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Transient Stability Analysis of Nigeria 330kv Power System Network Using Numerical Method: A Case Study of Calabar, Alaoji and Afam 330kv Network

Odu Patrick O[a*], Ojobe Obasi-Sam O[b], Lehiowo Obojor-Ogar[c],Onwe Peter D[d]

[a,b,c,d]*Department of Electrical/Electronic Engineering, University of Calabar, Calabar, Nigeria*
[a]*Email: patrickodu@unical.edu.ng*

Abstract

Instability constitutes part of the major challenges in the power system industry as a result of the increase in the complexity of power system networks. Electric energy demand keeps increasing while the expansion of electrical power generation and transmission is faced with severe challenges due to some factors which range from loss of synchronization as a result of some contingencies on the network. This study analyzes the transient stability of the Nigeria 330KV sub-network (Odukpani, Alaoji and Afam) with its analysis performed using MATLAB software to simulate a 3 - phase fault on the network to determine the fault clearing time of the system. The results obtained show that the relative swing between the generator rotor angles is less when the fault clearing time is less with fault clearing time at 0.1, 0.2, 0.3 and 0.4 seconds respectively. By these, there is a tendency for the system will regain stability due to the swing within the stability limit of 0.1sec to 0.4sec with a critical clearing time of 0.45sec. For an unstable condition, the fault clearing time increases at 0.5, 0.6, 0.7 and 0.9 seconds respectively with the rotor angle of the generator increasing out of limit or out of step. Hence, for a system to be stable the fault that occurs should be cleared within a minimum of 0.1sec to 0.4sec which implies the lesser the fault clearing time the greater tendency for stable condition and vice versa.

Keywords: Transient Stability; Nigeria 330 KV Network; Matlab Software; Numerical Analysis.

1. Introduction

The load on a typical power system is variable due to the uncertain demand for electricity at the consumer's end. Considering as complex as the power system network, it consists of large numbers of generators, transformers, transmission lines and different types of loads. The increasing demand for electrical power has set the transmission line to excessive stress even to the point of overloading thereby the problem of transient stability after a major fault can become a transmission limiting factor.

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* Corresponding author.

Transient stability means the ability of a power system to experience a sudden change or disturbance in generation, load, or system characteristics without a prolonged loss of synchronism [1]. Also, Transient stability could be described as the capability of a system to maintain synchronism when it is subjected to a large disturbance within a short duration. This unexpected disturbance affects the system's performance which could results to large variations in the generator's rotor angles, real and reactive power flows, bus voltages and other system parameters [2]. An accurate and fast transient stability assessment method is important to the security operation of electric power system [3]. The system must be designed and operated so that the more probable disturbance can be sustained with little or no loss of load and so the most adverse possible disturbance does not cause severe power interruptions [4]. Power system stability requires some studies which consider the system condition before contingencies, these studies examine the power system equations which comprise variables that influence stability, generator, protective device control as well as the time solution to the system functioning equations. This analysis poses to solve instability constrain thereby finding ways to help in power system stability assessment for multi-machine power systems during the planning and operation phases. It further provides design characteristics for protective equipment and a device such as protective relays and circuit breakers which protect the synchronous generators and transmission lines as well as the system when subjected to disturbance.

2.Literature review on power system stability

The techniques of power system stability analysis problems were affected by the development of computational tools, stability theories, and advent of new control technologies of the system. It is vital to review these theories and their developments relate to the proposed method in this research. In [5] a method was proposed for steady-state stability evaluation of synchronous machines. The method was based on the swing equation, which is a second-order differential equation whose variables are the internal phase angle and the rotational slip. The authors derived two criteria steady-state stability through the evaluation of the value of a linearized version of the swing equation, one for step-out instability and the other for hunting. The authors of [6] applied the method of steady state analysis to two types of synchronous machines, the ordinary synchronous machine and the two-way fed synchronous machine and discussed its capabilities. This technique was developed by considering the damping torque. It was concluded that the method presented is very practical and should be useful as a unified method for the stability determination of synchronous machines.

An article to review the theory of transient energy and stability as contained in [7, 8] discusses the theory based on the basic concepts which include the swing equation, stable and unstable equilibrium points, and equal criterion. Traditionally, the power system examines the subject of transient stability via the equal area criterion and step-by-step integration method. The purpose of this article was to give a concise idea of the equal area criterion and to introduce a transient energy method for the one machine infinite bus case. In an article cited in [9], the method to access accurate and effective transient stability were been developed and has been applied to the assessment of a three-phase to ground fault with multiple generators. By using this function, the average energy losses can be easily calculated and the effect of control and protection systems on transient stability can be easily and quantitatively assessed. A procedure for swing transient stability assessment was developed in [10, 11] using the energy function of individual machines and groups of machines. The energy function is depended on the different state variables of the typical power system which proves the hypotheses of the invariance theorem of La Salle enabling the findings of the asymptotic behaviour of the post-disturbance equilibrium of the entire power system.

Researchers in [12, 13] adopted a method which presented a new simulation technique to evaluate the transient stability of the power system including three-phase unbalanced impedances. The phase coordinate technique was adopted, as it is easy to analyze the power system that contains elements of unbalanced three-phase impedances by the phase coordinate technique.

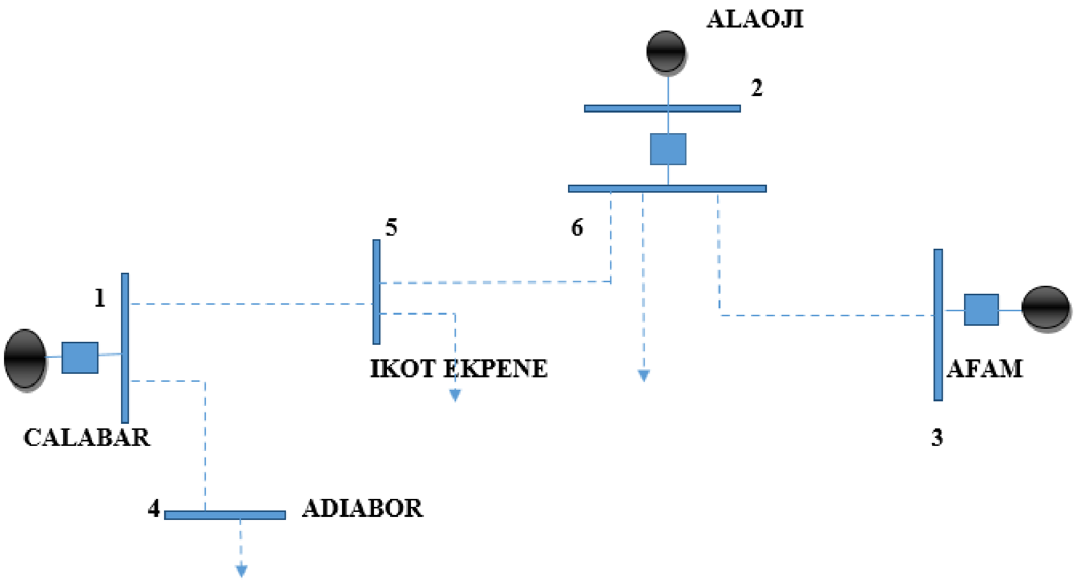
2.1. Overview of the Nigeria 330KV Power Sub-Network Under Study

The Nigerian power network consists of electrical equipment and generating stations mostly sited in remote locations near the raw fuel sources which are usually connected to the load centers by long transmission lines. Due to the privatization of the power sector Generation, transmission, and distribution of electricity in Nigeria are the statutory functions of the National Electric Power Authority (NEPA) later Power Holding Company of Nigeria (PHCN) is now divided into sectors which are controlled by generation, transmission and eleven (11) distribution companies [14].

The Nigeria power network installed capacity of existing power stations is12,522 MW and the maximum load ever recorded was 9,895MW with some of the generating stations partially operational or none operational due to limited available resources to carry out the needed maintenance and failure on the part of the of distribution companies to evacuate load. The transmission lines are radial and are overloaded, the switchgear is no longer in use while no maintenance has been done on the power transformers with the present estimated installed generating capacity of about12,522 MW and the maximum estimated generation of 4000MW for a population of about 160 million. Furthermore, the network consists of twenty-four (24) power generating stations comprising twenty (20) thermal which constitutes 10,592MW and (4) hydropower stations with 1,930MW which is a total installed generating capacity of 12,522MW (Nigeria Power Baseline Report, 2015). The thermal stations are mainly in the south-south, south-east and south-west parts of the country while hydroelectric power stations are in the country’s middle belt. The transmission network consists of 2,194km of 330KV lines, 809km of 132KV lines, 330/132KV capacity of 5,590 MVA with twenty (20) sub-stations and twelve (12) extensions and 132/33KV capacity of 3,313 MVA, nine (9) substations and twenty-two (22) extensions [15].

3.Materials and methodology materials

The study approaches the Collection of Information and data from the Transmission Company of Nigeria (TCN) for an accurate representation of the network for analysis based on the network under study. The study makes use of MATLAB Software for the performance of the analysis. The single-line diagram of the network under study is been extracted from the existing Nigerian 330KV network as shown in Figure 1.



Generator	
Bus	
Line	

Figure 1: Line diagram of Nigeria 330KV sub-network of Calabar, Aloaji and Afam.

Table 1: Calabar, Alaoji and Afam 330KV network.

GENERATOR	BUS	LINE
3	6	4

3.1. Methodology

A mathematical modelling for the implementation of load flow analysis was done using the Newton Raphson method based on the single-line diagram of the network under study. The system network equation and machine differential equation were solved interactively using the numerical integration method to find out the system machine response in the time domain.

A three-phase fault was created on different lines and busbar, the rotor angle, clearing time and critical clearing time will be displayed and analyzed.

3.2. Multi-Machine Stability Modeling in Power System Using Numerical Method

Multi-machine equations can be written similar to the one-machine system connected to the infinite bus. To reduce the complexity of the transient stability analysis [16].

Firstly, the initial load flow was solved, then the initial bus voltage magnitudes and phase angles was determined. Before disturbance the machine currents were calculated from;

$$\mathrm{I}_i = \frac{S_i}{V_i} = \frac{P_i - jQ_i}{V_i}, i = 1,2, \ldots, m \quad (1)$$

Where;

m = is the number of generators.

$V_i =$ is the terminal voltage of the ith generator.

P_i and Q_i are the generator's real and reactive powers.

The voltages behind the transient reactance's are obtained.

$$E_i' = V_i + jX_d'\mathrm{I}_i \quad (2)$$

Next, all load is converted to equivalent admittances by using the relation

$$y_{i0} = \frac{S_i}{|V_i|^2} = \frac{P_i - jQ_i}{|V_i|^2} \quad (3)$$

The node voltage equation with node 0 as reference for this network is,

$$\begin{bmatrix} I_1 \\ I_2 \\ \frac{I_n}{} \\ I_{n+1} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{1n} & Y_{1(n+1)} & Y_{1(n+m)} \\ Y_{12} & Y_{2n} & Y_{2(n+1)} & Y_{2(n+m)} \\ Y_{n1} & Y_{nn} & Y_{n(n+1)} & Y_{n(n+m)} \\ Y_{(n+1)1} & Y_{(n+1)n} & Y_{(n+1)(n+1)} & Y_{(n+1)(n+m)} \\ Y_{(n+m)1} & Y_{(n+m)} & Y_{(n+m)(n+1)} & Y_{(n+m)(n+m)} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \frac{V_n}{} \\ E_{n+1}' \\ E_{n+m}' \end{bmatrix} \quad (4)$$

$$\mathrm{I}_{bus} = \mathrm{Y}_{\mathrm{bus}}\mathrm{V}_{bus} \quad (5)$$

Where;

$\mathrm{I}_{\mathrm{bus}}$ is the vector of the injected bus current.

$\mathrm{V}_{\mathrm{bus}}$ is the vector of bus voltages measured from the reference Node

Where the vector I_{m} is the generator currents and the vector $\mathrm{E'm}$ and V_{n} are the generator and load voltages, respectively. Then, equation (4), in terms of sub-matrices, becomes;

$$\begin{bmatrix} 0 \\ \mathrm{I}_{\mathrm{m}} \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y_{nm}^t & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ E_m' \end{bmatrix} \quad (6)$$

Eliminating voltage vector V_{n} we have;

$$0 = Y_{nn}V_n + Y_{nm}E_m' \quad (7)$$

$$I_m = Y_{nm}^t V_n + Y_{nm} + E'_m \quad (8)$$

From equation 3.7,

$$V_n = -Y_{nn} - Y_{nm} E'_m \quad (9)$$

Substituting into equation 8 we have,

$$I_m = [Y_{mm} - Y_{nm}^t Y_{nn}^{-1} Y_{nm}] E'_m = Y_{bus}^{red} E'_m \quad (10)$$

The reduced admittance matrix is;

$$Y_{bus}^{red} = Y_{mm} - Y_{nm}^t Y_{nn}^{-1} Y_{nm} \quad (11)$$

The output power of each machine can be expressed as;

$$P_{ei} = R_e(E'_i I_i) \quad (12)$$

Where;

$$I_i = \sum_{j=1}^{m} E'_j Y_{ij} \quad (13)$$

Expressing voltage and admittance in polar form;

$E'_i = |E'_i| < \delta_i$ and $Y_{ij} = |Y_{ij}| < \theta_{ij}$

And substituting for I_i in equation (12) we have;

$$P_{ei} = \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_i) \quad (14)$$

The above equation is the same as the power flow equation. Equilibrium is experienced between the input mechanical power and output electrical power,

$$P_{mi} = \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_i) \quad (15)$$

An actual three-phase fault at bus k in the network results in $V_k = 0$. The electrical power of the i_{th} generator based on the new reduced bus admittance matrices is obtained from equation (14). The swing equation with damping neglected, for machine i becomes;

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m} |E'_i||E'_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_i) \quad (16)$$

Where;

Y_{ij} is the element of the faulted reduced bus admittance matrix

H_i is the inertia constant of the machine expressed on the common MVA Base

If H_{Gi} is the inertia constant of the machine expressed on the machine rated MVA S_{Gi}, then H_i is given as;

$$H_i = \frac{S_{Gi}}{S_{cb}} H_{Gi} \tag{17}$$

Showing the electrical power of the i_{th} generator by P_e^f and transforming equation (16) into state variable mode yields

$$\frac{d\delta_i}{dt} = \Delta\omega_i \tag{18}$$

$$\frac{d\Delta\omega_i}{dt} = \frac{\pi f_0}{H_i}\left(P_{mi} - P_{ei}\right) \tag{19}$$

The post-fault of the generator electrical power is ascertained from equation (14). Using the post-fault power, the simulation is kept running until the plots results indicate a definite output as to stability or instability. Usually, the slack generator is chosen as the reference machine to be plotted. If the angle differences do not increase, the system is considered stable. And If any of the angle differences increases indefinitely, the system is said to be unstable [16].

4.Results and discussions

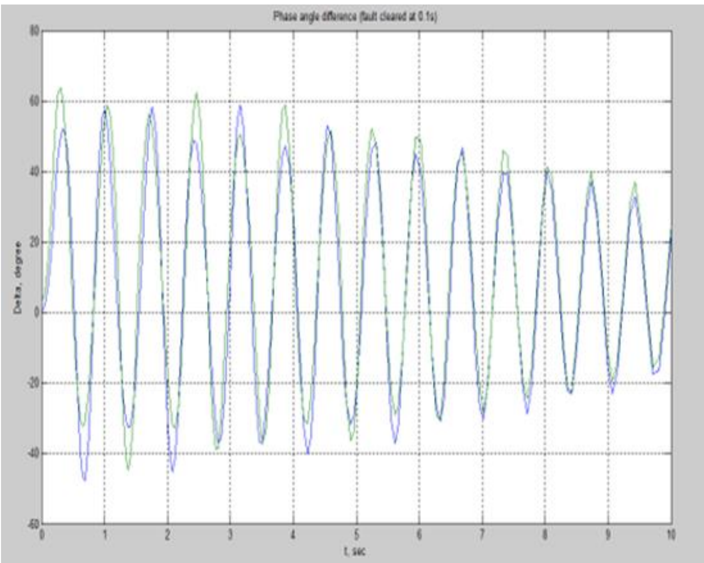


Figure 2: Three phase fault on lines 1-4 fault clearing time is 0.1-sec system is stable.

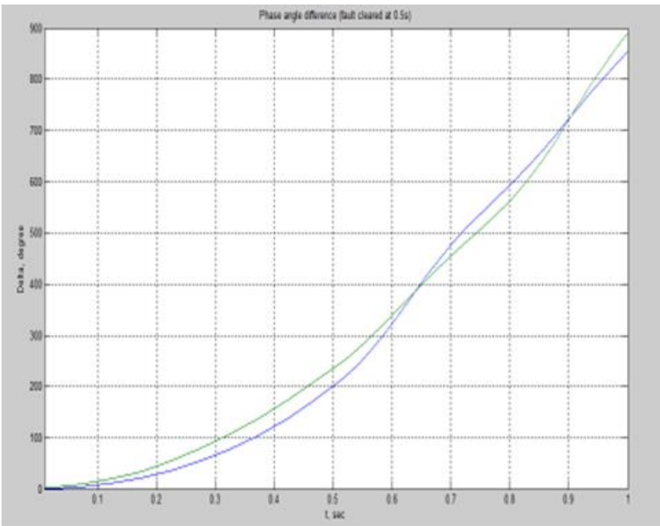


Figure 3: Three phase fault on lines 1-4 fault clearing time is 0.5-sec system is unstable.

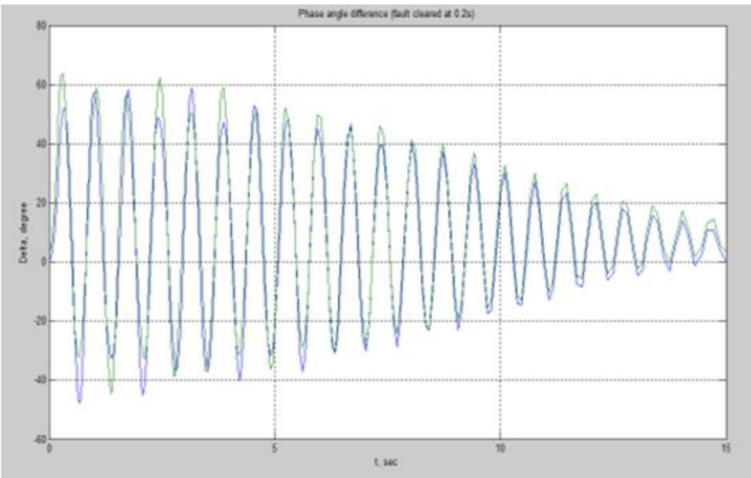


Figure 4: Three phase fault on lines 1-5 fault clearing time is 0.2-sec system is stable.

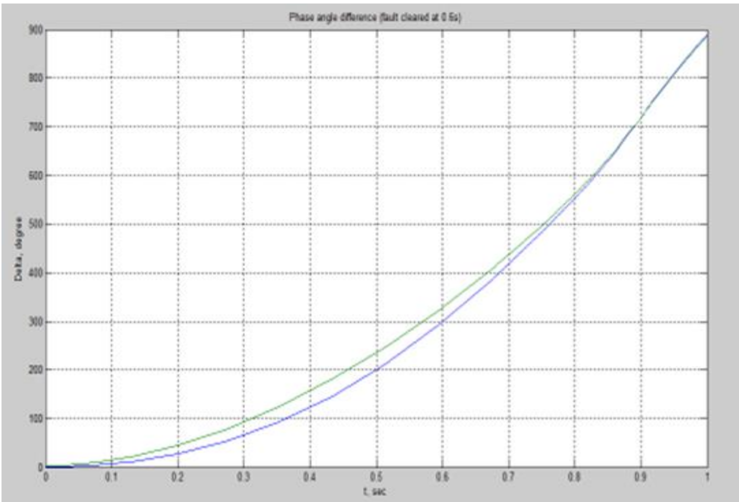


Figure 5: Three phase fault on line 1-5 fault clearing time is 0.6-sec system is unstable.

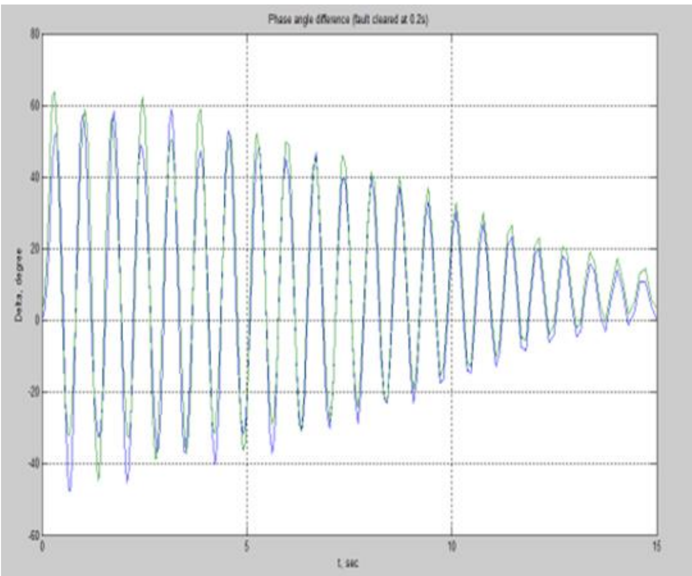


Figure 6: Three phase fault on lines 3-6 fault clearing time is 0.3-sec system is stable.

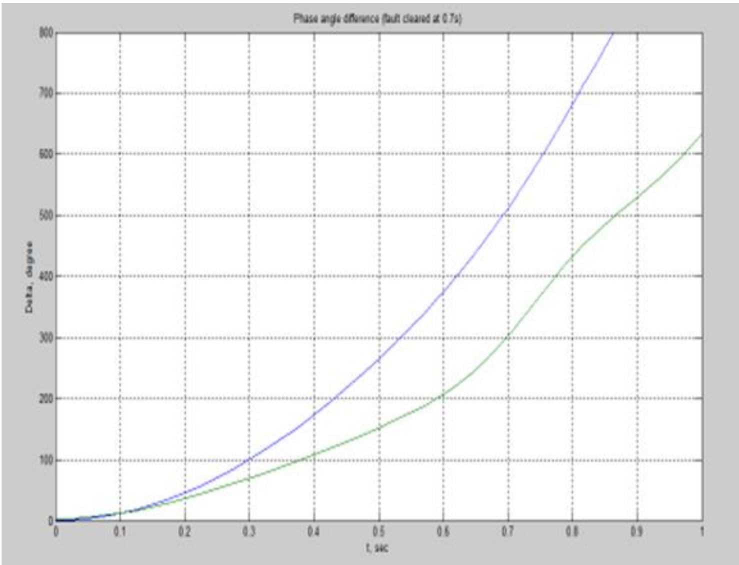


Figure 7: Three phase fault on lines 3-6 fault clearing time is 0.7-sec system is unstable.

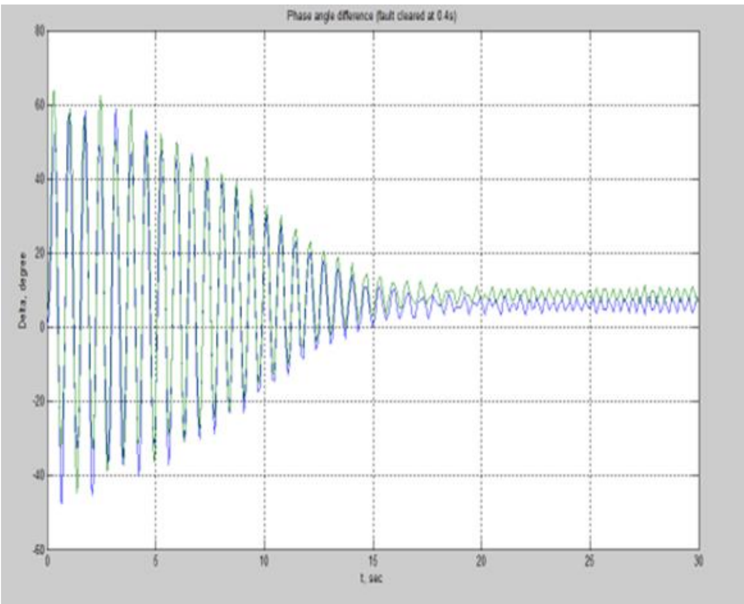


Figure 8: Three phase fault on line 6-5 fault clearing time is 0.4-sec system is stable.

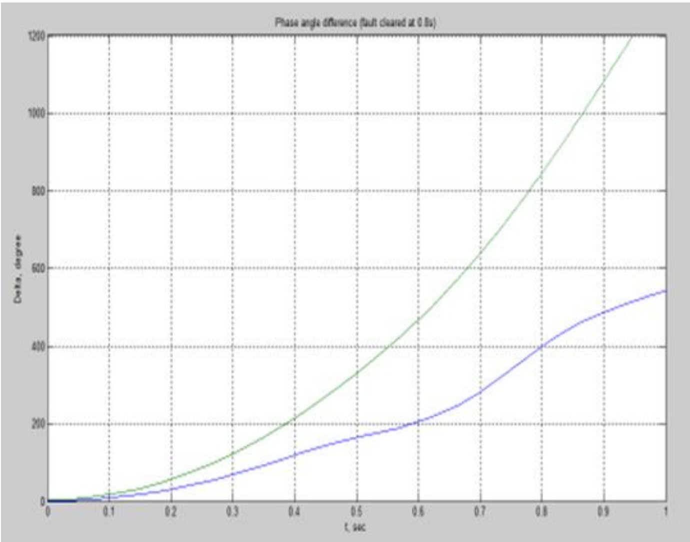


Figure 9: Three phase fault on line 6-5 fault clearing time is 0.8-sec system is unstable.

Table 2: Summary of Analysis Result.

S/N	Fault Bus No.	Removed Fault line	Clearing Time (s)	Phase Angle Difference Characteristics	Analysis Result
1	4	1-4	0.1s	Fig 2	Stable
2	4	1-4	0.5s	Fig 3	Unstable
3	5	1-5	0.2s	Fig 4	Stable
4	5	1-5	0.6s	Fig 5	Unstable
5	3	3-6	0.3s	Fig 6	Stable
6	3	3-6	0.7s	Fig 7	Unstable
7	6	6-5	0.4s	Fig 8	Stable
8	5	6-5	0.8s	Fig 9	Unstable

5.Discussions

The swing curves shown in the figures above (from figure 2 to figure 9) show various stability conditions of the Nigeria 330kv sub-network (which comprises Calabar, Alaoji and Afam) when a three-phrase fault occurs on the interconnected lines and figure 4.9 shows the line diagram of the network. From the results, it is observed that when fault occurs on the line connecting both Adiabor and Ikot Ekpene from Calabar at fault clearing time of 0.1sec and 0.2sec respectively there is a phase angle stability limit to indicate the system is stable while an increase in the fault clearing time to 0.5sec and 0.6 sec respectively result to an unstable condition. For the interconnected lines linking Alaoji to Ikot Ekpene and Afam, the fault clearing time is 0.4sec and 0.3sec respectively for a stable condition with 0.7sec and 0.8sec are fault clearing times for unstable conditions. It can also be observed that when a three-phase fault occurs the generator at Alaoji is the most critically disturbed with maximum phase angle difference and the line linking Ikot Ekpene from Calabar is the most critical as a result of its length. From the overall result, it can be seen that for a stable condition, there is an increase in the phase angle difference to a maximum limit thereby a decrease which results in a machine swing and fault being cleared at different favourable fault clearing times. While for an unstable condition it can be observed that the phase angle increases without limit or out of limit. Hence, the machine going out of step and fault is also cleared at different unfavourable fault clearing times.

6.Conclusion

From the above results, we can ascertain if the system is stable or unstable for a particular fault clearing time when subjected to a three-phase fault. A MATLAB simulation result shows a three-phase fault on a line during a particular time in seconds and the line is removed. Observing the result, it can be seen from the phase angle characteristic that the relative swing between the generator phase angles is less when the fault clearing time is less and when the fault clearing time is at 0.1, 0.2, 0.3 and 0.4 seconds respectively, there is a tendency the machine will regain stability due the swing within stability limit. For an unstable condition, the fault clearing time increases to 0.5, 0.6, 0.7 and 0.8 seconds respectively with the phase angle of the generator increasing out of limit or out of step. Furthermore, for a system to be stable the fault clearing time should be within the minimum time for system stability which implies the lesser the fault clearing time the greater tendency for stable conditions and vice versa. Due to the stability constraint in the Nigeria 330KV sub-network of Calabar, Alaoji and Afam, this research work study, therefore, recommend measures that will improve transient stability which may include; the installation of flexible alternating current transmission system devices into the transmission network, installation of fast-acting circuit breakers, installation of breaking resistors at generator buses, short circuit current limiters, etc. to prevent total system collapse if there is a three-phase fault occurring on transmission lines or buses.

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