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FAULT ANALYSIS FOR CIRCUIT BREAKERS RATINGS DETERMINATION ON NIGERIAN 330kv TRANSMISSION GRID

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--Abstract--

Fault Studies form an important part of power system analysis for stable and economical operations of a Power System. Faults on a power system are divided into symmetrical and unsymmetrical faults. In this paper, three-phase symmetrical fault was simulated on the Nigerian 330kV National Grid using Nigerian 24 bus power system from Power Holding Company of Nigeria. Two different MATLAB based programs were written; one program was for Load Flow Studies to determine the pre-fault conditions based on Newton-Raphson method, while the other was for three-phase short-circuit studies. It was observed that the fault currents were mostly excessively high. The information gained from the fault studies were used for the determination of circuit breaker ratings on the power system.

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

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I. Introduction

The Nigerian Power System has recently 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 current generates heat proportional to the square of the current magnitude; this large amount of heat 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 customers with reliability and economy. The greatest threat to this purpose of a power system is the short circuit. 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 [3]. The evaluation of fault currents and determination of circuit breaker ratings on a power system is therefore significant because the reliable and secure operations of the power systems depend on these.

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 [3]. The causes of faults were found to include lightning, insulation aging, heavy winds, trees falling across lines, vehicles colliding with poles, birds, kites, etc. [3], [4]. 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. [5].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

rounded generator's terminal [4]. 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 [6], [7], [8].The present dilapidated state of the power system infrastructure of the Nigeria Grid is attributed to poor maintenance [9]. Any country with poor level of power availability like Nigeria should first think about improvement of generation, transmission and distribution before thinking of industrialization [10]. 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 and system collapse in Nigeria has made this study important to the nation's newly expanded power industry. Figure1 is a single line diagram of the Nigeria 24-Bus, 330kV Transmission Grid.

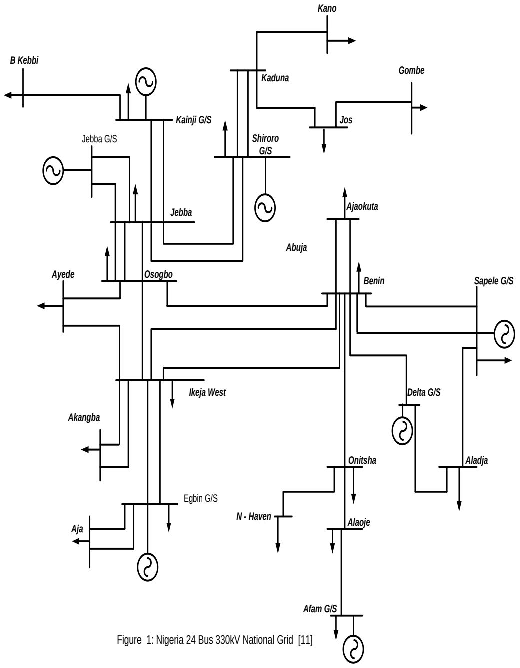

Figure 1: Nigeria 24 Bus 330kV National Grid [11]

II. Research Method

In short circuit studies, it is necessary to have the knowledge of pre-fault voltages and currents. These pre-fault conditions are obtained from the results of load flow studies by the Newton-Raphson iteration method. The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined. [12]. There are several different methods of solving the resulting nonlinear system of equations. The most popular is known as the Newton-Raphson Method. The Newton-Raphson method is preferred to other methods (Gauss-Seidel and Fast-Decoupled Methods) in this research work because of its advantages which include smaller time to perform one iteration of the computation, the number of iterations is more or less independent of the size of the power system and vary between 4 to 7 iterations. Also, the convergence characteristics of the Newton-Raphson method are not affected by the selection of slack bus [13], [14].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:

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

where ΔP and ΔQ are called the mismatch equations:

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

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

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: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. For a symmetrical fault, the negative and zero sequences are absent. The positive sequence network present and modified for fault analysis is shown in Figure 3.

The equations relating the sequence quantities are;

$$V_{0\text{-bus}} = -[Z_{0-bus}]I_{0\text{-bus}} \quad (7)$$

$$V_{1\text{-bus}} = E_{bus} - [Z_{1-bus}]I_{1\text{-bus}} \quad (8)$$

$$V_{2\text{-bus}} = -[Z_{2-bus}]I_{2\text{-bus}} \quad (9)$$

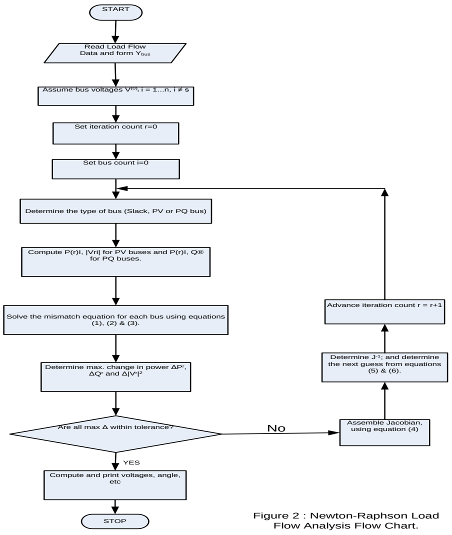

Figure 2 : Newton-Raphson Load Flow Analysis Flow Chart.

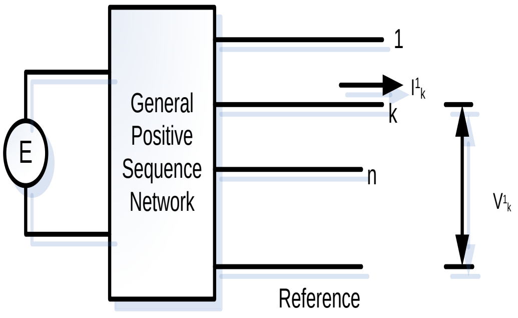

Figure 3: Positive Sequence Network Modified for Fault Analysis [15].

Since pre-fault currents are neglected, vector E contains $1\angle 0$ 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. [3], [4], [15].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.

$$V_k^1 = E - (Z_k^1 I_1^1 + Z_{k2}^1 I_{k2}^1 + \dots + Z_{kk}^1 I_k^1 + \dots + Z_{kn}^1 I_n^1) \qquad (10)$$

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

$$V_k^1 = E - Z_{kk}^1 I_k^1 \qquad (11)$$

If Z_f is the fault impedance

$$V_k^1 = I_k^1 Z_f \qquad (12)$$

From equations (11) and (12),

$$I_k^1 = \frac{E}{Z_{kk}^1 + Z_f} \qquad (13)$$

The voltage at ith bus is

$$V_i^1 = E - Z_{ik}^1 I_k^1 = E\left(1 - \frac{Z_{ik}^1}{Z_{kk}^1 + Z_f}\right) \quad for\ i = 1,2,\dots,n \qquad (14)$$

Where;

V_k^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 for bus k.

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

The short-circuit fault currents I_k^1 determined from equation (13) were converted to per unit values and the kA (Kilo-Amps) values were calculated from the following relations:

Base Current = base MVA/√3 X Base Voltage

Base MVA = 100MVA

Base Voltage = 330kV

Base Current = $100 X 10^6/\sqrt{3}$ 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 flowchart for calculating fault currents, voltages for the three-phase fault considered and selecting appropriate circuit breakers.

Two of the circuit breaker ratings which require computations of short circuit currents are:

(i) Rated momentary current and

(ii) Rated symmetrical interrupting current.

Symmetrical short circuit current is obtained by using sub transient reactance for synchronous machines. Momentary current is (rms) then calculated by multiplying the symmetrical momentary current by a factor of 1.6 to account for the presence of dc offset current (Nagrath and Kothari, 1994). The current that a circuit breaker can interrupt is inversely proportional to the operating voltage over a certain range of time.

If voltage and current are in per unit values on a three-phase basis, then;

$$SC\ MVA\ (3 - \Phi) = |V_{prefault}|\ X\ |I|_{sc}\ X\ (MVA)_{base} \qquad (15)$$

Obviously, rated MVA interrupting capacity of a circuit breaker is to be more than (or equal to) to the short circuit MVA required to be interrupted. For the selection of a circuit breaker for a particular location, the maximum possible short circuit MVA to be interrupted must be found with respect to the type and location of fault and generating capacity connected to the system. A three-phase fault though rare is generally the one which gives the highest short circuit MVA and a circuit breaker must be capable of interrupting it. An exception is a line to ground fault due to a synchronous generator.

III. Results and Analysis

The load flow analysis (pre-fault analysis) was carried out using the Newton-Raphson load flow method. This analysis determines the voltage magnitude and angle in degree 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 compared with the nominal values are similar. Where there are differences, they are within the tolerance range of ± 10% except for Kano and Gombe. These two buses low voltage profiles can be improved by incorporating voltage control devices on the lines. After the load flow analysis, a three phase fault was simulated; voltages and currents on the buses were calculated. Table 2 shows the voltage magnitudes and their angles in degree when a three phase fault occurs on buses 5, 9, 15, and 20 (as examples). Table 3 shows the fault current magnitudes and the angles in degrees for faults on buses 5, 9, 15, and 20 respectively.When a short-circuit occurs, the voltage at faulted point is reduced to zero [8]. One of the effects of faults on power system is that it lowers the voltage

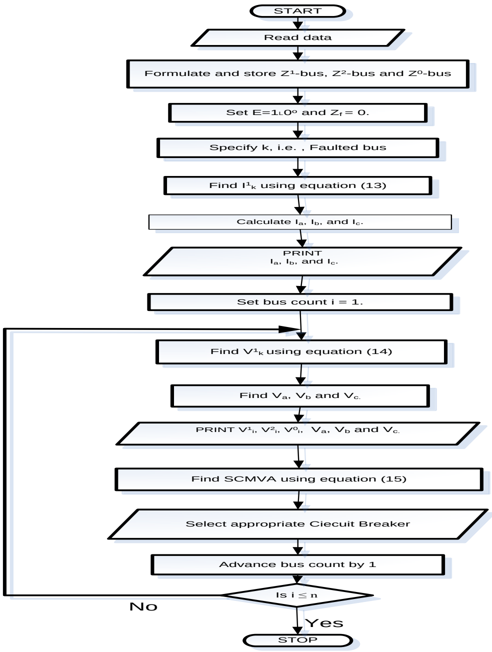

Figure 4: Flow Chart for Fault Calculation and Circuit Breaker Selection

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 can be 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, 9, 15, and 20 are the highest when the faults were simulated on these buses as compared to current magnitudes on other buses.

Table 1: Power Flow Solution by Newton-Raphson Method Nigerian 24 Bus, 330kV System

Bus Name	Bus No.	Voltage Magnitude (pu)	Angles (degrees)
EGBIN	1	1.050	0.00
DELTA	2	1.050	-1.14
AJA	3	1.045	-0.28
AKANGBA	4	0.988	-5.64
IKEJA-WEST	5	1.016	-5.19
AJAOKUTA	6	1.054	-7.00
ALADJA	7	1.046	-2.71
BENNIN	8	1.034	-6.63
AYEDE	9	0.974	-7.79
OSHOGBO	10	1.026	-4.93
AFAM	11	1.050	-17.27
ALAOJI	12	1.030	-17.89
NEW-HAVEN	13	0.929	-18.89
ONITSHA	14	0.971	-16.09
BIRNIN-KEBBI	15	1.010	-3.97
GOMBE	16	0.866	-31.67
JEBBA	17	1.050	-1.61
JEBBAG	18	1.050	-1.35
JOS	19	0.948	-24.01
KADUNA	20	0.999	-16.67
KAINJI	21	1.050	1.55
KANO	22	0.880	-24.88
SHIRORO	23	1.050	-12.22
SAPELE	24	1.050	-5.12

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

Table 2: Voltage Magnitudes and Angles for Faults on Buses 5, 9, 15, and 20.

Bus Name	Bus No.	Bus 5		Bus 9		Bus 15		Bus 20	
		Voltage Magnitude (pu)	Angles degrees	Voltage Magnitude (pu)	Angles degrees	Voltage Magnitude (pu)	Angles degrees	Voltage Magnitude (pu)	Angles degrees
EGBIN	1	0.0597	18.88	0.5329	17.85	0.9625	4.41	0.8819	8.01
DELTA	2	0.4512	13.65	0.6760	11.93	0.9715	2.56	0.8990	5.47
AJA	3	0.0655	21.19	0.5342	17.65	0.9587	4.13	0.8792	7.73
AKANGBA	4	0.0108	39.77	0.4766	13.33	0.9009	-1.06	0.8209	2.70
IKEJAWEST	5	**0.0000**	**0.00**	0.4742	13.64	0.9065	-0.61	0.8249	3.14
AJAOKUTA	6	0.3983	12.20	0.6454	8.41	0.9681	-2.86	0.8888	0.46
ALADJA	7	0.4453	12.73	0.6711	10.69	0.9671	1.05	0.8945	4.01
BENIN	8	0.3999	11.13	0.6384	8.10	0.9509	-2.61	0.8741	0.59
AYEDE	9	-.2312	17.98	**0.0000**	**0.00**	0.8478	-2.76	0.7351	1.41
OSOGBO	10	0.3609	15.99	0.3983	12.36	0.8414	0.13	0.6795	4.30
AFAM	11	0.7449	-4.47	0.8696	-7.37	1.0165	-14.55	0.9829	-12.40
ALAOJI	12	0.7285	-4.80	0.8529	-7.80	0.9994	-15.13	0.9659	-12.94
NEWHAVEN	13	0.5659	-2.11	0.7106	-6.18	0.8863	-15.48	0.8451	-12.75
ONITSHA	14	0.5624	0.20	0.7232	-3.45	0.9220	-12.65	0.8749	-9.92
BIRNINKEBBI	15	0.5354	16.48	0.5607	14.06	**0.0000**	**0.00**	0.6008	8.04
GOMBE	16	0.6851	-12.81	0.6929	-14.32	0.7778	-24.35	0.2401	22.39
JEBBA	17	0.4858	16.21	0.5178	13.77	0.7947	3.39	0.5726	7.40
JEBBAG	18	0.4876	16.31	0.5196	13.89	0.7956	3.62	0.5743	7.58
JOS	19	0.6923	-4.79	0.7043	-6.46	0.8257	-16.88	0.1279	39.79
KADUNA	20	0.6761	1.39	0.6927	-0.31	0.8486	-10.26	**0.0000**	**0.00**
KAINJI	21	0.5059	18.62	0.5369	16.36	0.7114	6.30	0.5897	10.40
KANO	22	0.6606	-7.23	0.6712	-8.73	0.7758	-18.22	0.1582	19.47
SHIRORO	23	0.6702	5.16	0.6905	3.41	0.8749	-6.25	0.2061	-0.09
SAPELE	24	0.4283	11.02	0.6619	8.74	0.9684	-1.27	0.8931	1.79

Table 3: Line Current Magnitudes and Angles for Faults on Buses 5, 9, 17, and 20.

From Bus	To Bus	Bus 5		Bus 9		Bus 15		Bus 20	
		Current Magnitude (pu)	Angles degrees	Current Magnitude (pu)	Angles degrees	Current Magnitude (pu)	Angles degrees	Current Magnitude (pu)	Angles degrees
1	5	3.3621	-63.56	3.9491	-33.89	5.6867	-24.41	5.2770	-24.54
1	5	3.3621	-63.56	3.9491	-33.89	5.6867	-24.41	5.2770	-24.54
2	7	1.0522	-17.63	1.7577	0.66	2.9456	-0.26	2.6370	1.32
2	8	1.7490	-47.04	1.9241	-20.39	2.9875	-5.07	2.6641	-6.60
3	1	1.4434	-38.88	0.5221	58.14	1.3886	-26.01	1.1675	-16.34
3	1	1.4434	-38.88	0.5221	58.14	1.3886	-26.01	1.1675	-16.34
4	5	2.1445	-42.25	0.7106	63.87	1.8184	-31.21	1.5067	-20.83
4	5	2.1445	-42.25	0.7106	63.87	1.8184	-31.21	1.5067	-20.83
5	**F**	**35.7392**	**-57.20**	-	-	-	-	-	-
5	8	-	-	2.1419	83.50	1.0027	34.20	1.0517	40.25
5	8	-	-	2.1419	83.50	1.0027	34.20	1.0517	40.25
6	8	0.2809	21.02	0.3402	-10.64	0.4559	-44.48	0.4250	-36.49
6	8	0.2809	21.02	0.3402	-10.64	0.4559	-44.48	0.4250	-36.49
7	24	1.1783	-31.07	1.3800	-3.87	2.2012	8.97	1.9606	8.00
8	5	4.8218	-68.72	2.0488	-79.92	0.6229	-72.08	0.6627	-78.60
8	5	4.8218	-68.72	2.0488	-79.92	0.6229	-72.08	0.6627	-78.60
8	6	0.0538	-46.33	0.2025	41.22	0.4981	34.82	0.4222	37.84
8	6	0.0538	-46.33	0.2025	41.22	0.4981	34.82	0.4222	37.84
8	14	4.6002	72.56	4.0812	40.22	4.3269	-9.56	4.1559	3.07
9	**F**	-	**-**	**-25.1446**	**-67.95**	-	-	-	-
9	5	5.6679	-63.81	11.6225	-68.15	1.8003	-48.56	2.3626	-60.45
10	5	4.8284	-64.34	1.0987	-50.15	0.9860	62.46	1.9685	85.49
10	8	0.7912	60.80	3.2644	-75.83	1.7227	61.39	2.7553	78.59
10	9	3.7976	-68.79	11.6269	-69.67	1.4404	12.36	1.9989	63.76
11	12	2.2872	-71.67	2.4184	-67.85	2.6921	-65.47	2.6144	-65.71
11	12	2.2872	-71.67	2.4184	-67.85	2.6921	-65.47	2.6144	-65.71
14	12	3.8622	73.99	3.1899	63.42	2.0244	48.10	2.3593	52.07

14	13	0.9392	13.61	1.4542	-16.15	2.2273	-42.91	2.0323	-36.62
15	**F**	-	-	-	-	**7.9466**	**-73.99**	-	-
15	21	0.3842	-47.93	0.3253	-49.51	-	-	0.2007	-44.33
17	10	2.7129	-62.49	2.6185	-60.62	1.5883	47.72	2.4513	81.78
17	10	2.7129	-62.49	2.6185	-60.62	1.5883	47.72	2.4513	81.78
17	10	2.7129	-62.49	2.6185	-60.62	1.5883	47.72	2.4513	81.78
17	23	3.0718	73.22	2.9317	69.60	2.5507	31.20	5.1389	-67.84
17	23	3.0718	73.22	2.9317	69.60	2.5507	31.20	5.1389	-67.84
18	17	0.9826	-44.08	1.0312	-37.82	1.6407	-6.05	1.2258	-29.43
18	17	0.9826	-44.08	1.0312	-37.82	1.6407	-6.05	1.2258	-29.43
19	16	1.4868	-5.29	1.4922	-8.73	1.7468	-31.95	1.3688	-72.14
20	**F**	-	-	-	-	-	-	**18.7715**	**-71.92**
20	19	1.4937	15.16	1.5079	10.53	1.9582	-17.73	2.0895	-41.23
20	22	1.7861	-3.20	1.8019	-7.59	2.2973	-34.80	2.3170	-61.24
21	15	0.5892	53.91	0.6054	44.24	7.7678	-72.95	0.6266	24.13
21	17	1.2658	-16.68	1.3393	-14.01	3.8364	76.25	1.5310	-11.44
21	17	1.2658	-16.68	1.3393	-14.01	3.8364	76.25	1.5310	-11.44
22	F	-	-	-	-	-	-	-	-
23	20	1.6805	17.46	1.6994	11.32	2.4497	-23.03	7.1999	-82.17
23	20	1.6805	17.46	1.6994	11.32	2.4497	-23.03	7.1999	-82.17
24	8	1.9083	-71.46	1.6714	-52.62	1.9901	-30.56	1.8376	-35.33
24	8	1.9083	-71.46	1.6714	-52.62	1.9901	-30.56	1.8376	-35.33

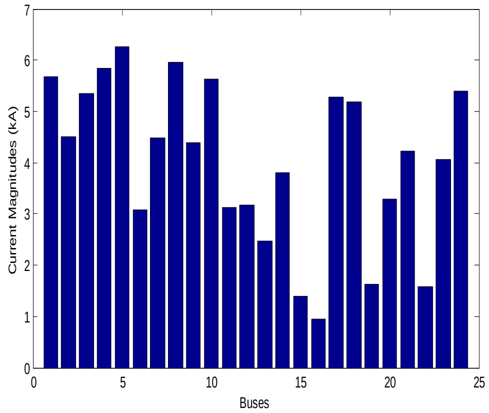

Figure 5: Fault Current Magnitudes in kA

The three-phase Short Circuit MVA which determines the ratings of the Circuit Breaker to be installed were calculated using equation (15). Table 4 shows the Short Circuit MVA ratings for the fault currents on each bus and the corresponding ratings of the Circuit Breaker to be installed. The range of the circuit breakers determined for the Nigerian Power System is within 100MVA and 650MVA.

Table 4: Short Circuit MVA and Circuit Breaker Ratings

Bus No	Current Magnitude (kA)	SCMVA (MVA)	Circuit Breaker Rating (MVA)
1	5.670	595.35	600
2	4.497	472.19	500
3	5.340	534.00	550
4	5.836	583.60	600
5	6.253	625.30	650
6	3.084	308.40	325
7	4.472	447.20	450
8	5.964	596.40	600
9	4.399	439.90	450
10	5.637	563.70	600
11	3.124	328.02	350
12	3.166	316.60	350
13	2.471	247.10	250
14	3.798	379.80	400

15	1.390	139.00	150
16	0.943	94.30	100
17	5.273	527.30	550
18	5.175	543.38	550
19	1.635	163.50	200
20	3.284	328.40	350
21	4.218	442.89	450
22	1.587	158.70	200
23	4.059	426.20	450
24	5.386	565.53	600

IV. Conclusion

Faults analysis on power system involves knowing the system performance at steady state and calculating the values of the current flowing in the system when fault occurs. Load flow analysis was carried out on the Nigeria power system to determine the steady state values, the results were found to be satisfactory. Fault analysis was subsequently carried out to determine the voltage and currents when fault occurs and the results show that excessively high currents flow in the power system when there is fault. The results of the fault analysis were used to determine the circuit breaker ratings for the power system. As could be observed from the results of this research work and for the reason that the system data were sourced from Power Holding Corporation of Nigeria (PHCN), the regular calculation of the currents which flow in the power system when a three-phase fault symmetrical fault occurs and the selection of appropriate circuit breaker are required for the proper operation of the power system because of the continuous expansion of the National Grid in Nigeria.

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