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Faults analysis on electrical power transmission lines using probabilistic transmission line model in Nigeria - a case study

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ABSTRACT

Faults on transmission lines occur frequently due to environmental and human factors disruption thereby resulting into economic losses. Mostly, these faults are difficult to locate since these transmission lines span several kilometres, requiring inspection of the transmission lines to trace such faults. Therefore, the need for fault analysis model that they can inform power service providers on the state of infrastructures on the transmission line as well as the precise site where the fault is located on the transmission path is very important. This research paper therefore developed a probabilistic model for analysis of occurrence of fault, in electrical transmission lines and the developed model was implemented on Nigerian transmission network of Iwo-Osogbo 132 kV transmission line to give a clear estimate of the performance and reliability in evaluating the performance transmission lines. Thus the probabilistic model enhanced power system reliability and helps reduce power outages as a result of faults occurrences.

Keywords: Fault, Transmission Line, Probabilistic Model, Reliability, Power System, Power outages.

1. INTRODUCTION

Transmission lines serve the function of transporting the generated power from generating station to energy consumer at different load centres. It is worthwhile to point out that Hydro-electric and thermal via fossil fuel generating plants are prevalent in Nigeria for the generation and supply of consumer required energy. As at 2014, its installed capacity stood at 8,457.6 MW which is approximately equal to 81 % of total installed capacity [1-5]. Electricity production from hydro-electric sources in Nigeria was found to be 17.59 %, based on the assessment of World Bank Collection of development indicators as at 2014 [6][9].

Power transmission network across all the states in Nigeria is solely managed by Transmission Company of Nigeria (TCN). In April 2004, Power

Holding Company of Nigeria (PHCN) was unbundled, consequently TCN emerged alongside with other seventeen companies, and TCN could as well be viewed as evolving from merging of transmission and operations arm of PHCN [7]. In July 1, 2008, TCN was officially issued with transmission license by the Nigeria Electricity Regulatory Council (NERC). The Nigerian transmission grid comprises of high voltage sub-stations having 7,500 MW as the transmission veering capacity while the transmission lines span over 20,000 km by length [8], [10].

The Nigerian levels of voltage transmission ranges from 330 kV, 132 kV to 33 kV, and these different voltage transmission levels enhanced transmission network interconnection which is referred to as the national grid. It is imperative to emphasize that energy generation up to these values are allowed from any generating stations for immediate connection to the national grid [3]. Fundamentally, the voltage level at the generation site is usually between 11.5 – 16 kV, this is then stepped up with the aid of step-up transformer to about 330 kV at the power stations and then delivered to the end-users through transmission network. Topologically, transmission commences with transportation of 330 kV voltage via transmission lines to the transmission sub-station where it is step-down via transformer to 132 kV, this is then transported again via transmission lines to injection substations for further step-down to 33 kV and at this point electricity distribution to the end-users begins. Figure 1 shows the various transmission line routes across Nigeria according to Buckminister, (2016) [5].

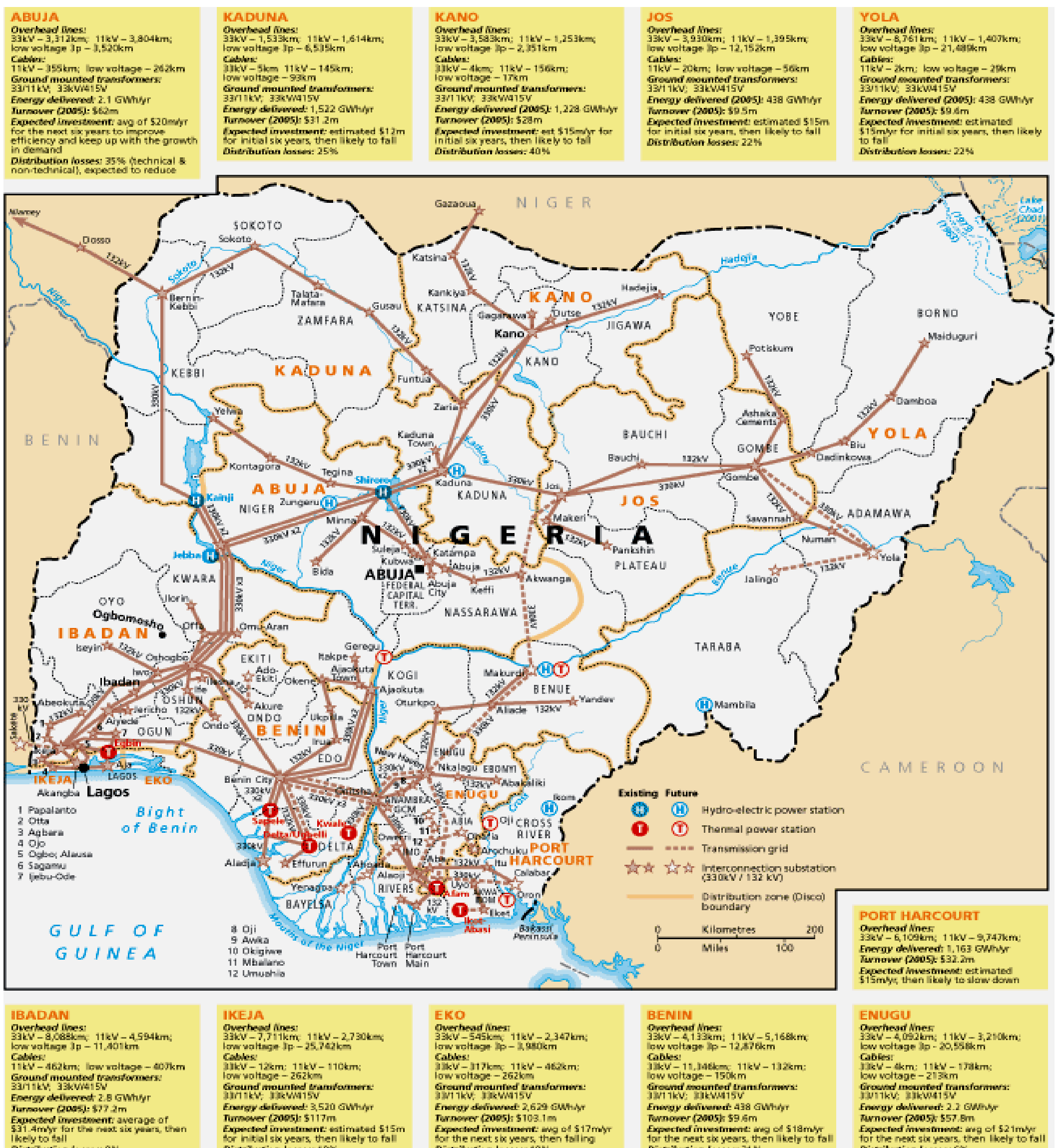

Figure 1: The Transmission Power Lines across Nigeria

Transmissions of power usually require various components to ensure power reliability and access. Balanced condition of power system exists at normal operation, this balanced condition is offset when fault occurred, faults on the power system can be caused by several factors such as blowing of wind, collapse of a tree, failure due to mechanical fault in transformer, ice storm rain

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and a host of others [1]. A power system can be analysed by computing system's voltage magnitude as well as the angle coupled with system's current both at normal and faulty conditions. Fault exists on power system when the magnitude of the current flowing within the system is comparatively larger than the designed value capable of damaging the system equipment. Surge in the value of current leads to system interruption and as a result system voltage level changes drastically, surge in voltage is undesirable within power system, it has adverse effect on insulation of power system associated equipment. Similarly, when the system voltage goes down beyond the minimum permissible level, system failure is unavoidably inevitable [2], [10].

Thus, power system analysis usually involve fault studies, especially when transmission lines are involved due to environmental and load conditions, and as such is an invaluable tool. These faults can be broadly classified into two; three-phase balanced faults and unbalanced faults. Selection and setting of phase relays rely on information obtained from three-Phase balanced faults, ground relays are determined from unbalanced faults, while fault analysis as a whole finds application in determination of protective switch gear rating [9], [12].

1.1. Transmission Line Assessment and Analysis Problems

The surge in the demand for electricity by this present day teeming population can be attributed to improved economic activities caused by geometric population increase and social advancement [11], [13]. The direct effect of this surge in power demand has placed increased burdens on the existing transmission accessories thereby causing the line to be over-stretched beyond their designed capability. Undue increased line loading expressed in form reduced power quality and severe power outages. Onojo, (2016) argued that energy consumption trails tracks with the national product, and therefore the degree of energy consumption per capita is a vital indicator of economic rejuvenation [13].

Generally, countries with higher per capita energy consumption are viewed to be well developed compared to those countries whose level of consumption is comparatively low. Onojo, (2016) reported that the security of power system against unanticipated outages is a vital requirement in determining the effective performance of any power system in terms of network security [13]. It is very important to be able to predict the extent of violations that can occur in the network in the event of unprecedented contingencies. This still comes down to inefficiencies present in power management in order to handle these unprecedented contingencies. According to Das, (2005), the then NEPA lacks satisfactory indigenous manpower to handle sophistication inherent with this modern energy and power industry, hence the reflection of power performance of its aging infrastructures engaged along its supply chain [7].

Abnormal condition is upset in power system when fault occurred, faults occurring on power transmission lines can be grouped into two balanced and unbalanced fault, otherwise called symmetrical and asymmetrical fault accordingly. By experience, unbalance faults occurred more frequently than the other [7], [12], [15]. Faults can as well be classified either as series and shunt faults; series faults occur in the line impedance and exclude involvement of neutral or ground connection, not the interconnection between the phases. Detection and classification of fault is an hurricane task and several classification approach has been attempted over time which boiled down to travelling waves, neural networks, adaptive Kalman filtering, fuzzy logic, and the fusion of diverse artificial intelligence approaches [6], [14], [18].

1.2. Fault Analysis

Interference with the normal flow of current which result into system failure is called fault in power system. Nifong, (2013) reported that lightning stroke which most times result in flashover in insulator is a major cause of faults that occur frequently on 132 kV transmission lines and higher version [10]. The high voltage between a conductor and the grounded supporting tower result in ionization, which creates a link to ground for lightning stroke induced. Once the ionized route to ground is created, the resultant low impedance to ground permits current flow from the conductor to ground and via the ground to the transformer grounded neutral or generator, thus the circuit is completed [11], [17], [20].

Faults like line-to-line fault rarely occurred; opening of circuit breakers with a view to disconnected the faulted part of the line from the remaining healthy lines interferes and consequently interrupts the flow of current in the ionized route, thereafter permits deionization to occur [16]. The circuit breaker many at time closes without establishing the arc after about 20 cycles interval of deionization. Over time, it has been shown that ultra-high-speed reclosing breakers employed on the operation of transmission lines re-recloses successfully after most faults. However, when permanent faults occur on the line, it is impossible for the circuit breaker to reclose irrespective of the interval involved in opening and reclosing of the circuit breaker [4], [19]. The causes of many of the permanent faults on transmission lines include breaking of insulator string as a result of ice loads, tower permanent damage, lines being on the ground and failure of the surge-arrester among others [18].

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The report of Nifong (2013) established that single line-to-ground faults account for about 70 and 80% of transmission-line faults, which was caused by flashover of only one line to the neighbouring tower and finally to the ground. An estimate of 5% of all faults occur at the three other phases [10]. Other types of transmission-line faults are line-to-line faults, which do not involve ground, and double line-to-ground faults. All the above faults except the three-phase type cause an imbalance between the phases, and so they are called unsymmetrical faults [13].

The current that flow prior and after the occurrence of faults in different section of power system differs considerably in magnitude much later after few cycle the circuit breaker has responded to perform its intended function [20]. These currents vary widely from the currents that normally flow under steady-state conditions as at when the faulty session has not been disconnected with the aid of the circuit breaker. The selection of circuit breakers depends on the current the breaker has the capacity to interrupt and the current that flows immediately the fault has occurred. Generally, when embarking on fault analysis, the values of these currents have to be re-evaluated for the different kind of faults occurring at different locations within the system. The data gotten from fault calculations are very vital in the determination of relays and control the circuit breakers settings [22-23].

1.3. Load Flow Studies

In fault analysis, one major analysis that helps to explain the behaviour of a system under fault is load flow. This gives a pictorial view of the parameters of the network under this condition such as the bus voltage, bus phase angle, line currents, power flow in the line and line losses [21]. In load flow, one-line diagram and per-unit system are utilized, and focuses on several AC power parameters such as voltage magnitude and angles, real and reactive power. Generally, the major information gotten from such analysis includes bus voltage magnitude and angle, the active and reactive power flowing along each transmission line. Most often performing such analysis by hand can be a tedious exercise, and such tasks are well suited for computers running specialized software that can execute calculations such as short-circuit fault analysis, economic dispatch, transient stability studies, steady-state stability studies, and unit commitment [2], [21].

In executing load flow studies, generation capacity and load conditions are usually specified at the onset of the program, this serves as the termination criterion. The information acquired from this study is useful in testing the system's ability to handover energy right from generation sites to load centres without the line being overloaded. It is well helpful in determining voltage regulation adequacy via devices such as On-Load Tap-Changing (OLTC) transformers, shunt capacitors, shunt reactors, and VAR-supplying potential of rotating machines. The power at i^{th} bus of an n-bus power system is given as; [17], [23]

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Li} - P_{Ti}) + j(Q_{Gi} - Q_{Li} - Q_{Ti}) \quad (1)$$

where;

S_i =i^{th} bus3∅ −complex power; P_i = 3∅ − real power at i^{th} bus, Q_i = 3∅ −phase reactive power at i^{th} bus, P_{Gi} = 3∅ −real generated power flowing into i^{th} bus, P_{Li} = 3∅ −real load power flowing out of i^{th} bus, P_{Ti} = 3∅ −real transmitted power flowing out of ith bus, Q_{Gi} = 3∅ −reactivegenerated power flowing into i^{th} bus, Q_{Li} = 3∅ −reactive load power flowing out of i^{th} bus Q_{Ti} = 3∅ −reactive transmitted power flowing out of i^{th} bus.

The basic assumption guiding load flow studies is that the power system is assumed to be a balanced three-phase system which operate at a steady state with a constant frequency of 50-Hz. Single-phase positive-sequence network either with a lumped series or shunt branches are employed to depicted the system to be investigated. In addition, both the impedance and admittance bus matrix can be used to address power flow studies of a given network. It is customary to use the nodal analysis approach. Given the magnitude of voltage at each bus, the current can be determined thus; [21]

$$[I_{bus}] = [Y_{bus}][V_{bus}] \quad (2)$$

$$[V_{bus}] = [Y_{bus}]^{-1}[I_{bus}] \quad (3)$$

$$[V_{bus}] = [Z_{bus}][I_{bus}] \quad (4)$$

The nodal real and reactive powers are treated as the independent variables while nodal voltages are treated as dependent variables in power flow analysis. The evaluation of nodal voltages appear to be simple when nodal currents are specified, however,

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it, becomes a nonlinear problem which can only be solved using iterative solution techniques. Every bus in a given network has real, reactive voltage magnitude and angle as it associated variables, two of these four variables can be handled as independent variables being specified, hence the remaining two has to be determined [18]. Real and reactive power are employed to define the physical features of both generation and load at each bus rather than using current at each bus. The complex power flowing into the i^{th} bus is given as [15];

$$V_i I_i^* = P_i + jQ_i \tag{5}$$

Thus, the current at bus i^{th} is obtained thus [20];

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{6}$$

In addition, buses in power system are classified as slack, generator and load buses during load flow analysis. The generator at the slack bus supplies the supplementary real and reactive power required as a result of transmission losses. In addition, at a bus where both voltage magnitude and angle are known such bus is termed slack bus, in that case both the bus real and reactive power has to be evaluated [18]. Similarly, bus voltages are known only when the iterative solution converged. In other words, the losses in the system cannot be known in advance, therefore specification of power at the slack bus becomes impossible. In addition, bus whose real power and its voltage magnitude are known, such bus is called generator bus, these known quantities can be controlled via the governor and excitation controls, accordingly. The generator bus is well-known as *P***V** bus. It is worth mentioning that overexcited synchronous generator delivers current at a lagging power factor, consequently the reactive power (*Q)* of a generator need not be specified [4], [19], [23].

The load bus called *PQ* bus has its real and reactive power specified bus. Table 1 presented a quick summary of different types of buses, the known quantities and the quantities that needs to be evaluated at each bus. The voltage at the slack bus called the reference bus usually has its voltage set to be 1.0 p.u and its phase angle is assumed to be 0°. Load buses with transformers that have the ability for tap-changing and shifting operations are otherwise called voltage-controlled load buses [9]. At the voltage-controlled load buses, there are has the voltage magnitude, real and reactive powers as known quantities while voltage phase angle and the turns ratio are the unknown quantities. Algorithms such as Newton-Raphson (NR), DC Power Flow,Gauss-Seidel (GS), Decoupled Power Flow (DPF), and Fast Decoupled Power Flow (FDPF) have been extensively used to address power load flow [11], [21].

Table 1: Summary of bus classification

Bus Type	Specified Quantities	Quantities to be determined
Slack	$\|V\| = 1.0$ $\theta = 0$	P, Q
Generator (PV bus)	P, $\|V\|$	Q, θ
Load (PQ bus)	P, Q	$\|V\|$, θ

1.4. Probabilistic Load Flow

The integration of renewable energy with the traditional national grid has drastically changed the face of modern power system and also several uncertainties has being introduced as constraints too. Such cases are best handled using probabilistic load flow, which provides all-inclusive information regarding operation and planning power system [9]. In addition, uncertainties can also be introduced due to environmental changes that might affect generating and transmission utilities and as such is vital in providing realistic results compared to conventional load flow. Lots of efforts have being made in the area of probabilistic load flow models which also taking into consideration uncertainty characterisation and uncertainty handling methods [1], [23].

Multivariate-Gaussian mixture approximation is an efficient analytical approach that has been proposed for accurate estimation of probabilistic load flow analysis. This technique takes into consideration peculiar uncertainties regarding photovoltaic generations load demands and incorporation of multiple input correlations [11]. This approach was tested and implemented on modified IEEE 118-bus test case system. The result obtained were compared with three different techniques

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such as Monte Carlo simulation, univariate-gaussian mixture approximation and series expansion based cummulant technique using execution and accuracy as the performance matrix [22].

In addition, probabilistic load flow can utilise the numerical approach adopting the Monte-Carlo (MC) method. The two foremost characteristics of Monte Carlo simulation include generation of number on random basis and the sampling is by randomization. Sampling approaches are rather sophisticated but with this deterministic approach actualisation of load flow is possible. However, for inputs of diverse combinations of nodal power the iteration has to run severally before it converges [15], [21].

Furthermore, arithmetic operation such as convolution method forms the fundamental basis of analytical approaches, with Probability Density Function (PDF), power system stochastic variable inputs such as system state variables as well as the line flows can be obtained. However, the challenges usually encountered when solving load flow by convolution of PDFs is that load flow equations are predominantly non-linear and similarly, power input variable at different buses within a typical power system are entirely independent of linear correlations [6]. Solving power flow problem with analytical technique entails the following basic assumptions: load flow equations are assumed to be linear, power variables are assumed to be totally independent of linear correlations, the network reconfiguration as well as the network parameters are assumed to be constant and lastly, load and generation are assumed to be normal and discrete in distribution.

The load flow equations are usually linearized around the approximated mean of the system states $\hat{X}$ usingTaylor expansion limited to the first-order. If the generalized form of this approach is expressed using equation 7 and 8, gives [12];

$$Y = f(X) \tag{7}$$

$$X \approx \hat{X} + A\left(Y - \hat{Y}\right) \tag{8}$$

"A" stands for matrix sensitivity coefficient and is given by equation (9) thus;

$$A = \left(\frac{\partial f}{\partial X}\bigg|_{X=\hat{X}}\right)^{-1} \tag{9}$$

Application of Newton-Raphson technique to solve deterministic load flow entails the formulation of Jacobian matrix A, which is calculated for each iteration until errors of the results are comparatively less than specified values usually proposed at the onset. However, with this approach, Jacobian matrix is only calculated once for the computation of each load flow. The errors resulting from load flow equation linearization should be well taken care of aside being noted. Equation 10 depicts that the system states are stated by linearizing combination of power input variables [4], [17], [19].

$$f(X_i) = f\left(Y_1 - \hat{Y}_1\right) \times f\left(Y_2 - \hat{Y}_2\right) \times \cdots \times f\left(Y_n - \hat{Y}_n\right) \tag{10}$$

2. MATERIALS AND METHOD

In this research paper, a fault location analysis on the transmission line model was performed with bus impedance matrix method on Iwo-Osogbo 132 kV transmission line network using the probabilistic transmission line model. The data required to carry out this study include the bus data (bus name, the magnitude of the voltage, and voltage angle) and the line data (the impedance and transformer tap setting). These data were collected from National Control Centre (NCC) of the Transmission Company of Nigeria (TCN), Osogbo, Nigeria. Table 2 showed the respective bus names of the Iwo-Osogbo 132 kV transmission line.

This bus impedance matrix method was used for fault analysis in conjunction with load flow study to establish network operation both at the steady state and under fault condition. Both three phase symmetrical fault and the un-symmetric faults were investigated. This technique makes the analysis of a typical three phase un-symmetrical faults easier coupled with the fact that it avoids unnecessary complexity associated with the three sequence networks when it comes to evaluation of bus voltage and bus current under fault condition.

The development of network sequence such as positive, negative and zero-sequence is vital for the analyses of unsymmetrical faults. The developed sequence is required to evaluate the impedance of 3 $\emptyset$- thevenin equivalent circuits viewed from the faulty points. In order to determine both 3 $\emptyset$-currents that flow from one bus to another as well as each bus 3 $\emptyset$- voltages, one needs to carefully connect three sequence networks distinctively for each fault category. With the usage of network having the whole of the

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three sequence linked together, it becomes increasingly difficult to appreciate the technique of impedance matrix for computing each bus voltage sequence under fault.

The above identified drawbacks was overcome with the technique proposed by Zhang and Kezunovic, (2009), the proposed technique unified the analysis of a typical three phase unsymmetrical faults [22]. With this approach, all steps were shared except the one involving computation of positive, negative, and zero-sequence components of phase--to-ground fault current at the point of fault. Similarly, understanding of impedance matrix approach for computing each bus sequence voltage becomes easier.

The mathematical representation below is valid when different un-symmetrical faults are applied. When fault occurred, the fault voltage magnitude is given using equation (11);

Table 2: Iwo-Osogbo 132 kV Transmission Line Bus Names

Bus Number	**Bus Names**
1	Akure
2	Ayede
3	Benin
4	Ife
5	Ijebu
6	Ikeja Wset
7	Ilorin
8	Iseyin
9	Iwo
10	Jebba
11	Jebba G
12	Jerico
13	Kainji
14	Omuaharan
15	Ondo
16	Osogbo
17	Shiroro

$$V_{ka} = Z_f I_{fa}, I_{fb} = I_{fc} = 0 \quad (11)$$

Upon the mathematical formulation, per-unit system was adopted, each bus zero-sequence voltage caused by equivalent current source is obtained using equation (12a) thus;

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$$\begin{bmatrix} Y_{11}^{(0)} & Y_{12}^{(0)} & \cdots & Y_{1k}^{(0)} & \cdots & Y_{1n}^{(0)} \\ Y_{21}^{(0)} & Y_{22}^{(0)} & \cdots & Y_{2k}^{(0)} & \cdots & Y_{2n}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{k1}^{(0)} & Y_{k2}^{(0)} & \cdots & Y_{kk}^{(0)} & \cdots & Y_{kn}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1}^{(0)} & Y_{n2}^{(0)} & \cdots & Y_{nk}^{(0)} & \cdots & Y_{nn}^{(0)} \end{bmatrix} \begin{bmatrix} V_{1f}^{(0)} \\ V_{2f}^{(0)} \\ \vdots \\ V_{kf}^{(0)} \\ \vdots \\ V_{nf}^{(0)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_{fa}^{(0)} \\ \vdots \\ 0 \end{bmatrix} \quad (12a)$$

where $Y^{(0)}$ giving by equation (12b) is the admittance matrix representing sub-transient or transient for zero-sequence system.

$$\boldsymbol{Y^{(0)}} = \begin{bmatrix} Y_{11}^{(0)} & Y_{12}^{(0)} & \cdots & Y_{1k}^{(0)} & \cdots & Y_{1n}^{(0)} \\ Y_{21}^{(0)} & Y_{22}^{(0)} & \cdots & Y_{2k}^{(0)} & \cdots & Y_{2n}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{k1}^{(0)} & Y_{k2}^{(0)} & \cdots & Y_{kk}^{(0)} & \cdots & Y_{kn}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1}^{(0)} & Y_{n2}^{(0)} & \cdots & Y_{nk}^{(0)} & \cdots & Y_{nn}^{(0)} \end{bmatrix} \quad (12b)$$

Then;

$$\begin{bmatrix} V_{1f}^{(0)} \\ V_{2f}^{(0)} \\ \vdots \\ V_{kf}^{(0)} \\ \vdots \\ V_{nf}^{(0)} \end{bmatrix} = \begin{bmatrix} Z_{11}^{(0)} & Z_{12}^{(0)} & \cdots & Z_{1k}^{(0)} & \cdots & Z_{1n}^{(0)} \\ Y_{21}^{(0)} & Z_{22}^{(0)} & \cdots & Z_{2k}^{(0)} & \cdots & Z_{2n}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{k1}^{(0)} & Z_{k2}^{(0)} & \cdots & Z_{kk}^{(0)} & \cdots & Z_{kn}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{n1}^{(0)} & Z_{n2}^{(0)} & \cdots & Z_{nk}^{(0)} & \cdots & Z_{nn}^{(0)} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_{fa}^{(0)} \\ \vdots \\ 0 \end{bmatrix} = \; = Z^{(0)} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_{fa}^{(0)} \\ \vdots \\ 0 \end{bmatrix} \quad (13)$$

where;

$$Z^{(0)} = \begin{bmatrix} Z_{11}^{(0)} & Z_{12}^{(0)} & \cdots & Z_{1k}^{(0)} & \cdots & Z_{1n}^{(0)} \\ Z_{21}^{(0)} & Z_{22}^{(0)} & \cdots & Z_{2k}^{(0)} & \cdots & Z_{2n}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{k1}^{(0)} & Z_{k2}^{(0)} & \cdots & Z_{kk}^{(0)} & \cdots & Z_{kn}^{(0)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{n1}^{(0)} & Z_{n2}^{(0)} & \cdots & Z_{nk}^{(0)} & \cdots & Z_{nn}^{(0)} \end{bmatrix} \quad (14)$$

So;

$$\begin{bmatrix} V_{1f}^{(0)} \\ V_{2f}^{(0)} \\ \vdots \\ V_{kf}^{(0)} \\ \vdots \\ V_{nf}^{(0)} \end{bmatrix} = \begin{bmatrix} -Z_{1k}^{(0)} I_{fa}^{(0)} \\ -Z_{2k}^{(0)} I_{fa}^{(0)} \\ \vdots \\ -Z_{kk}^{(0)} I_{fa}^{(0)} \\ \vdots \\ -Z_{nk}^{(0)} I_{fa}^{(0)} \end{bmatrix} \quad (15)$$

The positive-sequence voltage occurring at each bus as a result of equivalent current source is given by equation (16) thus;

$$\begin{bmatrix} Y_{11}^{(1)} & Y_{12}^{(1)} & \cdots & Y_{1k}^{(1)} & \cdots & Y_{1n}^{(1)} \\ Y_{21}^{(1)} & Y_{22}^{(1)} & \cdots & Y_{2k}^{(1)} & \cdots & Y_{2n}^{(1)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{k1}^{(1)} & Y_{k2}^{(1)} & \cdots & Y_{kk}^{(1)} & \cdots & Y_{kn}^{(1)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1}^{1} & Y_{n2}^{(1)} & \cdots & Y_{nk}^{(1)} & \cdots & Y_{nn}^{(1)} \end{bmatrix} \begin{bmatrix} \Delta V_{1f}^{(1)} \\ \Delta V_{2f}^{(1)} \\ \vdots \\ \Delta V_{kf}^{(1)} \\ \vdots \\ \Delta V_{nf}^{(1)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_{fa}^{(1)} \\ \vdots \\ 0 \end{bmatrix} \quad (16)$$

This gives;

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$$\begin{bmatrix}\Delta V_{1f}^{(1)}\\ \Delta V_{2f}^{(1)}\\ \vdots\\ \Delta V_{kf}^{(1)}\\ \vdots\\ \Delta V_{nf}^{(1)}\end{bmatrix}=\begin{bmatrix}Z_{11}^{(1)} & Z_{12}^{(1)} & \cdots & Z_{1k}^{(1)} & \cdots & Z_{1n}^{(1)}\\ Y_{21}^{(1)} & Z_{22}^{(1)} & \cdots & Z_{2k}^{(1)} & \cdots & Z_{2n}^{(1)}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ Z_{k1}^{(1)} & Z_{k2}^{(1)} & \cdots & Z_{kk}^{(1)} & \cdots & Z_{kn}^{(1)}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ Z_{n1}^{1} & Z_{n2}^{(1)} & \cdots & Z_{nk}^{(1)} & \cdots & Z_{nn}^{(1)}\end{bmatrix}\begin{bmatrix}0\\0\\ \vdots\\ -I_{fa}^{(1)}\\ \vdots\\ 0\end{bmatrix}=\begin{bmatrix}-Z_{1k}^{(1)}I_{fa}^{(1)}\\ -Z_{2k}^{(1)}I_{fa}^{(1)}\\ \vdots\\ -Z_{kk}^{(1)}I_{fa}^{(1)}\\ \vdots\\ -Z_{nk}^{(1)}I_{fa}^{(1)}\end{bmatrix} \quad (17)$$

Ignoring the pre-fault current, pre-fault voltage that occurred at each buses both the same and as well equal to bus k voltage (V_f) before the occurrence of fault. Equation (18) gives each bus positive sequence voltage at occurrence of fault occurs;

$$\begin{bmatrix}V_{1f}^{(2)}\\ V_{2f}^{(2)}\\ \vdots\\ V_{kf}^{(2)}\\ \vdots\\ V_{nf}^{(2)}\end{bmatrix}=\begin{bmatrix}-Z_{1k}^{(2)}I_{fa}^{(2)}\\ -Z_{2k}^{(2)}I_{fa}^{(2)}\\ \vdots\\ -Z_{kk}^{(2)}I_{fa}^{(2)}\\ \vdots\\ -Z_{nk}^{(2)}I_{fa}^{(2)}\end{bmatrix} \quad (18)$$

3. RESULTS & DISCUSSION

The simulation results obtained after successful implementation of probabilistic transmission line model on Iwo-Osogbo 132 kV transmission lines is presented. The technique employed was realized using MATLAB 8.1.0.604 (R2013b). Probabilistic load flow method was used as tool to carry out the system load flow. The load flow analysis results obtained with this technique under pre-fault condition are presented in Figure 2 to 6.

The voltage magnitude and phase angle under pre-fault scenario are depicted in Figures 2 and 3. The load flow results show the state of all the buses concerned in the analysis with all the buses operating within voltage operating limits; 1.1 per unit maximum and 0.9 per unit minimum, with an apparent power base of 100 MVA. It also showed the operating power injected by the various buses in per unit. Voltages at these buses were severe affected when fault was applied on Iwo-Osogbo 132kV transmission line, especially the non-generator buses with per unit values far below the bus voltage operating limit. These caused a total blackout to protect the generators. The effect of fault Kainji bus is as depicted in Figures 4 and 5 respectively.

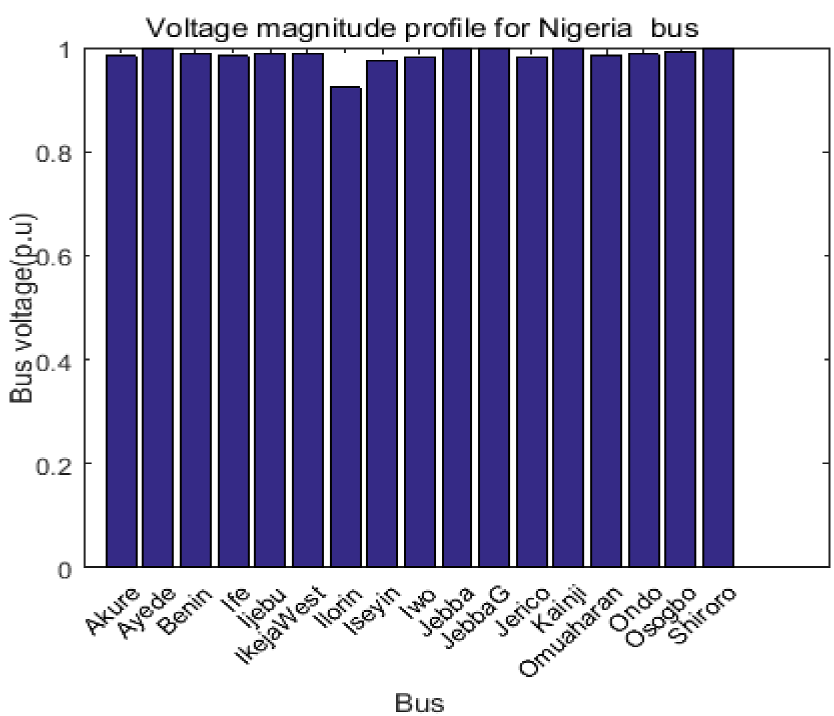

Figure 2: Pre-fault Bus Voltage Profile of Iwo-Osogbo 132 kV Transmission System

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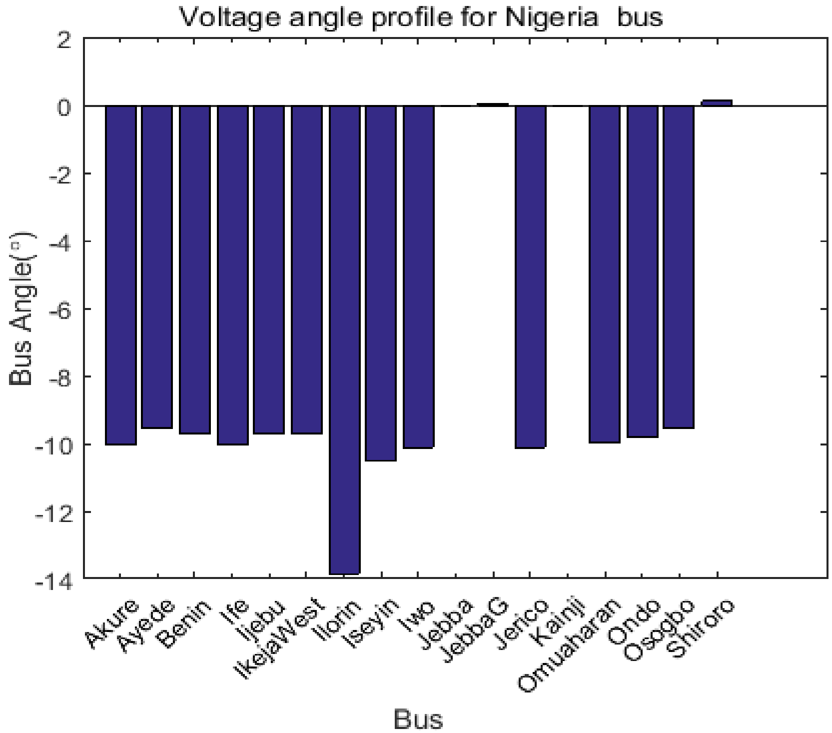

Figure 3: Bus Voltage Phase Angle

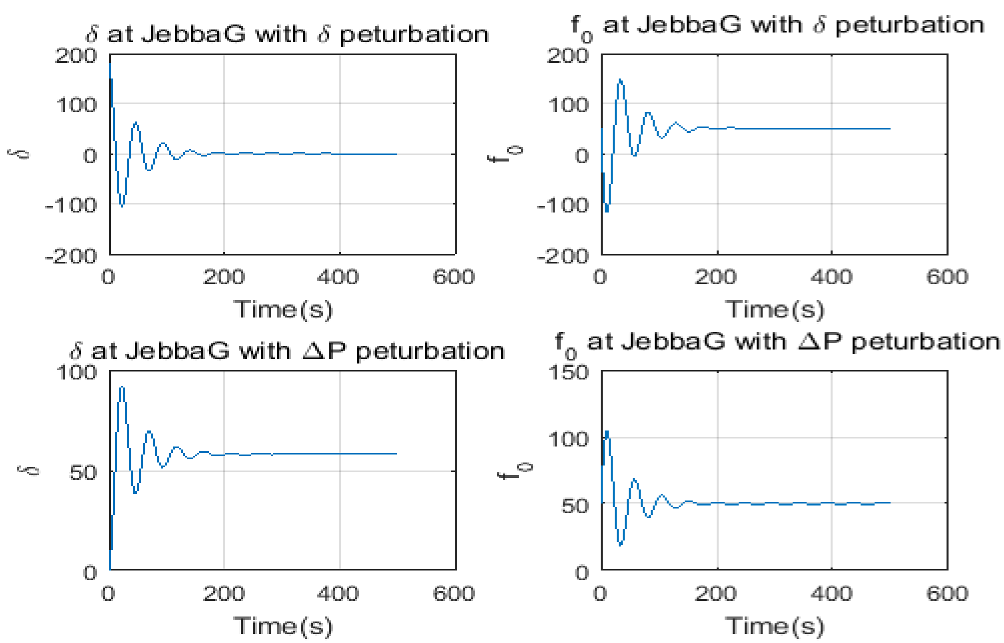

Figure 4: Stability analysis reveals the reaction of the generators buses at Jebba G.S (rotor angle perturbation at Jebba G.S) due to fault at Iwo-Osogbo Bus

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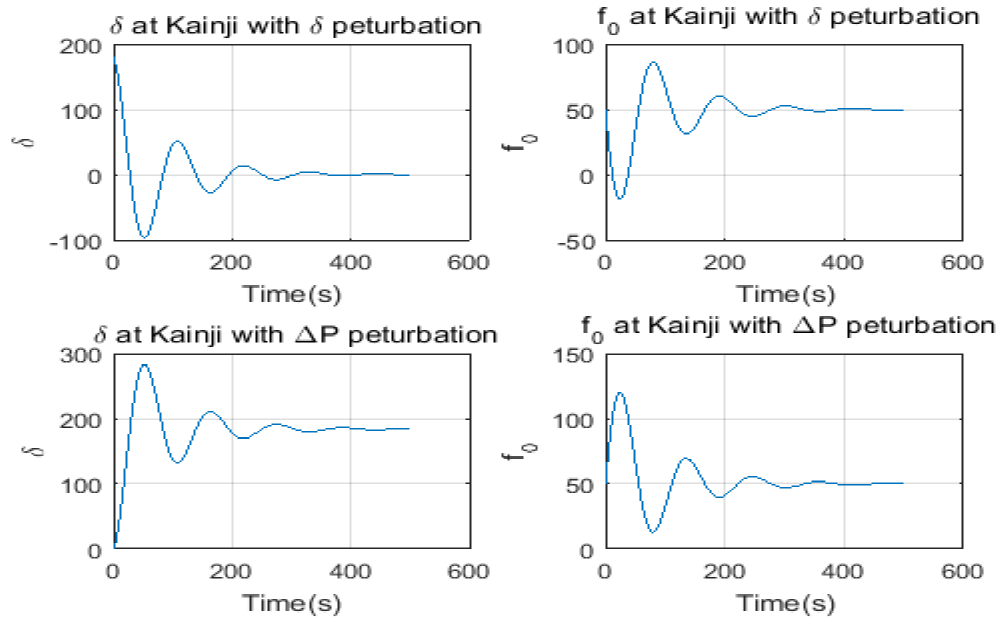

Figure 5: Stability analysis reveals the reaction of the generators buses at Kainji (rotor angle perturbation at Kainji) due to fault at Iwo-Osogbo Bus

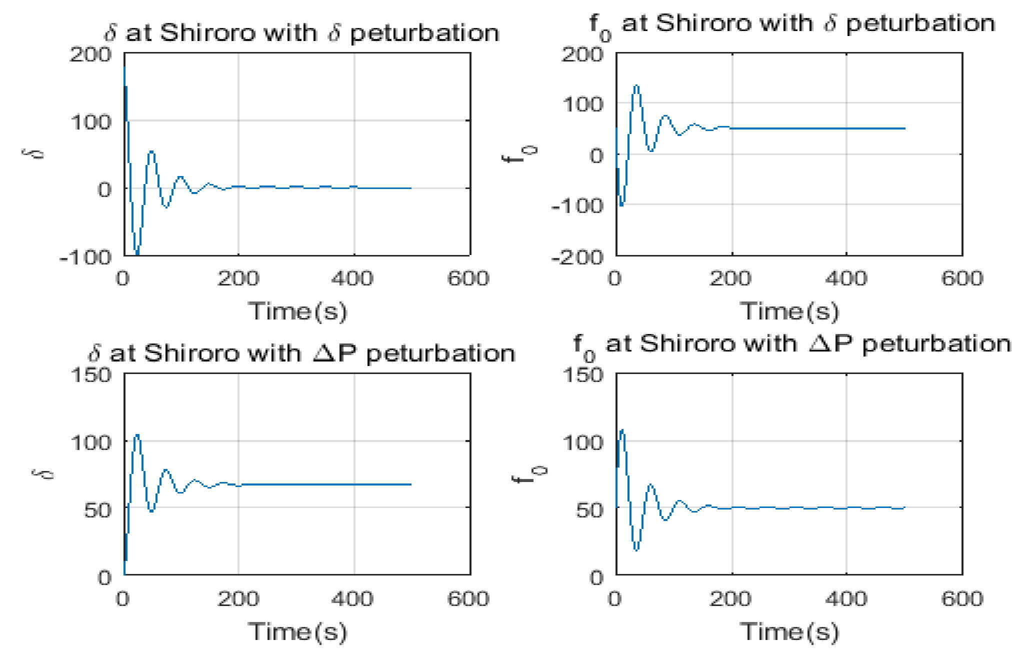

Figure 6: Stability analysis reveals the reaction of the generators buses at Shiroro (rotor angle perturbation at Shiroro) due to fault at Iwo-Osogbo Bus

It was obvious that the Iwo-Osogbo transmission line having a fault showed a tendency to bring down the network, but compared to a fault on the Kainji bus, a few of the bus, especially localized and close to the Kainji Bus experienced the fault, with the Iwo bus experiencing a slight drop in voltage but still within the operating limits. This is due to the Ayede bus in close proximity which helped in keeping the Iwo-Osogbo bus within operating limits.

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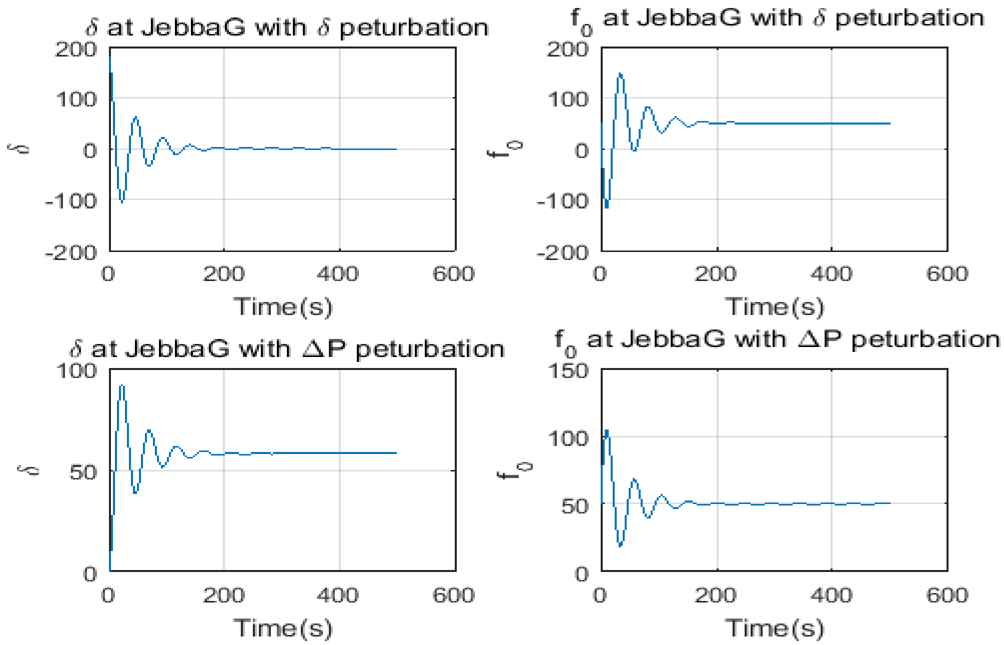

Figure 7: Stability analysis reveals the reaction of the generators buses at Jebba G.S (rotor angle perturbation at Jebba G.S) due to fault at Kainji Bus

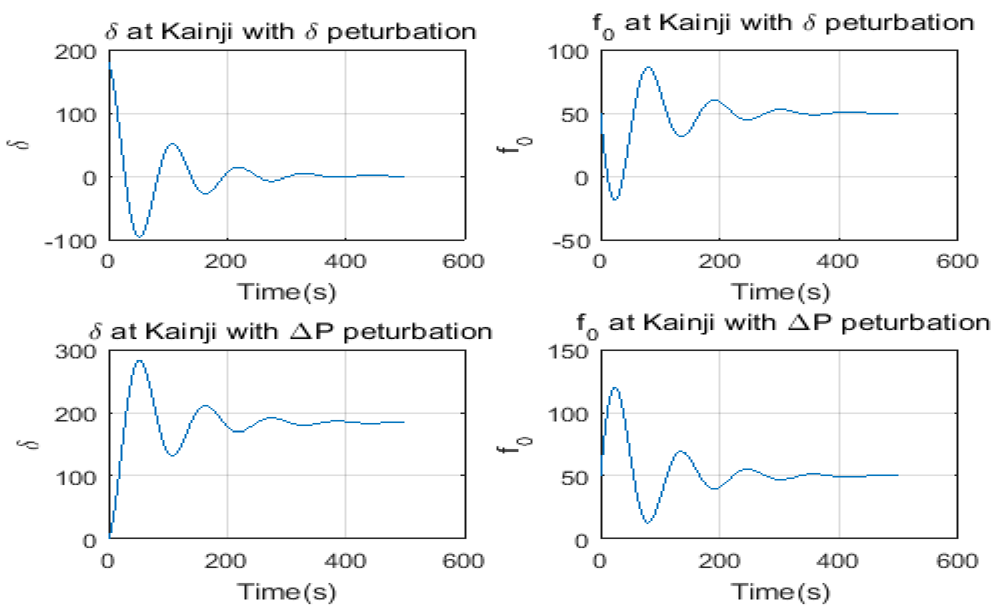

Figure 8: Stability analysis reveals the reaction of the generators buses at Kainji (rotor angle perturbation at Kainji) due to fault at Kainji Bus

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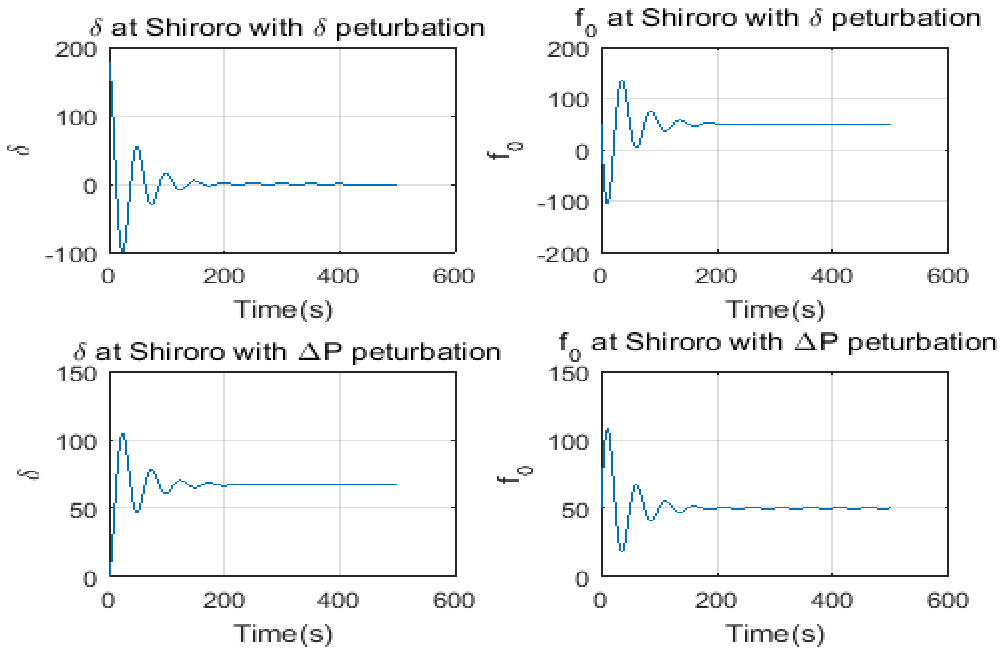

Figure 9: Stability analysis reveals the reaction of the generators buses at Shiroro (rotor angle perturbation at Shiroro) due to fault at Kainji Bus

The extent of stability as seen in Figures 4, 5 and 6 with the fault occurring on the Iwo-Osogbo 132 kV transmission bus compared to that of Figures 7, 8 and 9 was as a result of fault on the Kainji 132kV transmission bus, showing higher instability. The instability showed the effect of fault on the generators supplying power to the network as seen on the load angle. The upper half of the plots showed how the generator's variability due to perturbation on the generator prime mover itself and on how it affected the load angle compared to the lower half due to sudden power supply injected because of applied fault. It can be seen that perturbation was higher with power perturbation (ΔP) compared to prime mover perturbation ($\Delta\delta$). It was also observed that fault current was always much higher compared to non-faulty conditions.

4. CONCLUSION

This research paper has demonstrated the applications of Probabilistic load flow technique on fault analyses on Iwo-Osogbo 132kV transmission system using transmission line model. MATLAB/Simulink was used in implementing this model and the system stability was as well investigated. From the results obtained, it was discovered that the occurrence of fault at specified buses adversely affected the magnitudes of bus voltages and angles. It was also observed that faults on the generator bus showed higher instability compared to faults on non-generator bus like the Iwo-Osogbo buses. In addition, bus impedance method is a simplified approach for fault analysis, it is computationally less strenuous and a less complex approach. Finally, the major shortcoming identified with this approach was the computational speed which seems to be relatively lower. The result showed the possibility of applying probabilistic load flow techniques to load flow models with inherent uncertainties.

The research has successfully implemented bus impedance approach for three phase fault analysis on Nigerian sub-transmission systems. It has a well provided expanded literature on bus impedance approach for fault analysis on Nigerian sub-transmission system.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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