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THREE-PHASE FAULT CURRENTS EVALUATION FOR NIGERIAN 28-BUS 330kv TRANSMISSION SYSTEM

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Abstract

Fault studies are important power system analysis for stable and economical operations of power systems. Faults are categorised as symmetrical and unsymmetrical. In this paper, three-phase symmetrical fault is simulated using the Nigerian 28-Bus, 330kV Transmission Grid. Two different MatLab based programmes were developed; one program was for Load Flow Studies which determines pre-fault conditions for the power system based on Newton-Raphson method. The other program determines fault current magnitudes for three-phase short-circuit on the power system. The information gained from the fault studies can be used for proper relay selections, settings, performances and coordination.

Keywords*:* Power System, Power Flow, Three-Phase Fault, Short-Circuit Current.

1. INTRODUCTION

The Nigerian Power System has been expanded; therefore, probability of faults requires new device settings, co ordinations and calculations in order to withstand a fault. A fault is defined as any failure which interferes with the normal current flow [1]. A fault will cause currents of high value (short-circuit current) to flow through the network to the faulted point. Short circuit currents generate heat proportional to the square of their magnitudes may damage the insulation of power system devices such as bus bars, cables, circuit breakers and switches [2].

The purpose of an electrical power system is to generate and supply electrical energy to consumers with reliability and economy. The greatest threat to this purpose of a power system is the short circuit [3]. When the system is so large like the Nigerian system considered in this paper, the chance of a fault occurring and the disturbance it will cause are both so enormous that without equipments to remove faults, the system will collapse. The evaluation of fault currents on a power system is therefore significant because the protective devices to be installed on the system depend on the values of the fault currents.

Fault analysis can be broadly grouped into symmetrical and unsymmetrical faults. A fault involving all the three phases on the power system is known as symmetrical fault or three-phase fault while the one involving one or two phases is known as unsymmetrical fault. Single Line-to-ground, Line-to-line and Double line-to-ground faults are unsymmetrical faults [1][3]. The causes of faults are numerous and they include lightning, insulation aging, heavy winds, trees falling across lines, vehicles colliding with poles, birds, kites, etc [1]. The effects of faults on power system are:

(i) Due to overheating and mechanical forces developed by faults, electrical equipments such as bus-bars, generators and transformers may be damaged.

(ii) The voltage profile of the system may be reduced to unacceptable limits as a result of fault. A frequency drop may lead to instability [4].

Majority of faults occurring on power systems are unsymmetrical faults, however, the circuit breaker rated MVA breaking capacity is based on three-phase symmetrical faults. The reason is that a three-phase fault produces the greatest fault current and causes the greatest damage to a power system. The only exception to this is a single line-to-ground fault occurring very close to a solidly grounded generator's terminal [3]. Short circuit studies involve finding the voltages and currents distribution throughout the power system during fault conditions so that the protective devices may be set to detect and isolate the faulty portion of the power system so as to minimize the harmful effects of such contingencies [5].

The state at which a power system is before a fault occurs is known as the steady state of the power system. The analysis performed at this state is called power flow analysis. Power flow analysis is the backbone of power system analysis; in this analysis, the power system network is modelled as an electric network and is solved for the steady state power and voltages at various buses [6].

Power system fault analysis is one of the basic problems in power system engineering. The results of power system fault analysis are used to determine the type and size of the protective system to be installed on the system so that continuity of supply is ensured even when there is a fault on the power system. The current trend of erratic power supply in Nigeria has made this study important to the nation's power industry. The single line diagram of the Nigerian National Grid is shown in Figure 1.

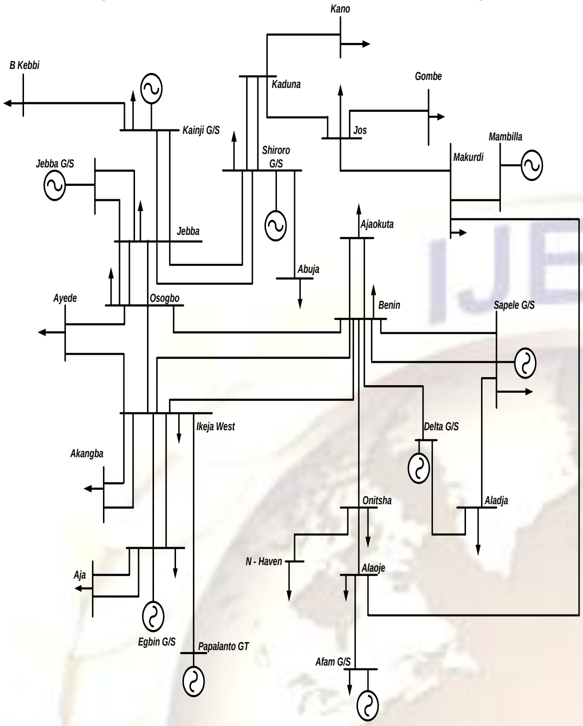

Figure 1: Nigerian 28- Bus Transmission Grid

2 MATERIALS AND METHODS

2.1. Preliminary Calculations

In short circuit studies, it is necessary to have the knowledge of pre-fault voltages and currents. These pre-fault conditions can be obtained from the results of load flow studies by the Newton-Raphson iteration method. The Newton-Raphson method is adopted due to quadratic convergence of bus voltages, high accuracies obtained in a few iterations. The number of iterations remains practically constant irrespective of the size of the power system. Convergence is not affected by the choice of slack bus and the presence of series capacitors which causes poor convergence in other methods of solution [7].

This method begins with initial guesses of all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses). Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations. The result is a linear system of equations that can be expressed as: [8].

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (1)$$

where ΔP and ΔQ are called the mismatch equations:

$$\Delta P_i = -P_i + \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right) \quad (2)$$

$$\Delta Q_i = -Q_i + \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right) \quad (3)$$

and J is a matrix of partial derivatives known as a Jacobian:

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix} \quad (4)$$

The linearized system of equations is solved to determine the next guess $(m + 1)$ of voltage magnitude and angles based on:

$$\theta^{m+1} = \theta^m + \Delta\theta \quad (5)$$

$$|V|^{m+1} = |V|^m + \Delta|V| \quad (6)$$

The process continues until a stopping condition is met. A common stopping condition is to terminate if the norm of the mismatch equations are below a specified tolerance. A rough outline of solution of the power flow problem using Newton-Raphson method is depicted in Figure 2:

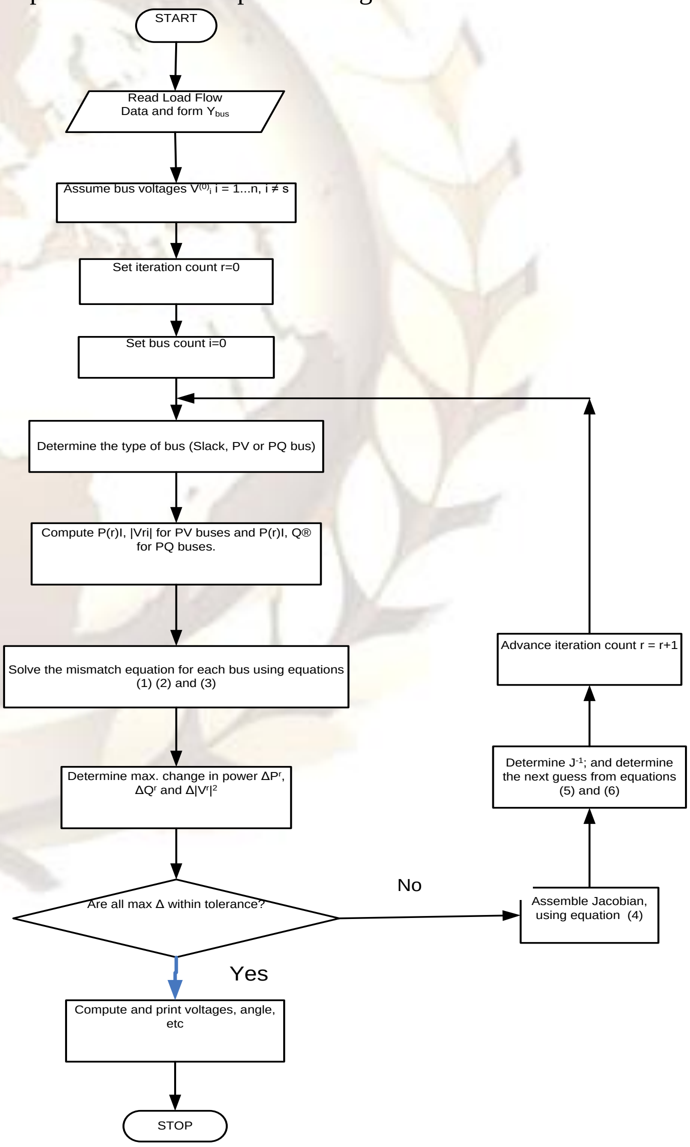

Figure 2: Flow Chart for Newton-Raphson Power Flow Method.

2.2 Fault Analysis Problem Formulation

2.2.1 Bus Impedance Formulation

The admittance bus matrix formed and used in load flow analysis has to be inverted to obtain the impedance bus matrix for easy calculation process. The best method employed for digital calculation is a step by step programmable technique, which proceeds branch by branch. It has the advantage that any modifications of the network do not require complete rebuilding of Z_{bus}. It is described in terms of modifying an existing bus impedance matrix designated as $|Z_{bus}|_{old}$. This new modified matrix is designated as $|Z_{bus}|_{new}$. [9]. This is described as follows:

Let Z_b = Branch Impedance

Zbus(old) ⟶ Zbus(new)

The general n-port network shown in Figure 3 can be described by the following system of equations.

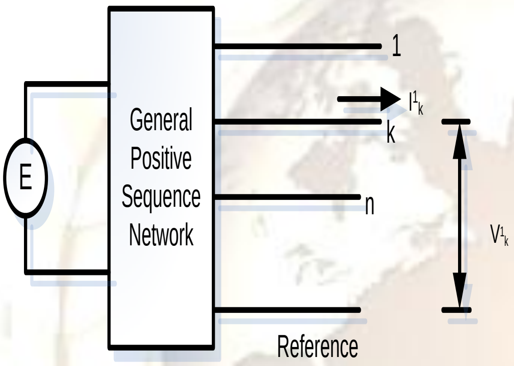

Figure 3: Positive Sequence Network Modified for Fault Analysis [9].

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{i1} & Z_{i2} & \cdots & Z_{in} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} \quad (7)$$

Or simply,

$$V_{bus} = [Z_{bus}] I_{bus} \quad (8)$$

Where

V_{bus} is the bus voltage (nx1) is a column vector,

I_{bus} is the bus current (nx1) is a column vector and Z_{bus} is the bus impedance (nxn) matrix.

In the process of adding a new bus to an old one, the likely modifications are;

(i) Addition of Tree Branch from a new bus to Reference

(ii) Addition of Tree Branch from a New Bus to Old Bus.

(iii) Addition of a Link between an Old Bus and Reference

(iv) Addition of Link between two Old Buses .

(v) Modification of $[Z_{bus}]$ for Changes in Network

2.2.2. Sequence Matrices

The following notations are defined: [9].

$V_{0\text{-bus}}$ = zero sequence bus voltage vector (nx1), general entry V_k^0.

$V_{1\text{-bus}}$ = positive sequence bus voltage vector (nx1), general entry V_k^1.

$V_{2\text{-bus}}$ = negative sequence bus voltage vector (nx1), general entry V_k^2.

$I_{0\text{-bus}}$ = zero sequence bus current vector (nx1), general entry I_k^0.

$I_{1\text{-bus}}$ = positive sequence bus current vector (nx1), general entry I_k^1

I_2-bus = negative sequence bus current vector (nx1), general entry I_k^2.

In the symbol V_k^0, I_k^1, etc. The subscripts refer to the bus number and the superscript indicates the sequence as shown in Figure 3.8. The sequence impedance matrices required for the short circuit studies are:

$[Z_{0-bus}]$ = zero sequence bus impedance matrix (nxn), general entry Z_{ik}^0.

$[Z_{1-bus}]$ = positive sequence bus impedance matrix (nxn), general entry Z_{ik}^1

$[Z_{2-bus}]$ = negative sequence bus impedance matrix (nxn), general entry Z_{ik}^2.

The positive sequence impedance network contains active sources. While forming the positive sequence bus impedance matrix the e.m.f.s of the sources are assumed to be short circuited.

A somewhat simplified, although approximate, short circuit study is made by neglecting the pre-fault currents. This means that all the bus voltages are 1 p.u immediately before the fault. The equations relating the sequence quantities are;

$$V_{0\text{-bus}} = -[Z_{0-bus}] I_{0\text{-bus}} \quad (9)$$

$$V_{1\text{-bus}} = E_{bus} - [Z_{1-bus}] I_{1\text{-bus}} \quad (10)$$

$$V_{2\text{-bus}} = -[Z_{2-bus}] I_{2\text{-bus}} \quad (11)$$

Each pre-fault currents are neglected, vector E contains 1 └0 in all the entries. The currents are all zero until the network is terminated externally. At a time only one bus (i.e. the faulted bus k) is terminated. Thus, only I_k^0, I_k^1, I_k^2 have non-zero entry. Very frequently, $[Z_{1-bus}]$ *and* $[Z_{2-bus}]$ are assumed to be identical to reduce computer memory requirement.

2.2.3 Equations for Short Circuit Studies

The equations for short circuit studies are developed using equations (9), (10) and (11) and terminating the network at the faulted bus (bus k).

For a symmetrical fault, the negative and zero sequence are absent, i.e., $V_{0\text{-bus}}$, $V_{2\text{-bus}}$, $I_{0\text{-bus}}$ and $I_{2\text{-bus}}$ are zero.

$$V_k^1 = E - (Z_k^1 I_1^1 + Z_{k2}^1 I_{k2}^1 + \ldots + Z_{kk}^1 I_k^1 + \ldots + Z_{kn}^1 I_n^1 \quad (12)$$

But all currents except at the faulted bus, i.e., I_k^1 are zero. Therefore,

$$V_k^1 = E - Z_{kk}^1 I_k^1 \quad (13)$$

If Z_f is the fault impedance

$$V_k^1 = I_k^1 Z_f \quad (14)$$

From equations (3.26) and (3.27)

$$I_k^1 = \frac{E}{Z_{kk}^1 + Z_f} \quad (15)$$

The voltage at i[th] bus is

$$V_i^1 = E - Z_{ik}^1 I_k^1 = E\left(1 - \frac{Z_{ik}^1}{Z_{kk}^1 + Z_f}\right) \quad for\ i = 1,2,\ldots,n \quad (16)$$

Where;

$V_i^1 = Positive\ Sequence\ bus\ voltage\ for\ bus\ k.$

$I_k^1 = Positive\ Sequence\ bus\ current\ for\ bus\ k.$

$Z_{kk}^1 = Positive\ Sequence\ bus\ impedance\ between\ buses\ k\ and\ n.$

$Z_f = Fault\ impedance$

$E = Induced\ e.m.f.\ under\ load\ condition.$

The short-circuit fault currents I_k^1 determined from equation (15) were converted to per unit values and the kA (Kilo-Amps) values were calculated from the following relations:

$$Base\ Current = \frac{Base\ MVA}{\sqrt{3}\ X\ Base\ Voltage}$$

Base MVA = 100MVA

Base Voltage = 330kV

$$Base\ Current = \frac{100\ X\ 10^6}{\sqrt{3} X\ 330\ X\ 10^3}$$

Base Current = 174.9546A

$$Actual\ Value\ of\ Current = Per\ Unit\ Value\ X\ Base\ Value$$

Figure 4 Shows the simplified computer flowcharts for calculating fault currents and voltages for the three-phase fault considered. The flowchart summarises the applications of the equations derived in sections (2.2.1), (2.2.2) and (2.2.3).

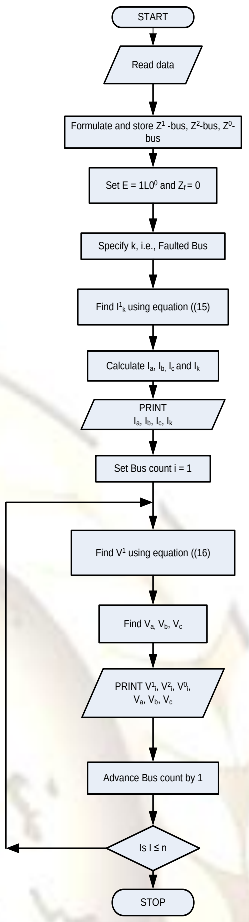

Figure 4: Flow Chart for Three-Phase Fault Calculation

3 RESULTS AND DISCUSSION

The load flow analysis was carried out using the Newton-Raphson load flow method. This analysis determines the voltage magnitude and angle in degrees at each bus in the power system. The result of the load flow is shown in Table 1. It can be observed that the voltage magnitudes and the angles are within the tolerance ranges of ± 10%.

After the load flow analysis, a three-phase fault was simulated on the power system at a bus, the total fault current was calculated, and currents flows in the transmission lines were also calculated. Table 2 shows the voltage magnitudes and their angles in degrees when a three-phase fault occurs on buses 5, 17and 20 (as an example). Table 3 shows the fault current magnitudes and the angles in degrees for fault on buses 5, 17and 20.

Table 1: Power Flow Solution by Newton-Raphson Method Nigerian 28 Bus, 330kV System

Bus Name	Bus No.	Voltage Magnitude (pu)	Angles (degrees)
EGBIN_GS	1	1.050	0.00
DELTA_GS	2	1.050	11.26
JA	3	1.045	-0.28
AKANGBA	4	1.008	0.50
IKEJA-WEST	5	1.016	0.93
AJAOKUTA	6	1.058	5.41
ALADJA	7	1.046	9.71
BENNIN	8	1.038	5.77
AYEDE	9	0.983	1.57
OSHOGBO	10	1.029	7.01
AFAM_GS	11	1.050	8.91
ALAOJI	12	1.030	8.30
NEW-HAVEN	13	0.936	0.08
ONITSHA	14	0.978	2.85
BIRNIN-KEBBI	15	1.010	10.14
GOMBE	16	0.904	1.62
JEBBA	17	1.050	12.45
JEBBA_GS	18	1.050	12.76
JOS	19	0.978	8.77
KADUNA	20	1.009	4.70
KAINJI_GS	21	1.050	15.66
KANO	22	0.892	-4.27
SHIRORO_GS	23	1.050	6.87
SAPELE_GS	24	1.050	7.30
MAKURDI	25	0.980	17.25
ABUJA	26	1.000	2.63
MANBILA_GS	27	1.050	41.88
PAPALANTO_GS	28	1.050	5.49

Table 2: Voltage Magnitude and Angles for Faults on Buses 5, 17 and 20.

Bus Name	Bus Number	Bus 5		Bus 17		Bus 20	
		Voltage Magnitude (pu)	Angle (degrees)	Voltage Magnitude (pu)	Angle (degree)	Voltage Magnitude (pu)	Angle (degree)
EGBIN_GS	1	0.0597	18.8758	0.6877	11.7819	0.8775	6.8952
DELTA_GS	2	0.4558	25.3495	0.7008	22.1935	0.8637	18.2667
AJA	3	0.0655	21.1904	0.6871	11.5522	0.8747	6.6250
AKANGBA	4	0.0106	45.9553	0.6429	12.8126	0.8336	7.6630
IKEJA-WEST	5	**0.0000**	**0.0000**	0.6426	15.1533	0.8375	8.0721
AJAOKUTA	6	0.4045	23.6588	0.6742	18.2236	0.8592	13.3508
ALADJA	7	0.4499	24.4140	0.6958	20.9036	0.8590	16.8336
BENNIN	8	0.4061	22.6378	0.6667	18.0222	0.8399	13.4440
AYEDE	9	0.2322	26.4904	0.4506	17.1670	0.7372	10.0729
OSHOGBO	10	0.3618	26.8922	0.2611	23.6034	0.6680	15.9351
AFAM	11	0.7776	20.4654	0.8261	19.3164	0.8075	16.7747
ALAOJI	12	0.7591	20.1144	0.8075	18.9259	0.7888	18.3377
NEW-HAVEN	13	0.5819	15.7158	0.7090	12.1801	0.7707	8.4774
ONITSHA	14	0.5803	17.9635	0.7212	14.7995	0.7912	11.1071
B/KEBBI	15	0.5347	29.7070	0.1247	62.1178	0.5909	22.2285
GOMBE	16	0.7186	15.8094	0.6088	19.4997	0.4025	21.8103
JEBBA	17	0.4867	29.2294	**0.0000**	**0.0000**	0.5617	21.4233
JEBBA_GS	18	0.4884	29.3326	0.0040	7.0697	0.5632	21.6033
JOS	19	0.7324	22.5265	0.5982	25.2350	0.3570	22.4750
KADUNA	20	0.6860	20.6321	0.4202	27.6921	**0.0000**	**0.0000**
KAINJI_GS	21	0.5066	31.7196	0.0367	29.4189	0.5790	24.4296
KANO	22	0.6725	11.9849	0.4769	20.9042	0.1667	43.3565
SHIRORO_GS	23	0.6719	22.7984	0.3507	30.0446	0.1986	20.6584

SAPELE_GS	24	0.4330	22.6528	0.6874	18.8557	0.8564	14.6233
MAKURDI	25	0.7596	28.2815	0.7128	28.6854	0.5911	25.7785
ABUJA	26	0.6755	19.3199	0.3916	28.9618	0.2488	26.4079
MANBILA_GS	27	0.8866	47.9770	0.8537	47.9210	0.7724	45.4877
PAPALANTO_GS	28	0.1043	-1.4665	0.6977	15.5556	0.8816	11.8582

Table 3: Line Current Magnitudes and Angles for Faults on Buses 5, 17 and 20.

From Bus	To Bus	Bus 5		Bus 17		Bus 20	
		Current Magnitude (pu)	Angles (degree)	Current Magnitude (pu)	Angles (degree)	Current Magnitude (pu)	Angles (degree)
1	5	3.3621	-63.5603	2.6812	-87.8260	2.4916	78.9838
1	5	3.3621	-63.5603	2.6812	-87.8260	2.4916	78.9838
2	8	1.7258	-33.1597	2.0154	-4.5333	2.5379	6.1308
2	7	1.0774	-53638	1.8789	11.6689	2.5046	13.1812
3	1	1.4434	-38.8827	0.6555	7.1933	1.1439	-18.7856
3	1	1.4434	-38.8827	0.6555	7.1933	1.1439	-18.7856
4	5	2.1008	-36.0655	0.7857	12.6820	1.4439	-17.3010
4	5	2.1008	-36.0655	0.7857	12.6820	1.4439	-17.3010
5	**F**	**43.0339**	**-58.4599**	-	-	-	-
6	8	0.2781	32.5903	0.3382	-3.0047	0.4064	-21.3779
6	8	0.2781	32.5903	0.3382	-3.0047	0.4064	-21.3779
7	24	1.1929	-18.0890	1.4750	9.4991	1.8748	18.6912
8	5	4.8966	-57.2029	1.0840	5.8418	1.4029	15.5810
8	5	4.8966	-57.2029	1.0840	5.8418	1.4029	15.5810
8	6	0.0582	-28.5269	0.2326	49.7354	0.3908	49.7792
8	6	0.0582	-28.5269	0.2326	49.7354	0.3908	49.7792
8	10	0.6518	-74.0570	5.4791	-64.5945	2.3587	-68.4845
9	5	5.6912	-55.2966	4.7878	-76.4738	2.6749	87.7865
10	5	4.8408	-53.4371	5.1851	-72.7593	2.8055	72.1867
10	9	3.7920	-53.6276	5.6358	-72.9683	2.9273	60.6358
11	12	2.5607	-46.8882	2.6221	-45.7471	2.6534	-46.9571
11	12	2.5607	-46.8882	2.6221	-45.7471	2.6534	-46.9571
12	14	3.9983	-52.2577	2.3870	-78.4513	1.8089	22.2580
14	13	0.9363	27.3547	1.3983	1.8862	1.6360	-10.3784
15	21	0.3737	-32.3173	1.0659	-4.5316	0.2149	-27.5228

17	10	2.7507	-43.4985	5.6262	-58.0512	2.6871	83.8753
17	10	2.7507	-43.4985	5.6262	-58.0512	2.6871	83.8753
17	10	2.7507	-43.4985	5.6262	-58.0512	2.6871	83.8753
17	**F**	**-**	**-**	**<u>31.4686</u>**	**-52.7371**	**-**	**-**
18	17	0.9592	-27.6019	2.0013	-77.2186	1.1814	-14.3142
18	17	0.9592	-27.6019	2.0013	-77.2186	1.1814	-14.3142
19	16	1.3926	19.1147	1.0299	34.8983	0.5724	-41.3526
19	20	1.0387	-20.2423	2.9357	-58.2295	5.8315	-58.5420
20	**F**	**-**	**-**	**-**	**-**	**<u>22.7007</u>**	**-55.7197**
21	17	1.2856	-2.5687	1.5210	-52.7376	1.5180	1.9174
21	17	1.2856	-2.5687	1.5210	-52.7376	1.5180	1.9174
23	17	2.6657	-68.9046	4.8464	-50.4010	5.0363	-57.5398
23	17	2.6657	-68.9046	4.8464	-50.4010	5.0363	-57.5398
23	20	1.1287	54.4886	2.4840	-64.5107	6.9364	-61.4138
23	20	1.1287	54.4886	2.4840	-64.5107	6.9364	-61.4138
23	26	1.5575	32.8959	1.4495	-59.6788	1.9406	-32.5274
24	8	1.8073	-58.0905	1.5691	-36.2834	1.6785	-20.0209
24	8	1.8073	-58.0905	1.5691	-36.2834	1.6785	-20.0209
25	12	2.3032	31.1607	3.1976	64.4583	4.3432	86.0558
25	19	2.0079	14.7924	2.8106	-32.4097	5.3147	-49.7231
27	25	5.4880	23.3698	5.2604	19.7754	5.1644	7.9480
28	5	8.7595	-83.6817	5.2272	-40.2952	5.9050	-21.2619

When a short-circuit occurs, the voltage at faulted point is reduced to zero [10]. One of the effects of faults on power system is that it lowers the voltage magnitudes. Comparing the voltage magnitudes in Table 1 with the voltage magnitudes in Table 2, it is observed that the voltage magnitudes fall below the acceptable levels of ± 10%. The voltage magnitudes of the faulted buses are lowered to zero.

One of the assumptions safely made in short-circuit calculations is that all the pre-fault currents are zero [7]. From Table 3, it is observed that current magnitudes of the buses when fault occurs are excessively high compared to the pre-fault currents assumed to be zero. Currents of abnormally high magnitudes flow through the network to the point of fault. As seen from Table 3, current magnitudes on buses 5, 17 and 20 are the highest when the faults were simulated on these buses as compared to current magnitudes on other buses.

Figure 5 shows the total fault current magnitudes on each bus when faults occur on the respective buses. The values of the fault current magnitude in Kilo-Amperes (kA) are plotted against each bus in the graph.

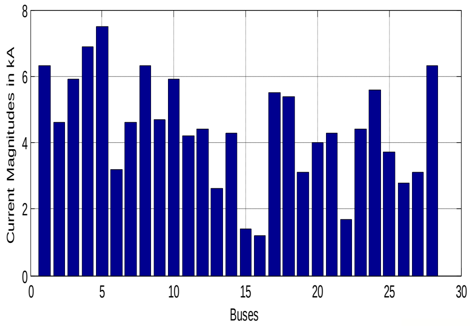

Figure 5: Fault Current Magnitudes in kA

3 CONCLUSION

Fault analysis on power systems involves knowing the system performance at steady state and determining the values of current flowing through the power system when a fault occurs. It was observed that the voltage magnitudes and the angles compared with the nominal values, where there are differences, they are within the tolerance range (The tolerance for the voltage magnitude is ± 10 %.), except for buses 16 and 22 (Gombe and Kano) which have their voltage magnitudes below the acceptable range. The fault analysis was performed to determine the fault currents magnitude and angle and the voltage magnitudes and angles when there is a fault on the power system. It can be observed from the results of this work that regular determination of currents which flow in the power system when three-phase faults occur is required for the Nigerian Power System because of the continous expansion of the National Grid. Information gained from this results can be used to obtain the ratings of protective switchgears installed on the power system.

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