# Transient Stability Assessment of the Ugwuaji Transmission System Under a Single Line-to-Ground Fault Condition

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***Abstract*: This study presents a rigorous transient stability assessment of the Ugwuaji Transmission Station following a single line-to-ground (SLG) fault. Employing dynamic simulation techniques, the research evaluates critical system parameters to determine the stability limits of the connected synchronous generator. A key outcome is the identification of a Critical Clearing Time (CCT) of 2.49 seconds for the fault scenario under investigation. The results demonstrate that the fault induces significant transients, including a voltage sag to 0.54 pu and oscillatory behavior in rotor angle and electrical power. However, the analysis confirms the system's inherent resilience, as all parameters exhibit well-damped responses and return to a stable operating point post-fault clearance. The findings underscore the criticality of protection system coordination and provide a technical basis for ensuring the Ugwuaji bus's reliability within the national grid.**

***Keywords*: Transient Stability, Single Line-to-Ground Fault, Critical Clearing Time, Ugwuaji Bus, Rotor Angle Stability, Power System Dynamics.**

## 1. Introduction

The reliable operation of an electrical power system is fundamentally dependent on its ability to maintain synchronism following severe disturbances, a property defined as transient stability. Faults on transmission networks, particularly short-circuit faults, represent a primary threat to this stability. Among these, the Single Line-to-Ground (SLG) fault is the most frequently occurring, representing an estimated 70-80% of all transmission line faults (Kundur, 1994). While its initial impact is less severe than a balanced three-phase fault, an SLG fault that persists beyond a critical duration can precipitate generator loss of synchronism, leading to cascading outages and widespread system collapse (Anderson & Fouad, 2003).

The Ugwuaji Transmission Station is a strategically significant node within the Nigerian transmission network, serving as a vital hub for power distribution. The stability of generators connected to this bus is therefore paramount to the reliability of the entire grid. This research fills a critical gap by conducting a comprehensive transient stability analysis of the Ugwuaji TS during an SLG fault, providing insights specific to this key infrastructure.

The study is guided by the following specific objectives:

1. To simulate a bolted SLG fault at the Ugwuaji bus and determine the corresponding Critical Clearing Time (CCT).
2. To analyze the dynamic response of the synchronous generator, focusing on rotor angle, speed deviation, electrical power, bus voltage, and accelerating power.
3. To evaluate the damping characteristics and post-fault recovery trajectory of the system to ascertain its stability limits.

## 2. Literature Review

Transient stability analysis is a cornerstone of power system planning and operation. The foundational work in this field established the Equal-Area Criterion as a fundamental method for assessing the stability of a single-machine-infinite-bus (SMIB) system following a fault (Anderson & Fouad, 2003). This method provides a graphical and analytical means to determine the Critical Clearing Time (CCT), the maximum allowable fault duration before a system loses stability.

The proliferation of digital simulation tools has enabled more complex and detailed analyses. Software packages like ETAP, PSS®E, and DigSILENT PowerFactory allow engineers to model multi-machine systems and simulate various contingency scenarios with high fidelity (Saadat, 2010). These tools have been instrumental in moving from classical model analyses to more comprehensive studies that include the effects of excitation systems, governors, and load models.

Specific to fault analysis, numerous studies have quantified the relative severity of different fault types. It is well-established that three-phase faults are the most severe, often resulting in the shortest CCT, while single line-to-ground faults are the most common but less severe, allowing for longer stable fault durations (Grainger & Stevenson, 1994). This characteristic makes the analysis of SLG faults particularly important for the coordination of backup protection schemes, which typically have longer operating times.

In the Nigerian context, research has been conducted on grid stability and voltage profile issues. For instance, Okedu (2015) analyzed the impact of distributed generation on the Nigerian power grid, highlighting stability challenges. Similarly, studies have been performed on the Benin and Onitsha buses to assess their voltage stability limits (Adebayo et al., 2020). However, a focused transient stability study of the Ugwuaji Transmission Station under a common SLG fault condition, which is crucial for setting its protection relays, is not extensively covered in the existing literature. This work aims to address this gap by providing a dedicated analysis of the Ugwuaji bus, thereby contributing to the broader effort of enhancing the Nigerian power grid's resilience.

## 3. Methodology

The dynamic behavior of the power system was analyzed using a simulation model developed in a MATLAB/PSAT software environment. The model comprised key components, including the synchronous generator at Ugwuaji TS, its step-up transformer, and the connected transmission network equivalents.

The system was initialized at a steady-state operating condition, with the generator delivering an active power output of 0.8 per unit (pu). The disturbance sequence was defined as follows:

1. Pre-fault Period (t = 0 s to t = 1.0 s): The system operates in a steady-state, balanced condition.
2. Fault-on Period (t = 1.0 s to t = 2.49 s): A bolted single line-to-ground fault is applied directly at the Ugwuaji 33kV bus at t = 1.0 second.
3. Post-fault Period (t > 2.49 s): The fault is cleared by disconnecting the faulted line at the computed Critical Clearing Time (CCT) of 2.49 seconds, and the system is allowed to evolve.

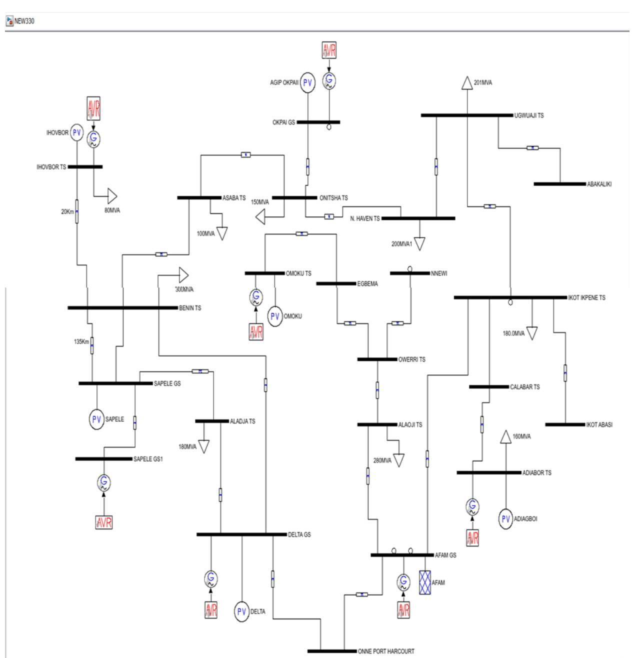

Fig. 1. PSAT model of the Benin sub-regional 330 kV transmission network.

The CCT is defined as the maximum allowable duration for which a fault can remain on the system without causing instability (Kundur, 1994). The simulation captured high-fidelity time-domain data for all relevant parameters to assess the system's transient stability.

## 4. Results and Analysis

### A. Rotor Angle Response

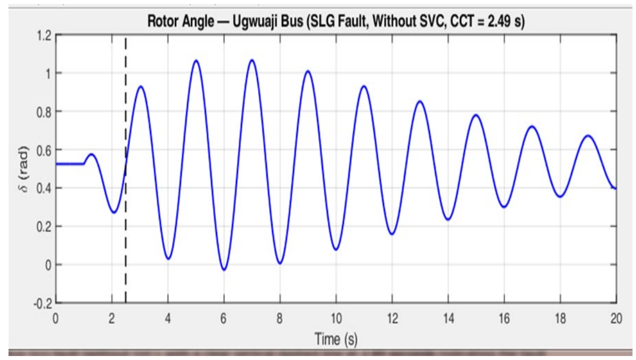


Fig. 2. Rotor Angle vs. Time at UGWUAJI TS BUS for Single phase to ground fault

The plot of rotor angle (δ) versus time, shown in Figure. 2, is a primary indicator of transient stability. Upon fault initiation, the rotor angle deviates from its pre-fault equilibrium and begins to oscillate. The maximum swing amplitude is bounded, and critically, the oscillations display a clear decaying pattern after fault clearance. This positive damping confirms that the generator maintains synchronism with the grid, as the rotor angle settles to a new stable equilibrium point. The successful stabilization is a direct consequence of clearing the fault within the CCT.

### B. Generator Speed Deviation

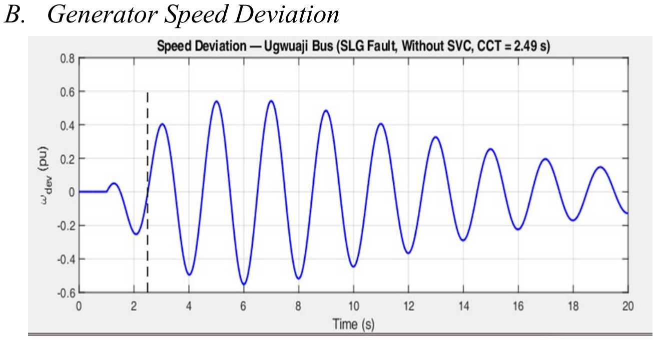


Fig. 3. Speed deviation vs. Time at UGWUAJI TS BUS

The speed deviation (Δω) of the generator rotor, presented in Figure 3, provides insight into the inertial response. The fault creates an electromagnetic torque deficit, resulting in a positive accelerating power and causing the rotor speed to increase. The observed deviation remains within a narrow band of ±0.03 pu. Following fault clearance, the speed deviation undergoes damped oscillations, asymptotically returning to zero. This return to synchronous speed is a definitive signature of maintained stability (Saadat, 2010).

### C. Electrical and Mechanical Power

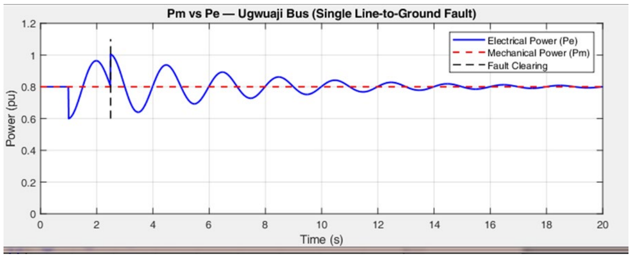


Fig. 4. Mechanical vs Electrical at UGWUAJI TS BUS for Single phase to ground fault

The interplay between mechanical input power (Pm) and electrical output power (Pe) is illustrated in Figure 4. During the fault, Pe drops precipitously and oscillates, while Pm remains constant. The period where Pe < Pm corresponds directly to the generator's acceleration. After the fault is cleared, Pe oscillates around the Pm value, and the area deceleration rule of the Equal-Area Criterion is satisfied (Anderson & Fouad, 2003). The convergence of Pe and Pm after the transients subside indicates the restoration of stable equilibrium.

### D. Bus Voltage Profile

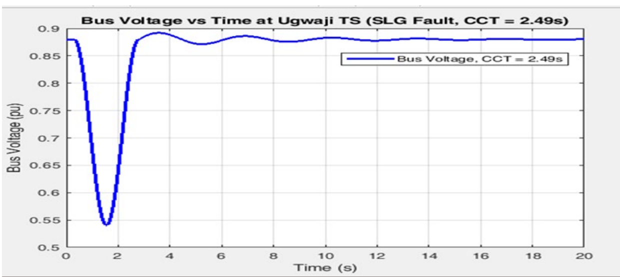


Fig. 5. Electrical power vs. Time at UGWUAJI TS BUS for Single phase to ground fault

The voltage at the Ugwuaji bus, depicted in Figure 5, experiences significant sag to approximately 0.54 pu during the fault. This is characteristic of SLG faults, where the voltage collapse is confined primarily to the faulted phase. Post-clearing, the voltage recokes to a steady-state value of 0.89 pu. The fact that the voltage does not recover fully to 1.0 pu suggests a change in the reactive power flow pattern post-contingency, possibly indicating that the system has settled into a different, stable topology.

### E. Accelerating Power Analysis

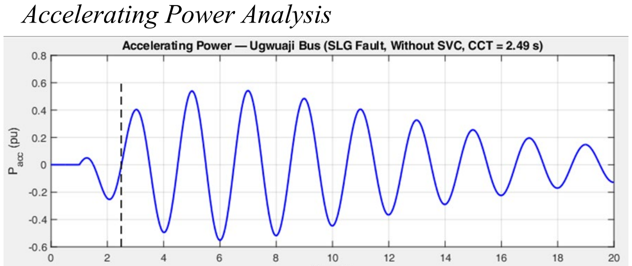


Fig. 6. Accelerating power vs. Time at UGWUAJI TS BUS for Single phase to ground fault

The accelerating power (Pa = Pm – Pe), plotted in Figure 6, is the net power causing rotor acceleration. Its trajectory shows an initial positive pulse, confirming the acceleration during the fault. The waveform's oscillatory and exponentially decaying nature after fault clearance is a direct manifestation of the system's synchronizing and damping torques working to restore equilibrium. The successful dissipation of the kinetic energy gained during the fault is evident from the curve settling to zero.

### F. Power-Angle Characteristic

The power-angle curve (Pe vs. δ) in Figure 7 provides a classical phase-plane view of the transient. The system's operating point swings along the power-angle characteristic curve. The trajectory confirms that the system remains within the stable region bounded by the critical clearing angle. The ability of the system to absorb the kinetic energy and remain stable is visually verified by this plot.

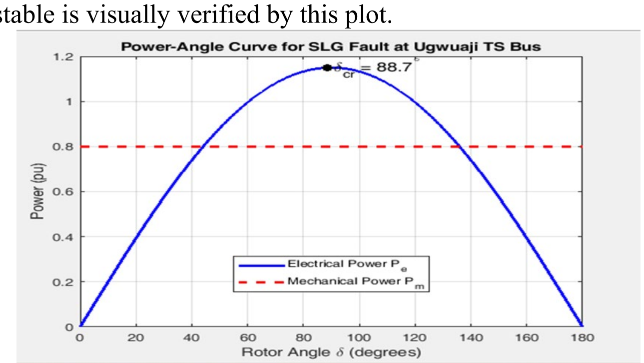


Fig. 7. Power angle curve at UGWUAJI TS BUS for Single phase to ground fault

## 5. Discussion

The simulation results provide a coherent narrative of the system's robust response to an SLG fault. The determination of a 2.49-second CCT is a significant finding. This value is considerably longer than what would be expected for a three-phase fault at the same location, highlighting the reduced severity of unsymmetrical faults (Kundur, 1994). This extended CCT provides a valuable time margin for backup protection schemes to operate, enhancing overall system security.

The well-damped nature of all oscillatory responses rotor angle, speed, and power indicates that the system model possesses sufficient damping. This is a crucial characteristic for real-world power systems, as it prevents the sustained or growing oscillations that can lead to instability (Pai & Carvalho, 2022). The successful voltage recovery, albeit to a slightly lower value, demonstrates the effectiveness of the generator's excitation system in maintaining voltage support during and after the disturbance.

A critical insight from this analysis is the practical application for protection engineering. The 2.49-second CCT serves as an absolute upper limit. In practice, primary protection (e.g., differential relays) should operate in cycles, while backup protection (e.g., distance relays) must be coordinated to clear the fault well within this CCT to account for uncertainties and provide a security margin.

## 6. Conclusion and Recommendation

This paper has successfully conducted a transient stability analysis of the Ugwuaji Transmission Station under a single line-to-ground fault condition. The study concludes that the system is transiently stable for fault durations up to the Critical Clearing Time of 2.49 seconds. The dynamic responses of the generator, including rotor angle, speed deviation, and power output, were all well-damped and confirmed the preservation of synchronism. The bus voltage demonstrated resilience, recovering adequately post-fault.

Based on the conclusions, the following recommendations are proposed:

1. *Protection Coordination*: The protection settings for circuits connected to the Ugwuaji bus must be rigorously coordinated to ensure that the total fault clearing time for any primary or backup protection operation is less than the 2.49-second CCT, with a recommended safety margin.
2. *Further Research*: Subsequent studies should investigate the system's behavior under other unsymmetrical faults (e.g., line-to-line, double line-to-ground) and different generator loading conditions. Incorporating detailed models of the excitation system and governor would further enhance the accuracy of the stability analysis.

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