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# Dynamic Response Assessment of the Nigerian 330kV Transmission System

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## ABSTRACT

This paper presents the dynamic responses of generators in a multi-machine power system. The fundamental swing equations for a multi-machine stability analysis are revisited. The swing equations are solved to investigate the influence of a three-phase fault on the network largest load bus. The Nigerian 330kV transmission network was used as a test case for the study. The time domain simulation approach was explored to determine if the system could withstand a 3-phase fault. The stability of the transmission network is estimated considering the dynamic behaviour of the system under various contingency conditions. This study identifies Egbin, Benin, Olorunsogo, Akangba, Sakete, Omotosho and Oshogbo as the key buses within the network, which could provide useful information when a three-phase fault occurs on Ikeja-West (Bus with the largest load). The results obtained also show that the system loses synchronism immediately a three-phase fault was simulated on the largest load bus, considering various contingencies with the generator at Geregu being the most severely disturbed generator.

**Key Words:** Transient stability, Critical clearing time, Nigerian 330kV transmission network, Swing equation, Disturbances, Dynamic responses.

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## 1. INTRODUCTION

The quest for providing a reliable and uninterruptible power supply to loads have resulted in the complexity of power system networks. Consequently, this increase in complexity of power network increases fault current and may lead to system instability if not properly managed and quickly controlled **(Phadke, et al., 2016).** One of the possible ways to avert system instability or to maintain the integrity of a power system network is to keep the synchronous generators in synchronism **(Fetissi, et al., 2015).** There is therefore the need to assess the dynamic responses of the generators in the event of a disturbance or fault. Transient stability assessment study is used in describing the dynamic responses of a synchronous generator in a power system network **(Xia, et al., 2018).** Transient stability refers to the ability of the network to remain stable even when subjected to a large disturbance such as 3-ϕ fault, sudden removal or addition of network elements such as loads or transmission line **(Gajduk, et al., 2014).**

One of the important derivatives of transient stability is Critical Clearing Time (CCT), which is a very significant factor for maintaining stability of a power network. CCT is defined as the highest allowable time limit that a fault must be cleared; hence, the system will lose synchronism **(Ayodele, et al., 2016).** The value of CCT of a power system network is obtained by gradual increase in fault clearing time, until the system loses its stability. Recent literatures have shown that the Nigerian 330kV transmission network is faced with various degrees of instability due to its structural characteristics **(Shereefdeen, et al., 2016; Oluseyi, et al., 2017).** The recovery of the Nigerian 330kV transmission network has been subjected to large disturbance, which has been a major problem to the System operators and Planners. This study, therefore aims at assessing the dynamic responses of the Nigerian 330kV transmission network by simulating a 3-Phase fault on the bus with the largest load at Ikeja-West.

## 2. STUDY SYSTEM

In this paper, the single-line diagram of the Nigerian 330kV transmission network used as the test system is as shown in **Fig.1.** It comprises of eleven (11) generators, thirty-six (36) transmission lines and twenty-one (21) load buses. The swing generator is the largest generator (Egbin) and the fault location is the bus with the Largest load (Ikeja-West). From **Fig.1**, there are seven (7) lines that could cause disturbance on the largest bus this includes Ikeja West-Egbin, Ikeja West-Benin, Ikeja West-Akangba, Ikeja West-Sakete, Ikeja West-Olorunsogo GS, Ikeja West-Omotosho and Ikeja West-Oshogbo.

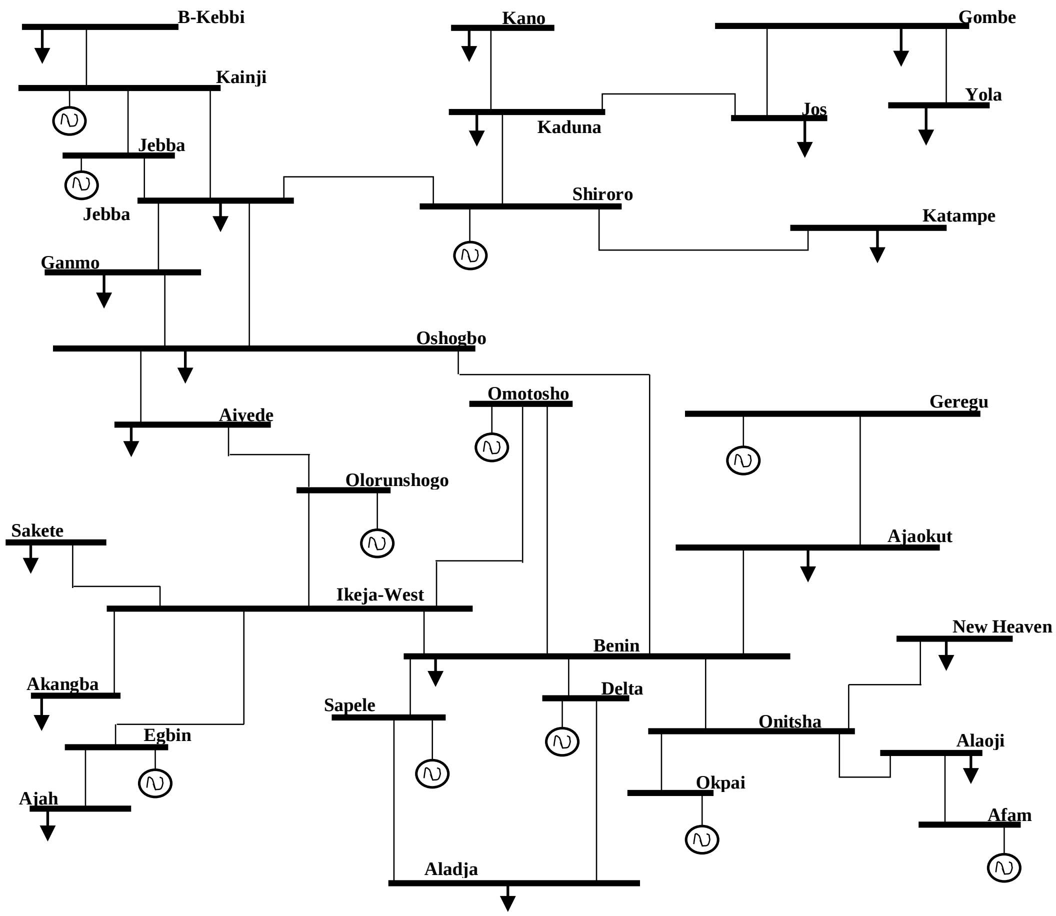


**Figure 1.** Single-line diagram of the Nigerian 330kV transmission system.

**Table 1.** Generation Parameters.

| Bus No | Bus Name | Pmax (MW) | Qmax (MW) | Qmin (MW) |
|---|---|---|---|---|
| 1 | Egbin G.S | Slack Bus | Slack Bus | Slack Bus |
| 7 | Olorunshogo G.S | 335 | 184 | -120 |
| 8 | Omotosho G.S | 335 | 184 | -120 |
| 11 | Shiroro G.S | 600 | 316 | -60 |
| 13 | Jebba G.S | 590 | 284.4 | -180 |
| 15 | Kainji G.S | 760 | 246.8 | -240 |
| 23 | Geregu G.S | 414 | 255 | -135 |
| 27 | Sapele G.S | 960 | 523 | -300 |
| 28 | Delta G.S | 900 | 504 | -288 |
| 29 | Okpai G.S | 480 | 238.8 | -150 |
| 30 | Afam G.S | 681 | 648 | -390 |

**Table 2.** Load Bus Parameters.

| | | Maximum Load Demand | | Minimum Load Demand | |
|---|---|---|---|---|---|
| **Bus No** | **Bus Name** | **MW** | **Mvar** | **MW** | **Mvar** |
| 2 | Benin | 298 | 144(+75) | 188 | 91 |
| 3 | Ikeja West | 510 | 246(+75) | 321 | 155 |
| 4 | Akangba | 471 | 228 | 297 | 144 |
| 5 | Sakete | 145 | 70 | 91 | 44 |
| 6 | Aiyede | 270 | 130 | 170 | 82 |
| 9 | Oshogbo | 235 | 114(+75) | 148 | 72 |
| 10 | Ganmo | 270 | 130 | 170 | 82 |
| 12 | Jebba T.S | 412 | 199(+150) | 260 | 125 |
| 14 | Birnin Kebbi | 112 | 54(+30) | 71 | 34 |
| 16 | Kano | 250 | 121(+75) | 157 | 76 |
| 17 | Kaduna | 275 | 133(+75) | 173 | 84 |
| 18 | Jos | 141 | 68 | 89 | 43 |
| 19 | Gombe | 180 | 87(+100) | 113 | 55 |
| 20 | Yola | 112 | 54 | 71 | 34 |
| 21 | Katampe | 300 | 127 | 189 | 62 |
| 22 | Ajaokuta | 96 | 46 | 60 | 29 |
| 24 | Onitsha | 162 | 76 | 102 | 48 |
| 25 | Alaoji | 266 | 124 | 167 | 78 |
| 26 | New Haven | 235 | 110 | 148 | 69 |
| 31 | Aja | 220 | 103 | 139 | 65 |
| 32 | Aladja | 167 | 81 | 105 | 51 |

**Table 3.** Parameters of Transmission Line.

| S/N | Transmission line | | Length | Impedance | | Shunt Admittance |
|---|---|---|---|---|---|---|
| | **From Bus** | **To Bus** | **(km)** | **Resistance (p.u)** | **Inductance (p.u)** | **1/2 B (p.u)** |
| L1 | 1 | 3 | 62.00 | 0.001122 | 0.008630 | 0.064350 |
| L2 | 1 | 31 | 14.00 | 0.000253 | 0.001950 | 0.014530 |
| L3 | 2 | 3 | 280.00 | 0.005070 | 0.038953 | 0.290590 |
| L4 | 2 | 8 | 51.00 | 0.001830 | 0.015501 | 0.096920 |
| L5 | 2 | 9 | 251.00 | 0.008990 | 0.076291 | 0.476980 |
| L6 | 2 | 22 | 195.00 | 0.003490 | 0.029640 | 0.185280 |
| L7 | 2 | 24 | 137.00 | 0.002450 | 0.020820 | 0.130171 |
| L8 | 2 | 27 | 50.00 | 0.000910 | 0.006960 | 0.051900 |

| | | | | | | |
|---|---|---|---|---|---|---|
| L9 | 2 | 28 | 41.00 | 0.001470 | 0.012462 | 0.077913 |
| L10 | 3 | 4 | 17.00 | 0.000304 | 0.002584 | 0.016053 |
| L11 | 3 | 5 | 70.00 | 0.002510 | 0.021280 | 0.133021 |
| L12 | 3 | 7 | 30.00 | 0.001074 | 0.009120 | 0.057010 |
| L13 | 3 | 8 | 200.00 | 0.007163 | 0.060790 | 0.380061 |
| L14 | 3 | 9 | 250.00 | 0.008953 | 0.075990 | 0.475080 |
| L15 | 6 | 7 | 60.00 | 0.002150 | 0.018240 | 0.114020 |
| L16 | 6 | 9 | 115.00 | 0.004120 | 0.034954 | 0.218540 |
| L17 | 9 | 10 | 75.00 | 0.002690 | 0.022800 | 0.142523 |
| L18 | 9 | 12 | 157.00 | 0.002811 | 0.023860 | 0.149174 |
| L19 | 10 | 12 | 80.00 | 0.002870 | 0.024320 | 0.152030 |
| L20 | 11 | 12 | 244.00 | 0.004370 | 0.037082 | 0.231840 |
| L21 | 11 | 17 | 96.00 | 0.001720 | 0.014590 | 0.091220 |
| L22 | 11 | 21 | 218.00 | 0.003944 | 0.030330 | 0.226244 |
| L23 | 12 | 13 | 8.00 | 0.000150 | 0.001113 | 0.008303 |
| L24 | 12 | 15 | 81.00 | 0.001450 | 0.012310 | 0.076962 |
| L25 | 14 | 15 | 310.00 | 0.005551 | 0.047112 | 0.589095 |
| L26 | 16 | 17 | 230.00 | 0.004120 | 0.034954 | 0.437070 |
| L27 | 17 | 18 | 196.00 | 0.003510 | 0.029790 | 0.372460 |
| L28 | 18 | 19 | 264.00 | 0.004730 | 0.040121 | 0.501681 |
| L29 | 19 | 20 | 240.00 | 0.004300 | 0.036474 | 0.456074 |
| L30 | 22 | 23 | 1.00 | 0.000020 | 0.000140 | 0.001040 |
| L31 | 24 | 25 | 138.00 | 0.004942 | 0.041945 | 0.262242 |
| L32 | 24 | 26 | 96.00 | 0.003440 | 0.029180 | 0.182430 |
| L33 | 24 | 29 | 60.00 | 0.001090 | 0.008350 | 0.062270 |
| L34 | 25 | 30 | 25.00 | 0.000452 | 0.003480 | 0.025950 |
| L35 | 27 | 32 | 63.00 | 0.002260 | 0.019150 | 0.119720 |
| L36 | 28 | 32 | 32.00 | 0.001146 | 0.009726 | 0.06081 |

## 3. MATHEMATICAL MODELLING

For an *N*-bus power system with *m*-generators as shown in **Fig. 2.**

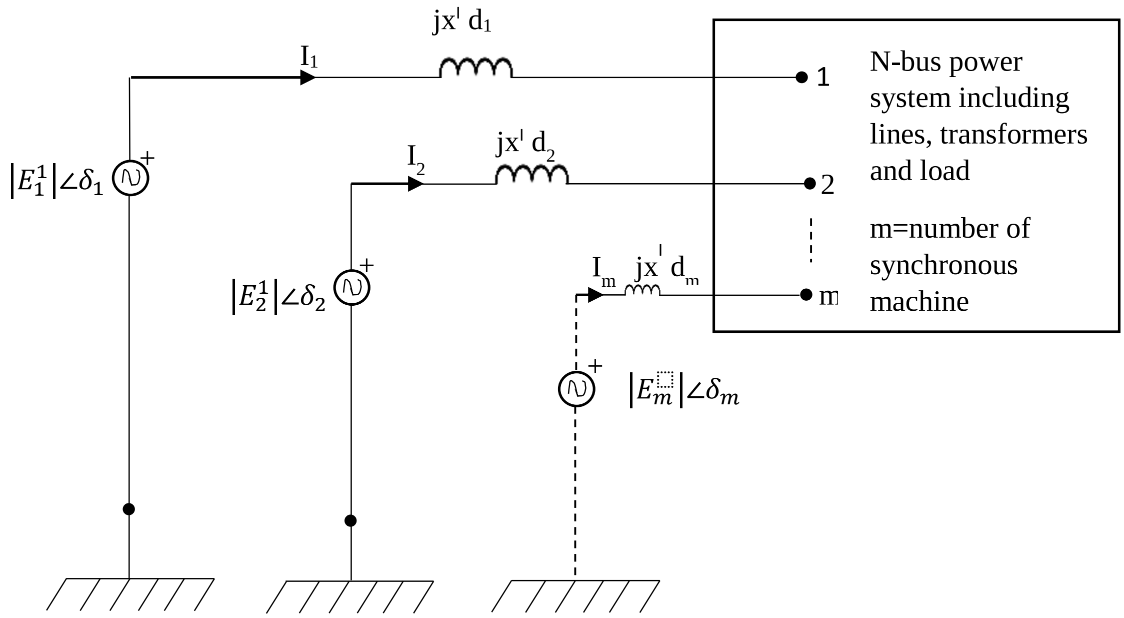


**Figure 2.** n-bus power network with m-generators.

There are three steps involved in assessing the transient stability of the system as follows: first, performing a pre-fault load flow study to determine initial bus voltages ($V_i = V_1, V_2..., V_n$), initial machine currents ($I_i = I_1, I_2, ... I_m$) and initial electrical power output of machines ($P_{ei} = P_{e1}, P_{e2}, ..., P_{em}$). The angles of the voltages are then obtained with respect to the slack bus. Secondly, the swing equations for each of the machines are formulated in the power system network. The swing equation represents the dynamics of the rotor angle (δ). These equations are non-linear differential equations. Lastly, this non-linear differential equation should be solved using numerical techniques.

### 3.1. Mathematical Modelling of Load Flow Study

For an '*n*' bus, the net current injected into the network is written as:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \tag{1}$$

where $I_i$ is the current injected into the network at bus *i*, $V_i$ is the bus voltage at bus *i* and $Y_{ij}$ is the bus admittance between buses *i* and *j* with the network.

The complex power injected at bus *i* is given as:

$$S = V_i I_i^* \tag{2}$$

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k$$

$$= Y_{i1}V_i + Y_{i2}V_2 + \cdots + Y_{in}V_n \tag{3}$$

Rewriting the complex power flow in equation 2 as
$S^* = V_i^* I$, we obtain

$$P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \tag{4}$$

The active and reactive powers injected into each bus can be derived as:

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) \tag{5}$$

and

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \tag{6}$$

where $V_i$ is the voltage magnitude of bus $i$, $\theta_{ik}$ is the voltage angle between buses $i$ and $k$, δ is the admittance angle.

Following the determination of $P_i$ and $Q_i$, the voltage magnitude and its angle can be calculated through iterative method like Newton-Raphson method as described by equation 7.

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{7}$$

where $J_1$, $J_2$, $J_3$ and $J_4$ are the elements of the Jacobian matrix of equation 7, the variables at the finish of each iterations are updated with equation (8) and (9).

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{8}$$

$$\left|V_i^{(k+1)} = \left|V_i^k\right| + \Delta\left|V_i^k\right|\right| \tag{9}$$

Solution is obtained when $\Delta P$ and $\Delta Q$ are lower than the stipulation tolerance.

### 3.2. Mathematical modelling of Swing Equation

For a power system network with 'm' generators, the internal voltage can be determined using equation (10).

$$E_i = V_i + jx_{di}\left[\frac{P_{gi} - jQ_{gi}}{V_i^*}\right] = E_i \angle \delta_i \tag{10}$$

where $E_i$ is the internal voltage of the machine, $V_i$ is the terminal voltage, $x_{di}$ is the impedance of the machine, $P_{gi}$ and $Q_{gi}$ are the real and reactive power of the machine respectively.

Loads are converted to equivalent admittance using equation (11).

$$y_{id} = \frac{P_{di} - jQ_{di}}{|V_i|^2} \text{ for } i = 1,2,\ldots,m \tag{11}$$

where $P_{di}$ and $Q_{di}$ are the respective equivalent real and reactive powers at each load bus.
The pre-fault bus admittance matrix $[Y_{bus}]$ is formed as given in equation (12).

$$Y_{bus} = \begin{bmatrix} Y_{mm} & Y_{mn} \\ Y_{nm} & Y_{nn} \end{bmatrix} \quad (12)$$

where $Y_{mm}$ is a sub matrix of dimension (m x m). It corresponds to the buses where generators are connected. $Y_{mn}$, $Y_{nm}$ and $Y_{nn}$ are other sub matrix.
Using the Kron's reduction method given by

$$Y_{ij(new)} = Y_{ij(old)} - \frac{Y_{ik(old)}Y_{kj(old)}}{Y_{kk}} \quad (13)$$

where node k is to be eliminated. Equation (12) can be reduced to

$$Y_{bus(reduced)} = Y_{mm} - Y_{mn}Y_{nn}^{-1}Y_{nm} \quad (14)$$

The electrical power output of the generator is given as

$$P_{ei} = |E_i|^2 Y_{ii} \cos\theta_{ii} + \sum_{j=1}^{m} |E_i||E_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (15)$$

for $i$=1, 2, …, m

The rotor dynamics is given by

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - P_{ei} \quad (16)$$

where H is the inertia constant, $f_0$ is the frequency and $P_{mi}$ is the mechanical input power.

The solution of the swing equation is obtained by using a numerical solver "ODE45" in MATLAB Software.

## 4. RESULT AND DISCUSSION

This section presents the simulation results obtained when the network was subjected to various contingency scenarios. The fault was cleared after 5 cycle by opening the breakers of the seven lines connected to this bus (Ikeja-West), one after the other. **Fig. 3** to 9 show the dynamic responses of the generators.

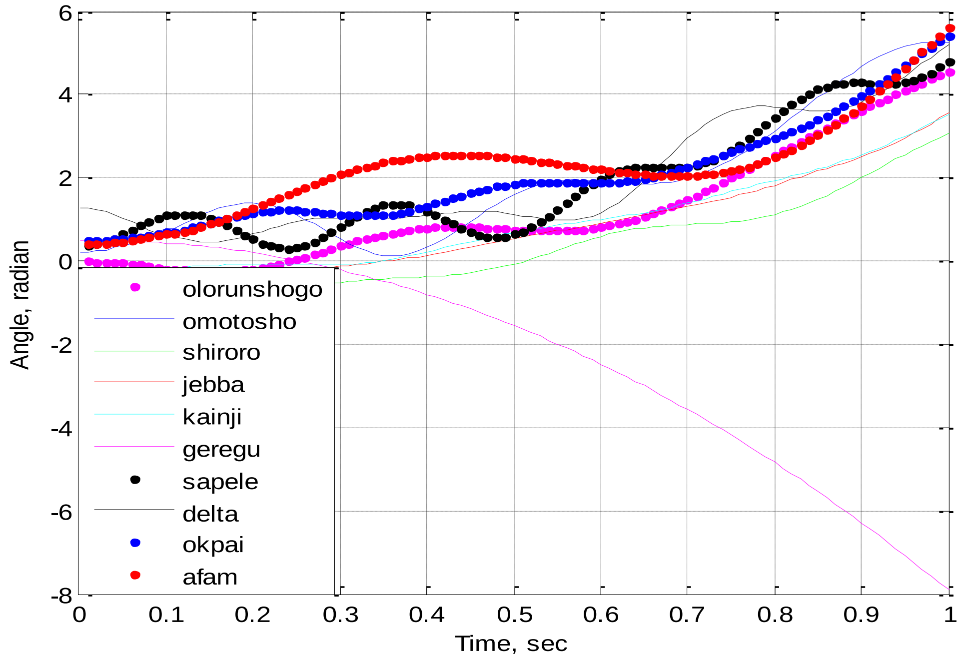


**Figure 3.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Egbin line.

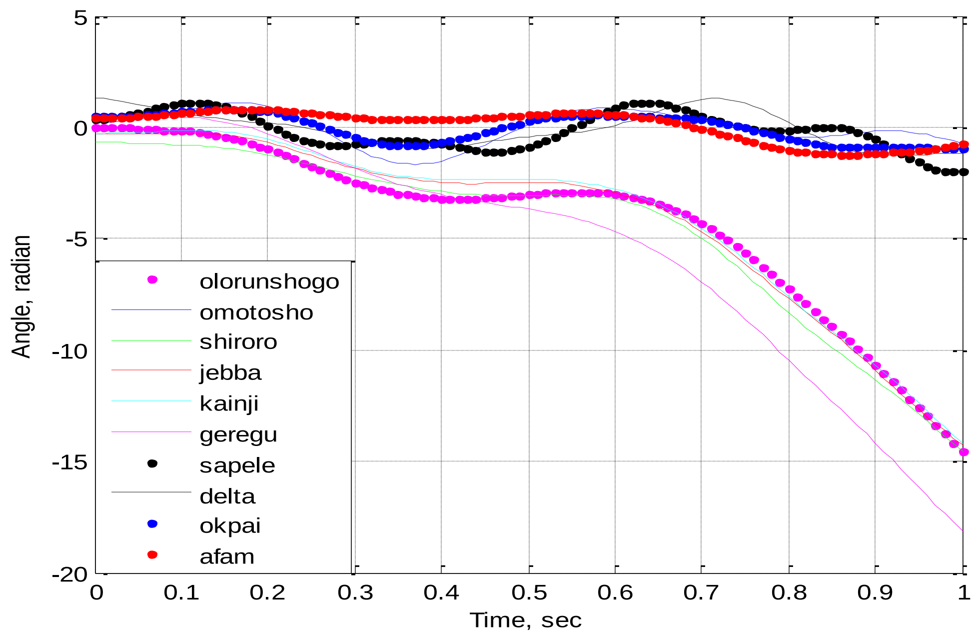


**Figure 4.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Benin line.

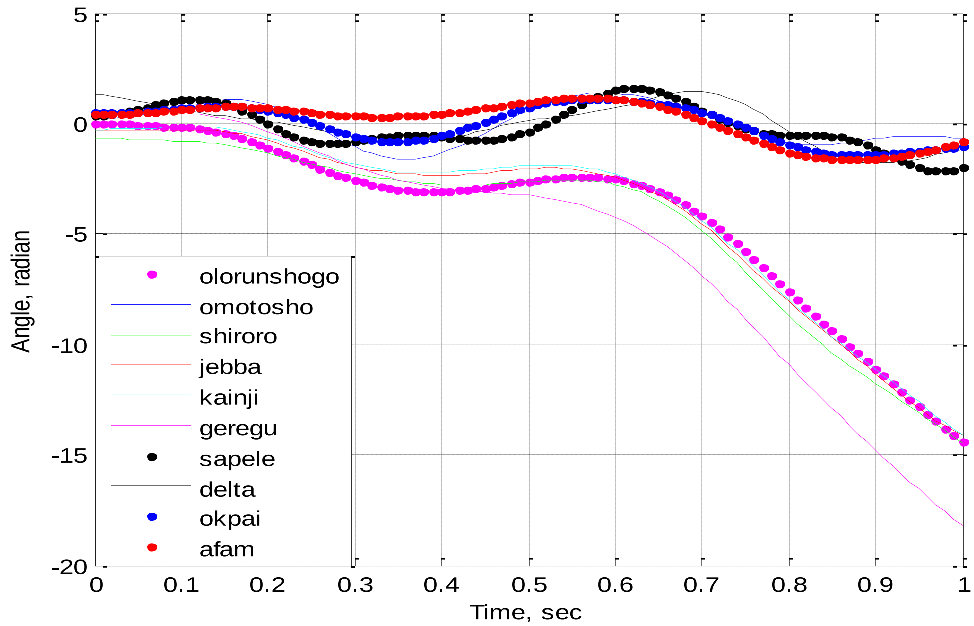


**Figure 5.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Olorunsogo line.

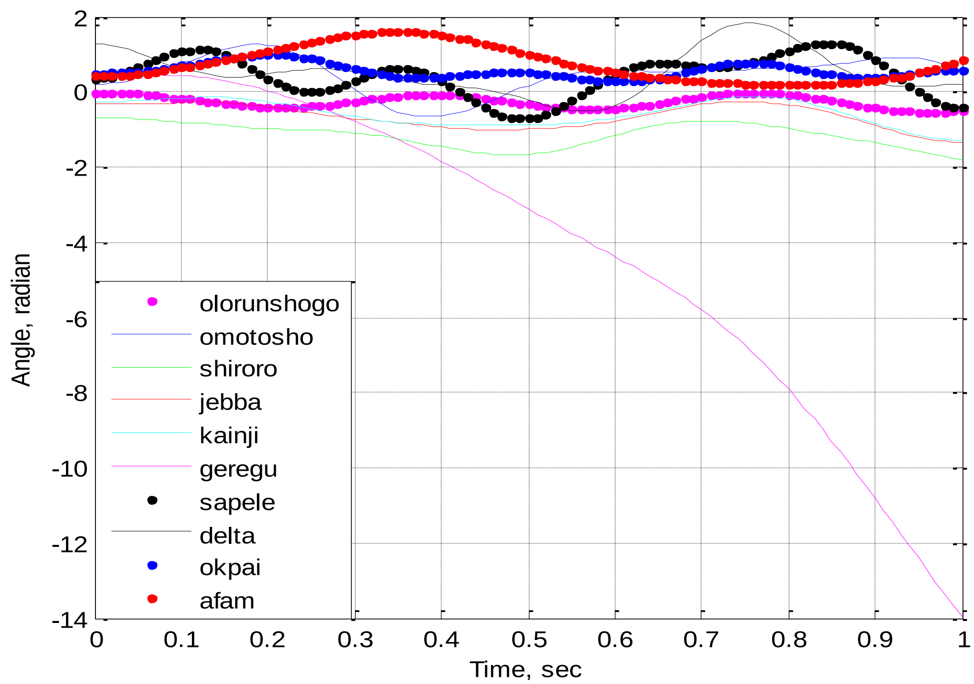


**Figure 6.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Akangba line.

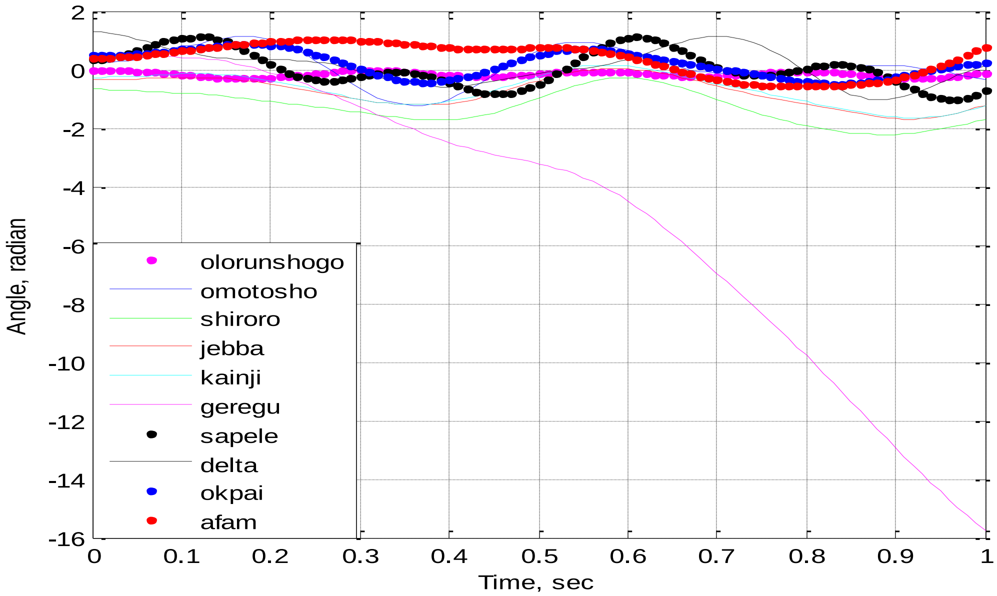


**Figure 7.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Sakete line.

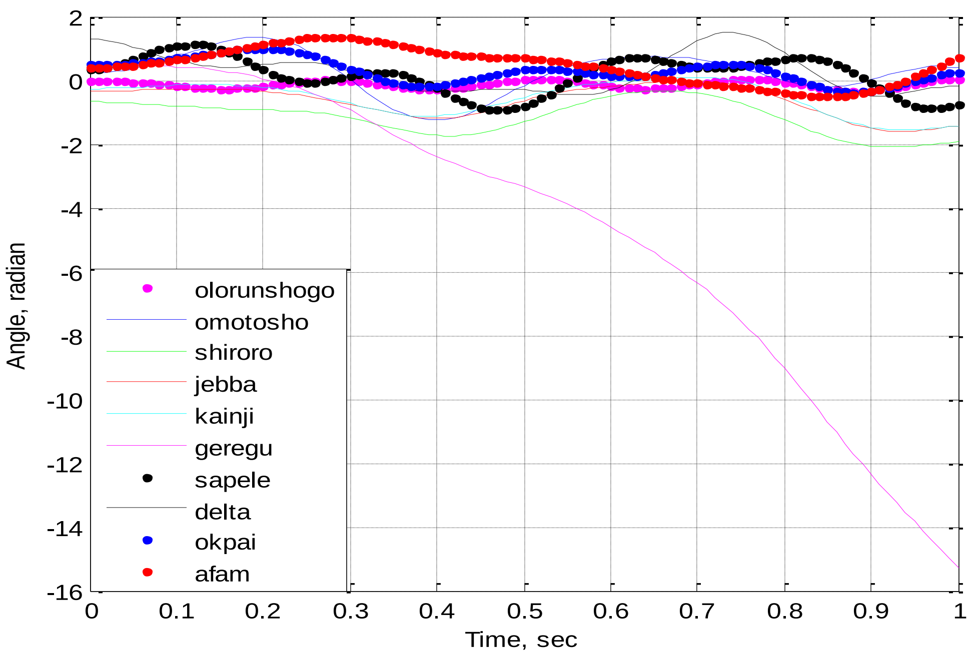


**Figure 8.** Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Omotosho line.

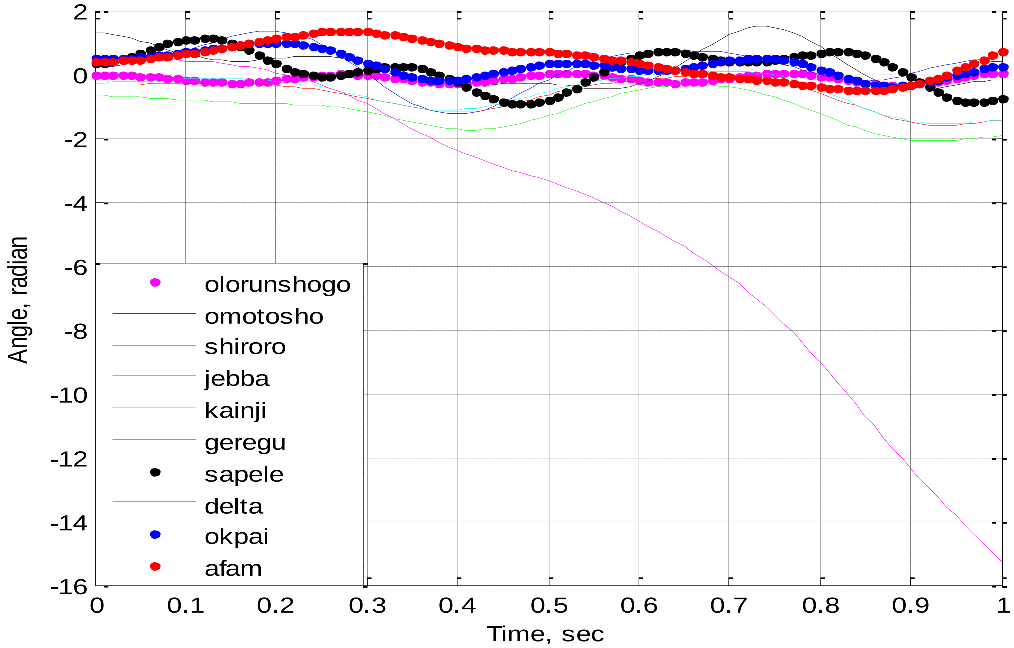


**Figure 9**. Dynamic responses of the generators when a fault on Ikeja West bus is cleared by removing Ikeja/west-Oshogbo lines.

**Fig.3** shows the responses of the generators to a 3-phase fault at bus-3 with L1 removed to clear fault. The figure shows that all the generators experienced instability with Nine generators (Olorunshogo, Omotosho, Shiroro, Jebba, Kainji, Sapele, Delta, Okpai and Afam) occasioned by continues acceleration and one generator (Geregu) occasioned by continues deceleration. **Fig. 4** and 5 again depict the dynamic responses of the generators with a faulted bus-3 with L3 and L12 removed to clear fault respectively. The figures shows that five generators (Olorunshogo, Shiroro, Geregu, Jebba and Kainji) experienced instability, while the remaining five generators (Sapele, Okpai, Afam, Delta and Omotosho) remained stable. At faulted bus-3 with L10, L11, L13 and L14 removed to clear fault respectively, **Fig. 6 to 9** illustrates the dynamic responses of the generators. The figures (**Fig. 6 to 9**) indicates that only the generator (Geregu) lost synchronism by continues deceleration while others were stable. **Table 4** shows the summary of the dynamic responses of the Nigerian 330kV transmission network under a 3-phase fault at bus-3 with different lines contingencies.

**Table 4.** Summary of dynamic responses of Nigerian 330kV transmission network.

| Faulted bus | Line removed to clear fault | Types of fault | Clearing time | System remark |
|---|---|---|---|---|
| **3** | L1 | 3-phase fault | 0.1 | Unstable |
| **3** | L3 | 3-phase fault | 0.1 | Unstable |
| **3** | L12 | 3-phase fault | 0.1 | Unstable |
| **3** | L10 | 3-phase fault | 0.1 | Unstable |
| **3** | L11 | 3-phase fault | 0.1 | Unstable |
| **3** | L13 | 3-phase fault | 0.1 | Unstable |
| **3** | L14 | 3-phase fault | 0.1 | Unstable |

From the above cases, the system was unstable, irrespective of opening any breaker connecting the different transmission lines connected to the faulted bus-3. Hence the Critical Clearing Time (CCT) was unable to be determined because the system went into instability immediately the 3-phase fault was initiated. This shows that the Nigerian 330kV transmission network is on a red-alert, hence, the need for urgent control measures. This assessment is in concordance with **(Ayodele, et al., 2016; Izuegbunam, et al., 2011),** results, which also identified some critical buses that could insight system instability in the Nigerian 330kV Transmission network.

## 5. CONCLUSIONS

In this paper, the dynamic response assessment of generators within the Nigerian 330kV Transmission Network was carried out. The system fault location was on the bus with the largest load. Several transmission lines contingency that could cause instability problem as a result of the system fault locations were considered. The simulation was done using MATLAB Software. The result reveals that the system was unstable, irrespective of any of the identified lines triggering a 3-phase on the largest load bus, with at least one generator losing synchronism. The generator at Geregu was identified as the most severely disturbed generator in the network. The study recommend that Geregu-bus should be looped with more transmission lines in order to avoid network instability caused by Geregu generator. This study will be useful to the Transmission Company of Nigeria (TCN) for effective planning of the Nigerian 330kV transmission network in order to mitigate against the problem of an already stressed network.

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