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DYNAMIC SECURITY ASSESSMENT OF 330KV NIGERIA POWER SYSTEM

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ABSTRACT

The security of power system operation is a measure of its reliability; hence the planning and real-time operation of power system requires regular security assessment. This paper presents a dynamic security assessment of the Nigeria 330 kV power network. It considered the installed capacity of the power system alongside the available capacity as well as network structure in terms redundancy for flexibility. Some weak areas of the system were identified and the security status of the network assessed under large disturbance condition. Results match expectations as the system's response to impressed contingencies were discussed. Feasible corrective measures proffered for improved system's security.

Keywords: Power system, Security assessment, transient stability, state transition.

INTRODUCTION

Electric power energy is one of the most widely used forms of energy in the universe, and hence, has one of the most complex designs that is built and operated by engineers. The modern power system is ever increasing in size and complexity due to the high load demands from power energy consumers. Economic and technological reasons have caused most utilities to be interconnected into vast power grids in order to maximize efficiency of generation and distribution of electric power [1], [2]. In response to further economic pressure, another possible means of increasing efficiency is to operate assets closer to their thermal and stability limits [2]. However, electric power networks operating at this state are constantly subjected to contingencies in form of internal and external disturbances which are capable of causing instability. The need to determine the security status of these power systems during such conditions thus, evolves. The Nigerian 330 kV grid system is not an exception; this system has been plagued by multi – faceted deficiencies with causes that are financial, structural and socio-political, none of which are mutually exclusive [3]. The operational capacity of network for over a decade now has been below 50% of installed capacity. It thus becomes expedient to assess the security level of this power network during perturbations. This paper evaluated the effect(s) of large disturbances (contingencies) on the dynamic behaviour of the system, identified weak areas and made recommendations towards improving the network security.

OVERVIEW OF POWER SYSTEM SECURITY

Power System Security concerns the technical performance and quality of service when a disturbance causes a change in system conditions. The changes considered in this paper are 'large changes' generally referred to as Contingences. In other words, the security of a power system is its ability to withstand a set of severe but credible contingencies and to survive transition to an acceptable new steady – state condition [4]. This is assessed by detection of operating limit violations and contingency analysis. While security assessment is the process of determining whether a probable contingency will cause the system to enter the emergency state; if the answer is yes, the system is considered to be insecure and some action should be taken to make it secure [5]. Security assessment can be categorized into static security assessment and dynamic security assessment [4]. A static security assessment is usually based on a load flow analysis and deals with steady-state limit violations [4].

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The process of obtaining this steady-state condition is known as security monitoring [5], while the process of obtaining limit violations depicts static security assessment. So many techniques have been developed to assess the steady-state operation of a power system using the power flow measure. In addition to the steady-state operation, the power system must be able to survive dynamic events. Dynamic security assessment is more computationally intensive as it requires the electro – mechanical transient stability analysis of the system which concerns the transient behaviour of the power system when moving from the pre to post – contingency operating point [4]. Dy Liacco [1] explained the security of the power system based on the control level required for the maintenance of electric power service under all conditions of operation, and thus, established three operating states of a power system as normal, emergency and restorative. While Fink and Carlsen [6], further extended the power system operating states to five which include: normal, alert, emergency, in-extremis and restorative. Figure 1 is a depiction of the state transition diagram of the power system.

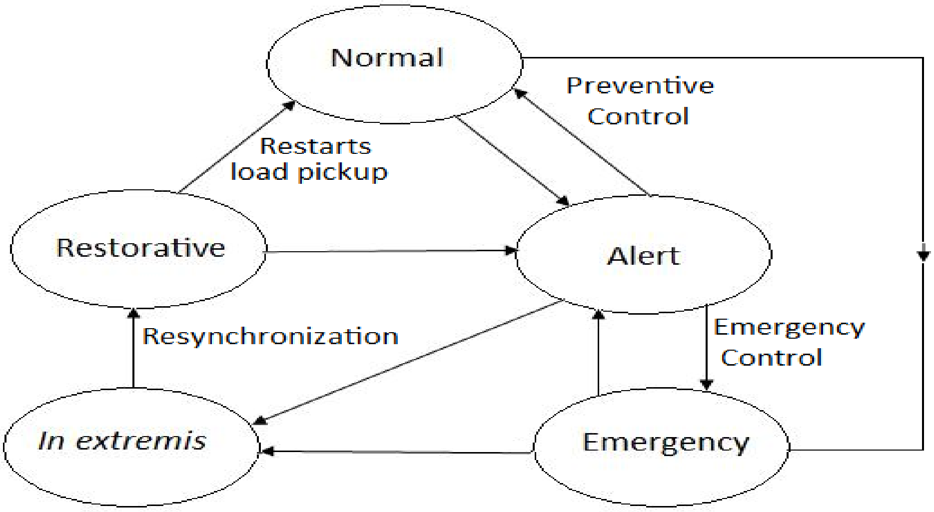

Figure 1: State transition diagram of a power system

These operating states are defined as follows [1, 7]: (i) the normal state implies that all system variables are within the normal range and no equipment is overloaded, while all customer demands are met. (ii) In the alert state, the system variables are still within limits and constraints satisfied. However, the system has been weakened to a level where a contingency may cause an overloading of equipment. (iii) If a sufficiently severe disturbance occurs when the system is in the alert state, the system on occasion enters the emergency state. (iv) If the control measure initiated at the emergency state should fail, the system will go into the in extremis state, i.e., disintegrating into sections or islands. All constraints are violated and the system no longer remains intact. (v) The system enters the restorative state if there were any remaining equipment operating within their total capacity or some equipment had been restarted following the total collapse. It is known that an underlying pattern exists with regard to the events that could cause transition from the alert state to the in extremis state. The initiating event could be a disturbance of natural origin, a malfunction of equipment, or a consequence of human factors [7].

Dynamic Security Assessment

Dynamic Security Assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition [8]. This is dependent on the transient stability evaluation which provides information in relation to the ability of a power system to retain stable operation during major disturbances resulting from either the loss of generation or transmission facilities, sudden or sustained load changes, or momentary faults [9]. In the event of disturbances, the electro-mechanical oscillation of synchronous generator will be used to measure the transient stability. It is determined by observing the variation of the rotor angle as a function of time throughout the duration of the fault. The transient stability depends on the magnitude of the fault, duration of the fault and the speed of the protective devices. If the system is transiently stable, the oscillation of the rotor angle will damp down to a safe operating limit. Dynamic security assessment identifies those disturbances that cause instability and the results of the transient stability analysis are used to determine the system's security level. In most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved [10].

MATERIALS AND METHODS

In transient stability studies, a load flow calculation is made first to obtain system conditions prior to the disturbance [9]. The Newton-Raphson method for power flow analysis was adopted in this study.

Mathematical Formulation

The mathematical model of the power system for transient stability studies require the use of equivalent circuits (saliency ignored) for synchronous machines, static impedances for loads, equivalent π-circuit for tap-changing transformers. Figure 2 shows an n-bus power network.

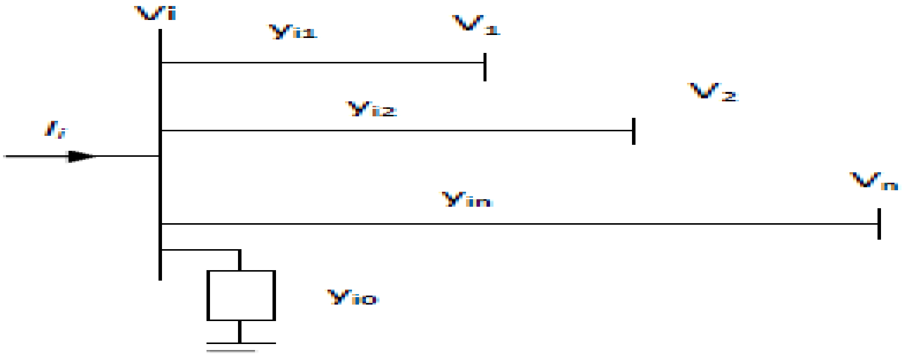

Figure 2: An *n*-bus power network

The matrix form of current injection into the network given as:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1i} \cdots Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2i} \cdots Y_{2n} \\ \vdots & \vdots & & \vdots \qquad \vdots \\ Y_{i1} & Y_{i2} & \cdots & Y_{ii} \cdots Y_{in} \\ \vdots & \vdots & & \vdots \qquad \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{ni} \cdots Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} \tag{1}$$

The mathematical model of the power system for transient stability studies require the use of equivalent circuits for synchronous machines, static impedances for loads, equivalent π-circuit for tap-changing transformers.

The electro-mechanical equation that describes the dynamics of the ith machine of an *n*-machine power system can be written as:

$$M_i \frac{d^2\delta i}{dt} \quad P_{mi} - P_{ei} - D_i\omega_{\mathrm{i}} \tag{2}$$

Where, $\boldsymbol{\frac{d\delta i}{dt} = \omega_i}$

The angular momentum, M_i, also referred to as inertia constant is a function of angular speed or frequency. The frequency deviation is usually assumed negligible under transient condition in comparison to the rated frequency; while the inertia constant, M_i is considered a constant coefficient.

The damping coefficient, D_i is also assumed a constant quantity. The performance of the power system during the transient period can be obtained from the network performance equations.

Network Reduction

In order to simplify the network complexity, all nodes other than the generator internal nodes are eliminated using the Kron reduction approach [10]. The admittance matrix of Equation (1) is thus modified to include the generator reactance, the generator buses and equivalent loads. The equivalent network obtained, when partitioned is as shown in Equation (3).

$$\begin{bmatrix} 0 \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y_{nm}^{t} & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ E'_m \end{bmatrix} \quad (3)$$

The subscript m denotes the generator buses that are to be retained, and n denotes the load buses that are to be eliminated.

From Equation (3) I_m can be calculated as:

$$Im = [Ymm - Y^tnm\, Ynn^{-1}\, Ynm]\, E'i \quad (4)$$

Where,

$$Y = Ymm - Y^tnm\, Ynn^{-1}\, Ynm \quad (5)$$

Is the reduced order admittance matrix of the system and the off – diagonal element, $((k,i)^{th}$ element), Y_{ki} denotes the transfer admittance between the k^{th} and i^{th} generators.

The electrical power output of each machine may be expressed in terms of the machines internal voltages, as:

$$P_{ei} = \Re[E_i{}' I_i]; \text{ where, } I_i = \sum_{j=1}^{M} E_j{}' Y_{ij};$$

Hence,

$$P_{ei} = \sum_{j=1}^{M} |E_i| |E_j| |Y_{ij}| cos(\theta_{ij} - \delta_{ij}) \quad (6)$$

Prior to disturbance,

$$Mechanical\ input\ Power, P_{Mi} = P_{ei} \quad (7)$$

When the effect of damping is neglected Eqn. (2) can be re-written as:

$$Mi\frac{d^2\delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m} |E_i||E_j||Y_{ij}| \cos(\theta_{ij} - \delta_{ij}) \quad (8)$$

Eqn. (8) is nonlinear and a popular technique for providing numerical solution of non-linear equations is the Runge-Kutta method which is based on formulas derived by using an approximation to replace the truncated Taylor Series Expansion [10, 11].

MATLAB provides two powerful functions for the numerical solution of differential equations employing the Runge-Kutta-Fehlberg method: Ode23 based on the Fehlberg second and third- order pair of formulas for medium accuracy [10] and Ode45 for higher accuracy. The slack generator is selected as the reference, and phase angle difference of all other generators with reference to the slack machine are plotted. Based on the stated process, the program '**transtab**' is developed for transient stability analysis of multi-machine systems subjected to a balanced three –phase fault. This is one of the sub-programs that constitute the '**SECURITY ASSESSMENT TOOL' (SAT)** software package.

The algorithm for the program is as seen in Figure 3.

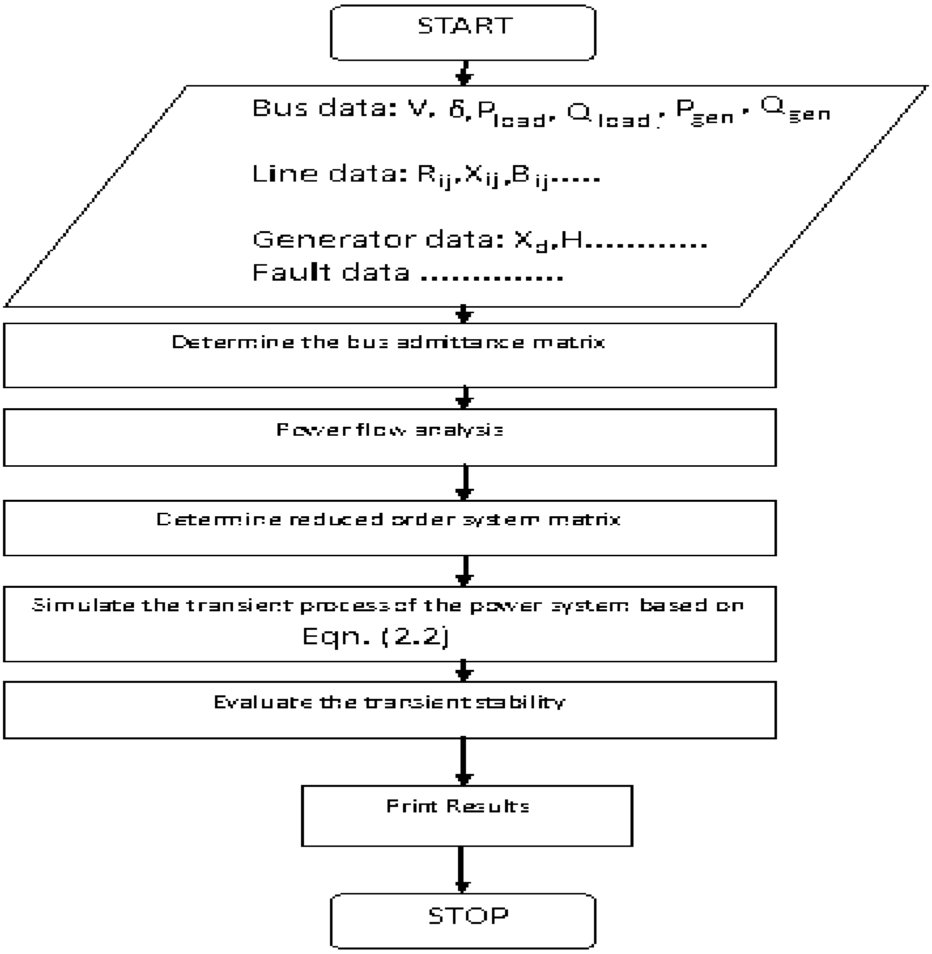

Figure 3: Algorithm for transient stability analysis for a multi machine power system

This paper considers extreme contingency stability threats which include a permanent three-phase fault on any generator, transmission circuit, transformer or bus section, with delayed fault clearing. For a three-phase fault, the typical maximum fault clearing time (including the relay operating time plus circuit breaker opening time) is 8 cycles [12]. When the machine's rotor angle swings around 90^o and decays very rapidly, then the generator is considered stable, but if the rotor angle goes beyond 180^o in the first cycle, it is considered unstable. When the rotor oscillates continuously without damping, the generator is said to be oscillatory. The unstable and oscillatory cases are usually unacceptable.

RESULTS AND DISCUSSION

The performance of the Nigerian grid in transient state is depicted in this section. The Table 1 depicts the present generation profiles of hydro and thermal power generating stations in the country [3]. It is assumed in this paper that the total installed capacities of all the generating units are available for utilization.

Table 1(a): Hydro Installed Plants

Plant	Age (years)	No. Units installed	Installed Capacity (MW)	Current No. Available	Capacity Available	Operational Capability (MW)
Kainji	38 to 40	8	760	6	440	400
Jebba	25	6	578.4	4	385.4	300
Shiroro	22	4	600	4	600	300
Total	--	18	1938.4	14	1431.6	1000

Table 1 (b): Thermal Installed Plants

Plant	Age (years)	No. Units installed	Installed Capacity (MW)	Current No. Available	Capacity Available	Operational Capability (MW)
Egbin	23	6	1,320	4	880	600
AES	7	9	270	9	270	220
Sapele	26 to 30	10	1020	1	90	65
Okpai	3	3	480	3	480	400
Afam	26	20	702	3	350	300
Delta	18	18	840	12	540	300
Total	--	66	4632	32	2610	1885

A pie chart drawn using the values of the installed capacity of Table I presents the percentage power contribution of different plants to national grid is shown in Figure 4. Egbin generator which has the highest percentage contribution is used as the reference.

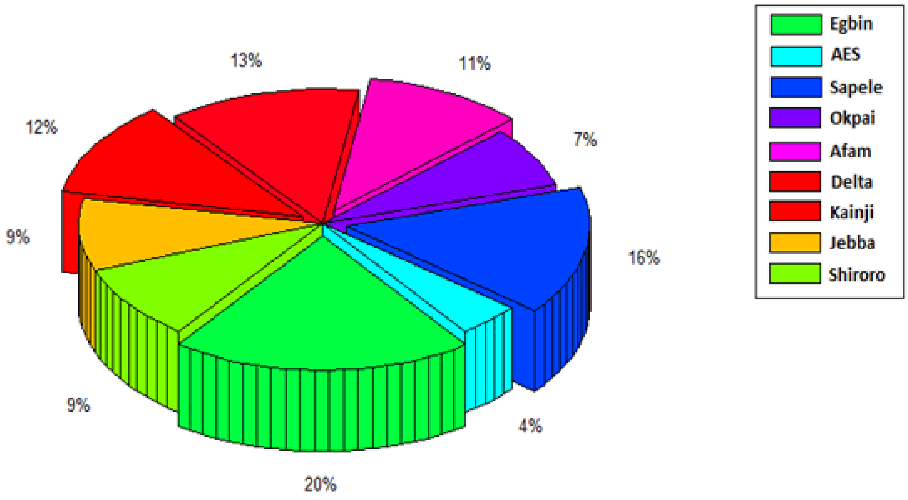

Figure 4: Pie chart showing percentage contribution of generating stations

The single line diagram of the Nigeria 330 kV Power network is shown in Figure 5.

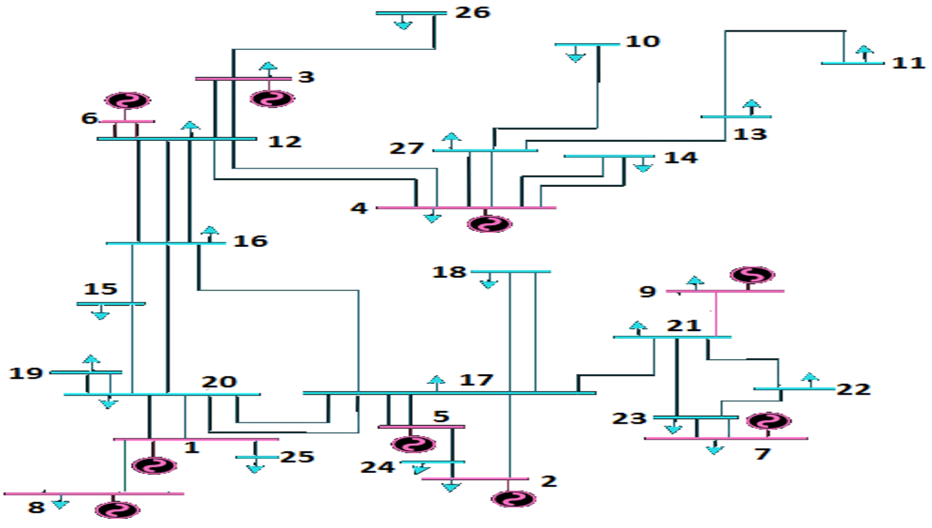

Figure 5: Single line diagram of the Nigeria 330 kV transmission network

The bus nomenclature is shown in table 2.

Table 2: Network bus nomenclature

BUS NO	BUS NAME	BUS NO	BUS NAME
1	EGBIN	14	KATAMPE
2	DELTA	15	AYEDE
3	KAINJI	16	OSHOGBO
4	SHIRORO	17	BENIN
5	SAPELE	18	AJAOKUTA
6	JEBBA GS	19	AKANGBA
7	AFAM	20	IKEJA WEST
8	AES	21	ONITSHA
9	OKPAI	22	NEW HAVEN
10	KANO	23	ALAOJI
11	GOMBE	24	ALADJA
12	JEBBA TS	25	AJA
13	JOS	26	BIRNIN KEBBI
		27	KADUNA

If the Southern and Northern parts of the 330 kV network are seen as two operating regions, the only link between these regions are the line connecting Oshogbo and Jebba. The grid in this view can be seen as a two area network as shown in Figure 6 and thus, any major fault on this link can lead to system islanding.

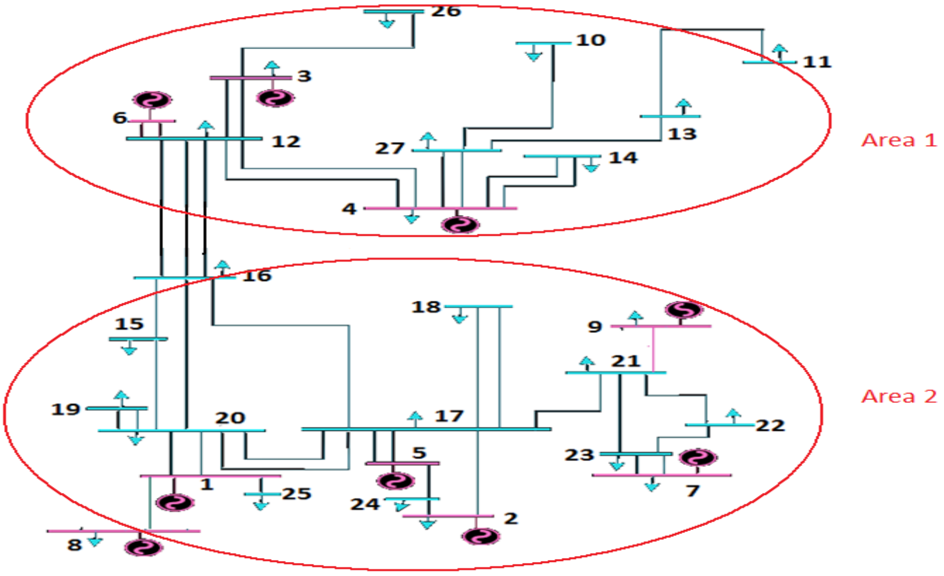

Figure 6: Nigeria 330 kV network as a two area Power system

The generator data used to obtain the transient responses are shown in Table 3. **Table 3: Network Generator data**

M/c No	Bus Name	Transient Reactance, X'd	Inertia Constant, H	Damping Coefficient, D
1	Egbin	0.0520	39.0	0.0764
2	Delta	0.0117	135.1	0.1304
3	Kainji	0.0401	26.32	0.1273
4	Shiroro	0.0750	12.96	0.2546
5	Sapele	0.0213	12.72	0.0097
6	Jebba	0.0800	19.5	0.0955
7	Afam	0.0104	133.8	0.0138
8	AES	0.0306	27.9	0.0000
9	Okpai	0.0833	9.3	0.0044

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Figure 7(a) shows a plot of the swing curves of the generators when a three-phase fault occurs at Bus 12 (Oshogbo) and the circuit breaker trips the Oshogbo – Jebba line at 0.25s. The simulation lasted for 2 seconds.

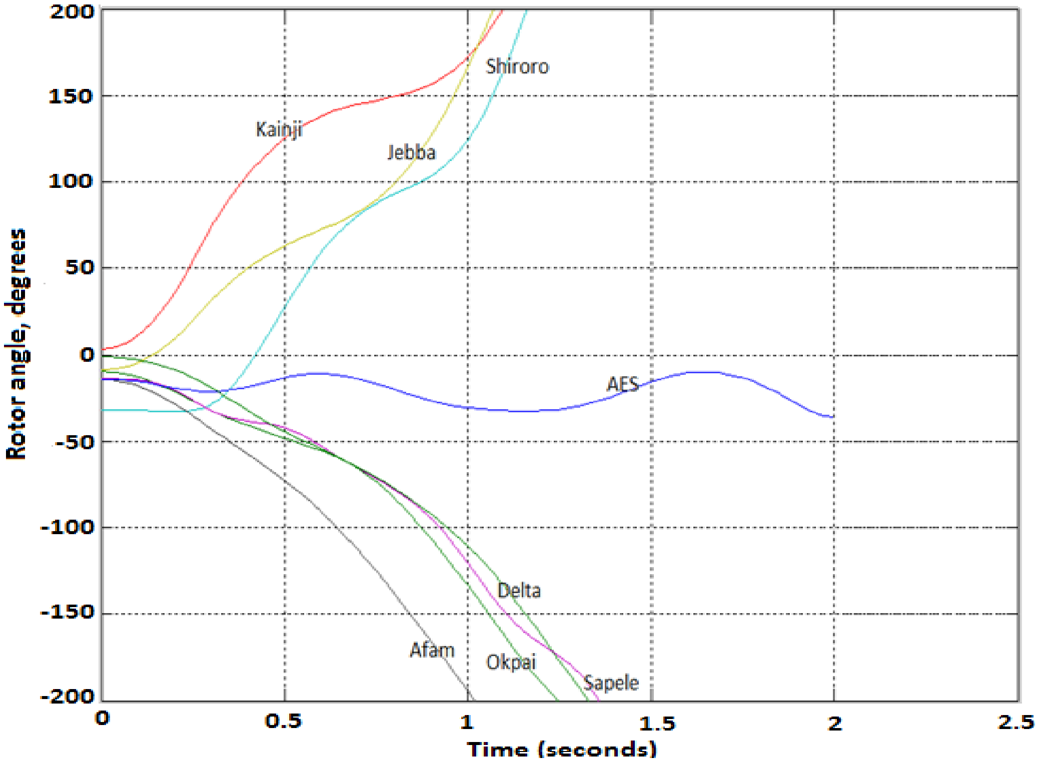

Figure 7(a): Swing curves for Fault at Oshogbo with clearing time of 0.25s

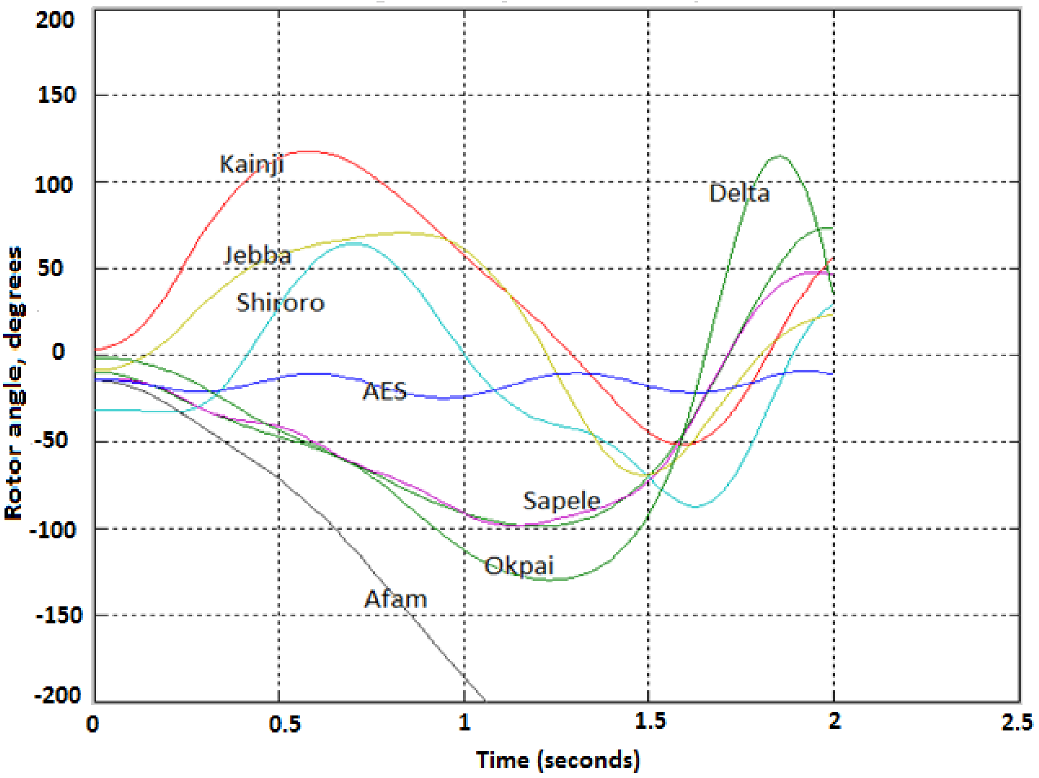

Figure 7(b): the swing plot for the same fault condition but with a clearing time of 0.24s

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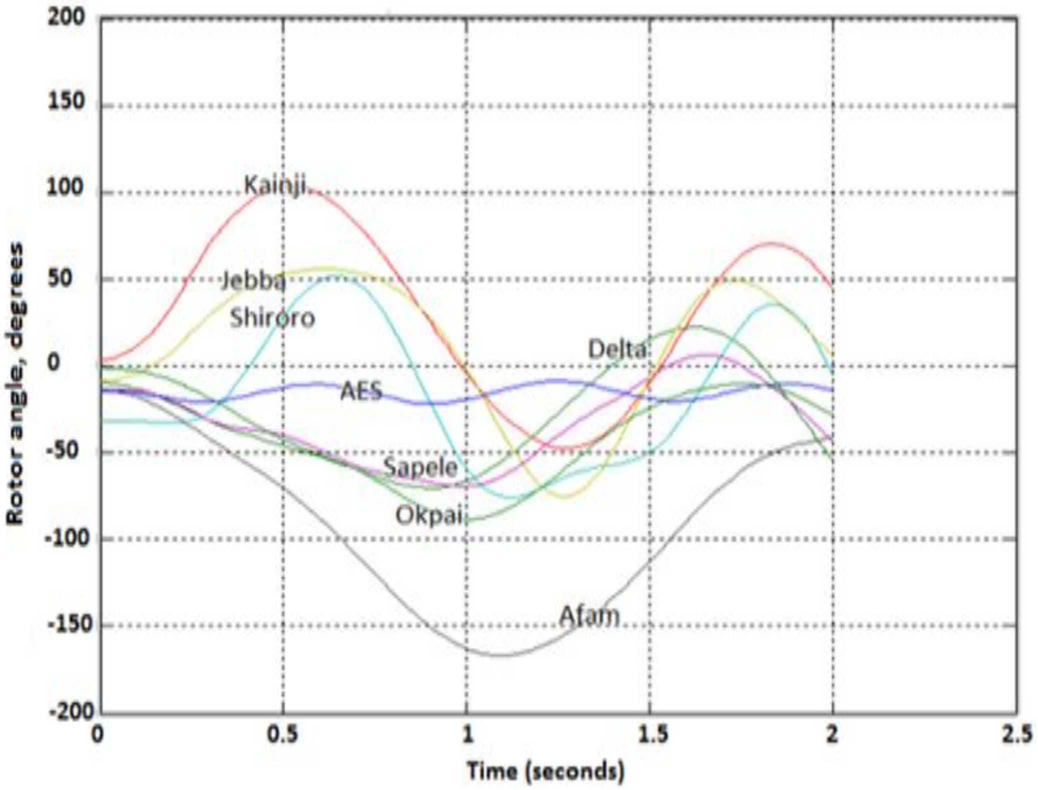

Figure 7(c): the swing plot for the same fault condition but with a clearing time of 0.23s

It can be clearly seen from the plot of Figure 7(a) that the system is unstable for a fault at Oshogbo busbar when fault is cleared at 0.25s. This confirms the proposition that the system will separate into islands as it can be seen that machines at Kainji, Jebba and Shiroro experience increasing rotor angle above the stability limits, while Afam, Okpai, Sapele and Delta experience the exact opposite depicting an ***in extremis*** state.

Figures 7(b) and (c) show that with a clearing time of 0.24s under the same fault conditions, all machines are stable except Afam. But with a clearing time of 0.23s, the system attains stability. This proves that the **critical clearing time** for this fault condition is **0.23s**. Hence, for any clearing time beyond 0.23s the system will experience instability.

The absence of a loop to create alternate power flow paths show that the system is operating in the **alert state** i.e., has low reserve margin. Figure 8 shows swing curves for a fault at Benin, with the tripping of the line, Benin – Onitsha at 8 cycles (0.16s).

The result of Figure 8 exposes the lack of transmission redundancy in the network, as a major path of the system is isolated when the Benin – Onitsha line, considered a weak link, is tripped. Other generators remain intact, while the generators at Afam and Okpai decelerate to instability as they are suddenly serving a large amount of loads. The only major loop in the system is the Benin – Ikeja West – Ayede – Oshogbo – Benin. The system's response when a fault occured at the heavily loaded Benin–Ikeja West line and fault cleared at 0.25s is shown in Figure 9.

It is clear that despite the high loads at these two buses and a clearing time of 12.5 cycles (0.25s), because of the presence of a loop, the system still retains synchronous operation.

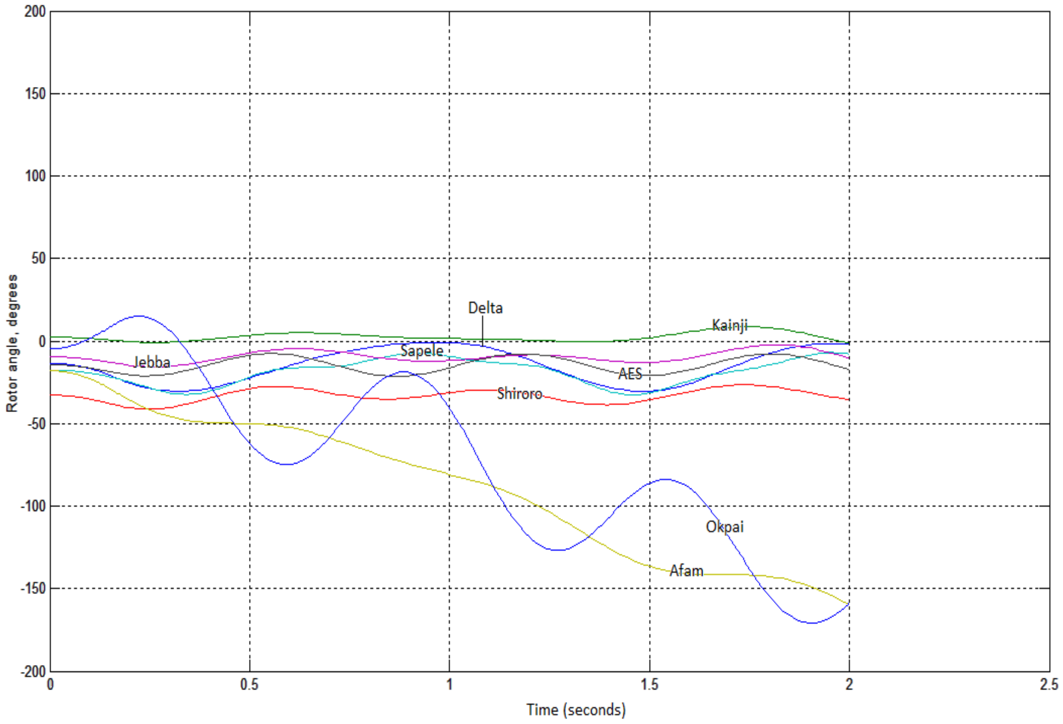

Figure 8: Swing plot for three-phase fault at Benin bus

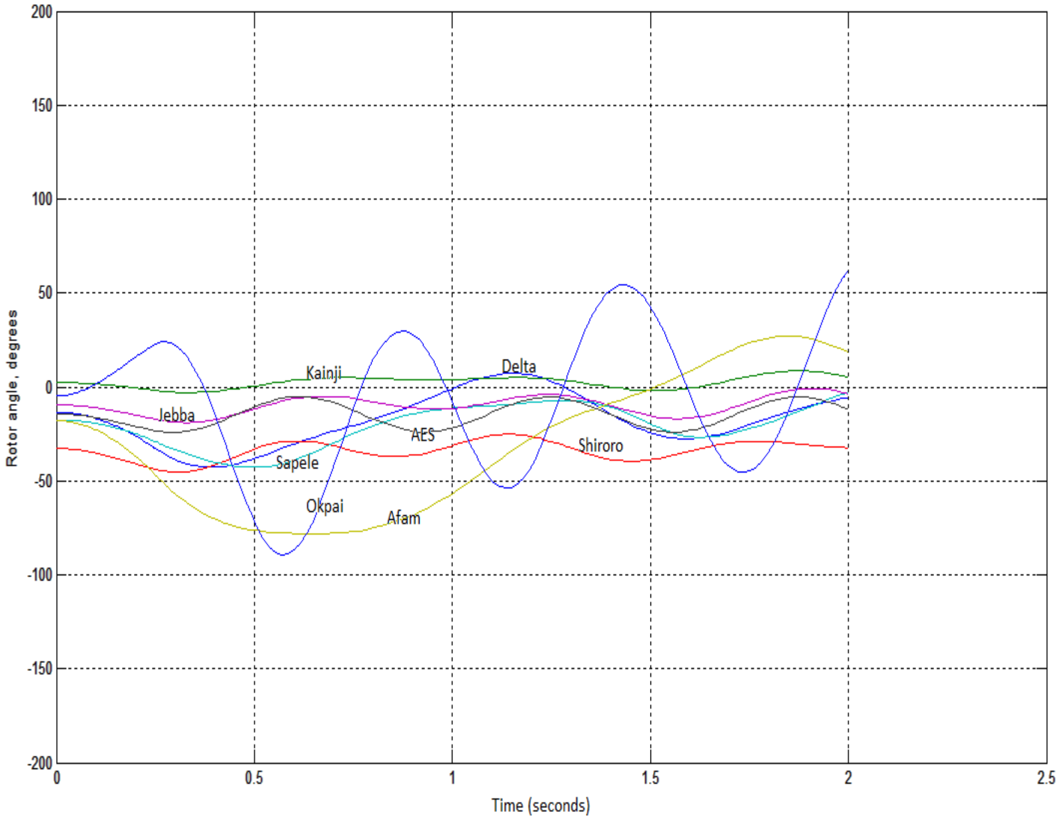

Figure 9: Swing plot showing fault on Benin – Ikeja West line

RECOMMENDATIONS AND CONCLUSION

It is highly recommended that measures should be taken to restore the system to the normal operating state. This basically involves the improvement of the generation and transmission reserve margins to reasonable threshold. The creation of more loops in the transmission system will allow for alternative power routes in case of faults. This will also reduce the monstrous effects of system islanding which is never economical. This greatly enhances the security of the system as this redundancy accounts for the operation of the system in the normal state. Use of highly coordinated and efficient security control strategies that restore the system to normal operation is recommended. This would involve fast clearing times circuit breakers, system controllers with power rerouting capability during system disturbances and sufficient generation despatch.

CONCLUSION

The Nigeria 330 kV transmission network is presently operating in the alert state. This state of vulnerability is as a result of the vertically integrated structure of the system, which in-turn accounts for the disintegration of the network if seriously perturbed at some weak links.

Also, the inadequacy in the reserve margin prepares the system to easily transit to the emergency or in extremis state, as the case may be, when be-devilled by large disturbances.

Efficient control methods as seen can salvage the system from total collapse. It would seem that the assumption of the total installed capacities of all machines being available for use made the response of the system more realistic. Hence, measures should be taken to put this in place.

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