transmission station.

The two plants work together to feed the Benin-Onitsha-Alaoji 330 kV transmission lines having the thermal capacity of 760 MVA [1]. Plant 1 and 2 are modelled with $P_{ref\,1} = 0.23922$ and $P_{ref\,2} = 0.26993$ to represent the equivalent power availability of the generating stations of 455 MW for plant 1 and 386 MW for plant 2.

C. Fault Scenario Modeling

The three-phase fault block model in Simulink was used to implement a fault (short-circuit) between any phase-to-ground. When the external switching time mode is selected, a Simulink logical signal is used to control the fault operation.

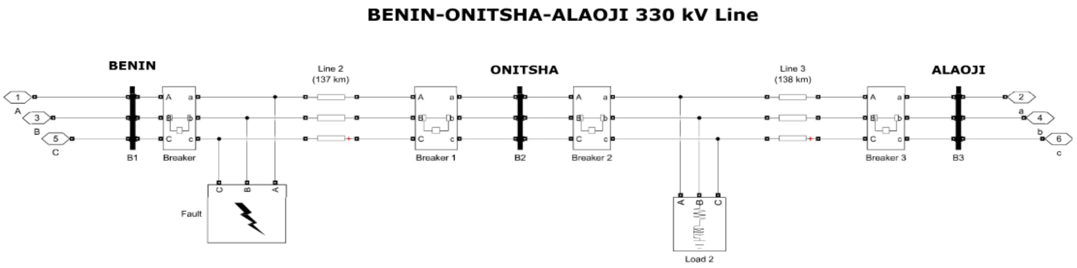
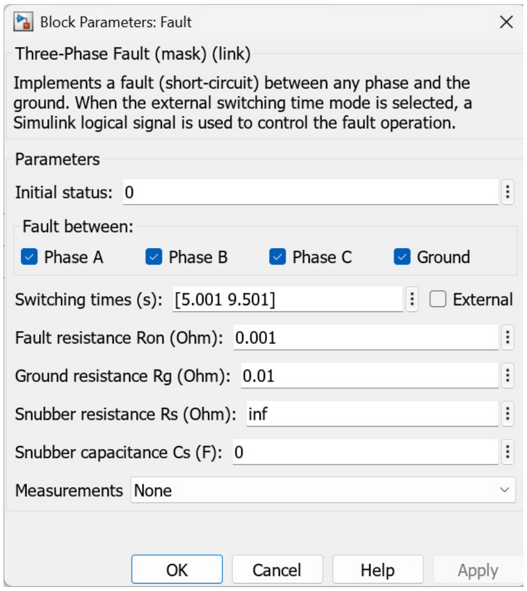


Figure 2: Matlab/Simulink model of Benin Onitsha-Alaoji 330-kV transmission line power system



Block Parameters: Fault

Three-Phase Fault (mask) (link)

Implements a fault (short-circuit) between any phase and the ground. When the external switching time mode is selected, a Simulink logical signal is used to control the fault operation.

Parameters

Initial status: 0

Fault between:

☑ Phase A ☑ Phase B ☑ Phase C ☑ Ground

Switching times (s): [5.001 9.501] ☐ External

Fault resistance Ron (Ohm): 0.001

Ground resistance Rg (Ohm): 0.01

Snubber resistance Rs (Ohm): inf

Snubber capacitance Cs (F): 0

Measurements None

Figure 3: The parameters in the three-phase fault block needed to be filled to simulate various types of faults

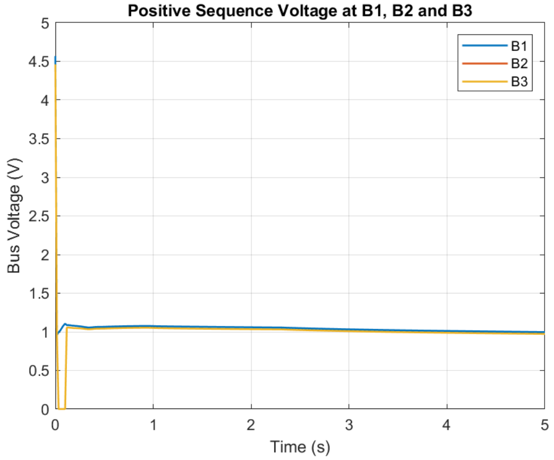


Figure 4: Steady-state graph for positive sequence voltage at bus 1, bus 2 and bus 3

5. Results and Discussion

The results for this research are in two phases, namely the steady-state stability, the dynamic stability, a proposed improvement to reduce the severity of faults.

A. Steady-State Stability

A steady-state simulation is carried out to analyze the typical power flow within the network, along withkeyoperationalparameterssu-chasbusvoltagesandpowerlevels(bothrealandreactivepower) [1].

Two generating stations supply power through transmission lines to serve the loads connected across three buses. The load demands are as follows: Bus 1 (B1) consumes 136 MW and 84 MVAR, Bus 2 (B2) draws 236 MW and 146 MVAR, while bus 3 (B3) requires 248 MW and 153 MVAR. The simulation model attained steady-state conditions within 5 seconds while the fault breaker remained inactive (off-mode). The results obtained from the steady state simulation is tabulated in table 2. Figure 4.1, 4.2 and 4.3 show the steady-state stability waveforms for bus voltages, active and reactive power at the various buses.

Bus Name	bus No	Voltage (p.u)	P (MW)	Q (MVAR)
Benin	1	0.9972	197.1	80.03
Onitsha	2	0.9733	194.6	131.4
Alaoji	3	0.9733	-28.74	50.4

Table 1: Steady-State Simulation Results

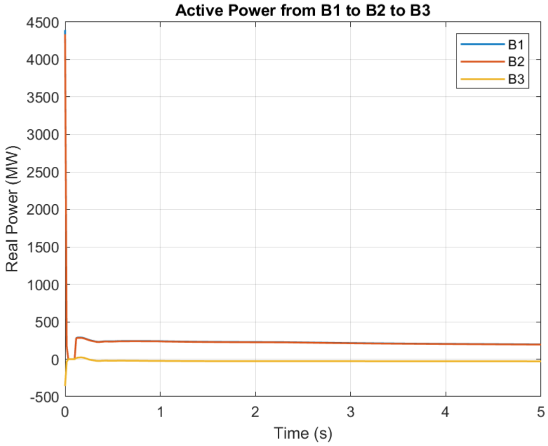


Figure 5: Steady-state graph for positive sequence active power at bus 1, bus 2 and bus 3

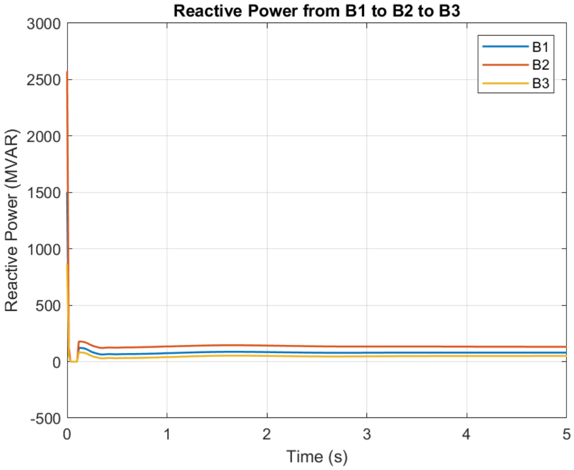


Figure 6: Steady-state graph for positive sequence reactive power at bus 1, bus 2 and bus 3

The graphs for the bus voltages, real power and reactive power maintained steady values as there was no disturbance in terms of faults. In cases where either of the blue or red line were not clearly seen, it does not imply that they are zero but that two buses maintained similar values as can be seen in figure 4 and 5. Table 1 shows the steady state values for all of them and implies the system maintained steady-state stability, with the per unit voltage close to each other.

B. Dynamic Stability

The dynamic state simulation was performed using the same model, this timetabling fault breaker to simulate various fault scenarios at the three buses. The fault types considered include single line to-ground fault, double line-to-ground fault, three-phase-to-ground fault, line-to-line short circuit, and sudden loss of generation from one of the plants. These fault conditions were introduced to assess and analyze system collapse behavior under different disturbances. The total simulation time was set to 20 seconds, with faultsinitiatedatthe5-secondmark(5.001s) and lasting for 2seconds. Thisduration was chosen based on the characteristics of the numerical solver used (ode23tb), as a 20-second window provides a comprehensive view of the dynamic response of the system. Shorter simulations would not adequately capture the system behavior before fault clearance. After the fault is cleared by the breakers, automatic reclosure of the affected lines is triggered 5 seconds later.

Table 2 below summarizes the responses of the system to various forms of disturbance that can be introduced to a power system. The graph for each of the disturbances follows.

Fault Type	Bus	Voltage (p.u.)	P (MW)	Q (MVAR)
Single Line-to-Ground	1	0.6753	131.1	96.63
	2	0.6851	111.5	79.16
	3	0.6851	−33.28	25.20
Line-to-Line Short Circuit	1	0.5531	282.4	86.29
	2	0.5952	247.6	32.36
	3	0.5952	111.9	−18.09
Double Line-to-Ground	1	0.4014	130.5	32.77
	2	0.4676	90.39	−50.47
	3	0.4676	−10.37	−88.68
Three Phase-to-Ground	1	0.000762	5.823	0.01922
	2	0.1541	−59.68	−158.9
	3	0.1541	−67.41	−159.3

Sudden Drop in Gen. Station	1	0.9794	0.1001	−0.082 79
	2	0.7743	−0.1007	35.81
	3	0.7743	−141.7	−13.42

Table 2: Dynamic State Simulation Results at The Point of Fault Clearing

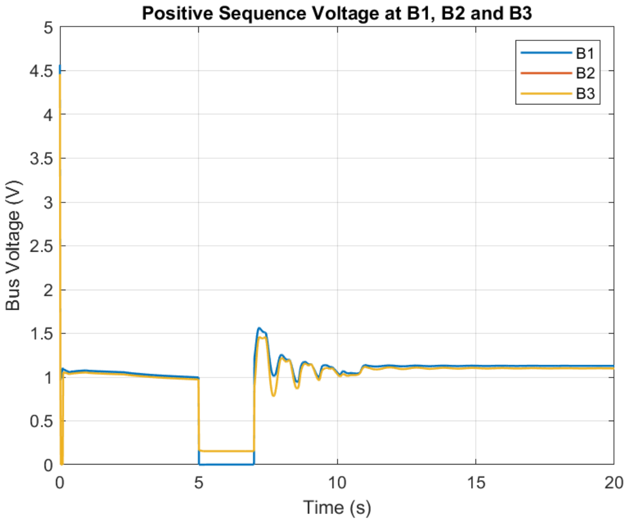


Figure 7: Three Phase-to-Ground fault waveforms for positive sequence voltage at bus 1, bus 2 and bus 3

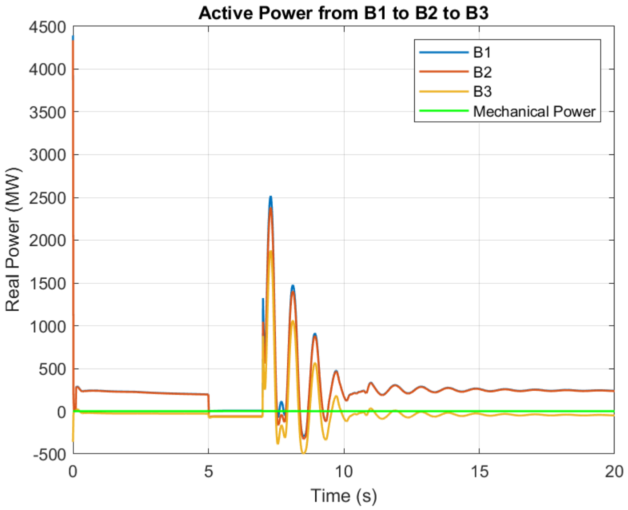


Figure 8: Three Phase-to-Ground fault waveforms for positive sequence Active Power at bus 1, bus 2 and bus 3

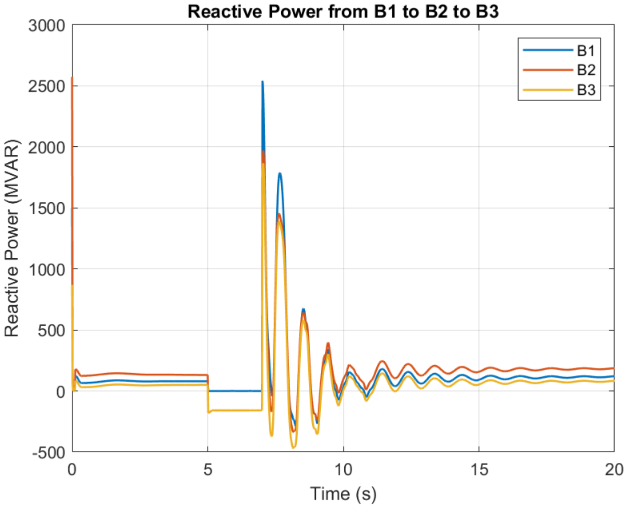


Figure 9: Three Phase-to-Ground fault waveforms for positive sequence Reactive Power at bus 1, bus 2 and bus 3.

6. Discussion

The simulation results for both steady-state and dynamic fault analyses of the Benin–Onitsha–Alaoji 330 kV transmission line within the Nigerian National Grid (NNG) have been thoroughly examined.

A. Steady-State fault Analysis

Based on the steady-state simulation results in table 1, the bus voltages are very close to the nominal value of 1.0 p.u. In addition, the active and reactive power values tell us that the transmission lines and other equipment are not heavily overloaded.

In addition to this, the negative value of power in bus 3 of Alaoji implies that the flow of active power is in the opposite direction, that is, from Afam II-V to Delta and Sapele Generating station. Finally, it is not a coincidence that the Benin bus (B1) has the highest active power of the three buses. This is because it is closer to the Delta-Sapele generating plant which is of higher capacity compared to Afam II-V generating station.

B. Dynamic-State fault Analysis.

For the simulation results in table 2, it was observed that the single line-to-ground fault had the highest bus voltage in bus 2 and 3 with a value of 0.6851 p.u while the three phase-to-ground fault had the lowest bus voltage of 7.62e-4 p.u. The implication of this is that single line-to-ground fault is the least severe type of fault while the three phase-to-ground fault is the severest of fault that must be cleared as quick as possible because of the damage it can cause to the equipment. In fact, further simulations stated that the critical clearing time, tcr, is about 4.5 seconds and any second after that causes a power system collapse of the grid network under study. This result was compared to the conclusion made in [4] and it was realised that with the incorporation of the multi-band power system stabilizer to assess the Benin-Onitsha-Alaoji line, it offered a better critical clearing time and more room for the breakers to act both for both the primary and back-up.

In addition to this, it was observed that a sudden drop in generation (in this case is the Delta-Sapele generating station) had the bus voltage values close to the nominal values but the active and reactive power were really small. The following need to be taken note of:

- Load 3 is rated at 248 MW active power and 153 MVAR reactive power
- The capacity of Afam II-V Generating Station (GS) is 386 MW

With the consideration of losses along the line and other parameters not accounted for, load 3 consumed a bulk of the active power generated by Afam II-V GS and leaving crumbs for the remaining loads to consume as reflected in low active power values in table 2.

The highest active power, 282.4 MW was observed during the line-to-line short circuit fault. This was because the fault created a low-impedance path between two phases, causing a surge in fault current while line-to-line voltage remained relatively stable (up to 0.5962 p.u). With active power being a product of voltage, current and power factor, the large current leads to a spike in calculated power, even though it is not useful load power but energy flowing into the fault.

7. Conclusion

This research assessed the power transient stability of the Benin-Onitsha-Alaoji 330 kV network as a case study. The assessment done so far involved the simulation of various forms of fault that could occur in a power system network.

At the end of the analysis, it was observed that the severest of the fault that could happen to a power system is the three phase-to-ground faults (temporary or bolted). Furthermore, a bolted three phaseto-ground fault would eventually collapse the Nigeria National grid because it would last longer than the critical clearing time, tcr, whose value was gotten to be approximately 4.5 seconds.

To this end, it can be said that the objectives and aim of this study have been achieved [9,10]. For a better, improved and reliable system, more improved methods can be incorporated and will be recommended in the next section.

Recommendations

Based on the deductions from the assessment of the modeled grid network of the Benin-OnitshaAlaoji 330 kV line, there is a pressing need for sustained investment in expanding and modernizing Nigeria's transmission infrastructure, especially in stability-critical corridors like the Benin–Onitsha– Alaoji line. To enhance resilience, the system should adopt adaptive protection schemes, fast-acting control mechanisms, and ensure scheduled maintenance of critical breakers, particularly those near bus 2, which play a vital role in maintaining grid stability during disturbances.

In addition, transmission operators should institutionalize regular transient stability studies using advanced tools like ETAP and MATLAB/Simulink, reflecting evolving load profiles, new generators, and infrastructure upgrades. Continuous professional training for engineers and operators in dynamic stability and fault analysis, alongside stricter regulatory standards mandating stability compliance before commissioning new network components, will further strengthen the reliability and security of Nigeria's power grid.

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