Stability Study of the Nigerian 330KV Integrated Power System Network: A Case Study of Benin Regional Control Centre

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Abstract

The study examined the stability of existing Nigerian 330kV grid network of the Benin regional control centre which coordinates and monitors the grid network within the south-south and south-east region of Nigeria. Presently, the National grid consist of thirty (30) power generating stations, fifty six (56) buses and eighty (80) transmission lines. Due to the availability of natural gas, the Benin regional control centre is strategic and unique to the National grid as it consist of about seventeen (17) generating stations, 28 buses, and 30 transmission lines. The swing equation, equal area criterion and modified Euler's method was used for the study and the network was modelled in Electrical Transient analyzer program (ETAP12.6) software to investigate the impact a three phase fault created 96km along Onitsha–Benin transmission line will have on the power system. The result obtained shows that at pre-fault (0.00-0.991 seconds), the frequency is within the acceptable limit of 50Hz ± 0.5%. During fault (1.001-1.191 seconds), the frequency was gradually moving out of its acceptable limit and there was violation of voltage statutory limits of 95%-105% until the oscillation was damped. The buses that were mostly affected are Sapele GS (217.1 KV), Delta GS (200.2 KV), Ihovbor GS (201.8 KV), Azura GS (201.8 KV), Okpai GS (213.5 KV) Benin TS (169.5 KV), Asaba TS (182.6 KV), Aladja TS (237 KV), and Onitsha TS (191 KV). At post-fault 1.210 seconds the fault is cleared. However if the fault is not cleared after 1.210 seconds, there will be loss of synchronism between the generating plants and the system will become unstable. The bus voltages after 1.210 seconds are Sapele GS (405.3 KV), Delta GS (365 KV), Ihovbor GS (366 KV), Azura GS (366 KV), Okpai GS (213.5 KV) Benin TS (372 KV), AladjaTS (370.9 KV), Asaba TS (341.9 KV) and Onitsha TS (191 KV).

INTRODUCTION

1.1 Background of the Study

Electricity is the basic requirement for the socio-economic and technological development of any society (Gupta, 2006). In Nigeria, the electrical need is far above its supply. This indeed has brought about the management of the power infrastructures at its optimal level. The major cause of this optimal operation is due to poor evacuation of electricity predicated on lack or weakness of existing transmission infrastructures (Egeruoh, 2012).

The Nigeria transmission system which operates at 330kV, interconnects all major power stations and load consumers in the country. The power infrastructures consist of different generating plants in their respective location littered within the country, transmission lines, different forms of power transformers, electricity consuming devices and protective infrastructure (Odia, 2007).
The complex nature of the national grid offers or makes it possible for the occurrence of different forms of system problems. The major issue on power sector affectingor confrontingthe efficiency of the grid are voltage and transient stability (Enemuoh, 2012). Instability of the power system have undesirable consequences. Limitation in the quantity of transmitted power, loss of synchronization after its normal condition is distorted, power outage and voltage collapse experienced by consumers due to power system instability (Tejaswini, Komal, Tushar, Naved&Altaf, 2015).
In 2005, the Nigerian grid recorded a total number of about 529 outages. Amongst these, 42.53% were forced outages compared to 35.1% in 2004(Onahaebi, 2007).
The ever rising cost of modifying our network has made it imperative for the Transmission Company of Nigeria (TCN) to use different design alternatives, and effect a wholesome study of the impact on the system predicated on specific predictions under steady and transient state condition. In order to make this an achievable possibility, specific computer software are duly employed to assist system engineers, planners and other relevant stakeholders to collect and precisely use large network data. These programs includes power-flow, short-circuit, transients stability etc. Power flow program carry out the act of the computing the magnitude of the system voltages, phase angles for a system under steady-state conditions. (Glover, Sarma, & Overbye, 2012).

1.2Statement of Problem

Transient stability analysis in recent time has become a major challenge in power system operation. The Nigerian 330kV power system network due to its lack of flexibility is highly stressed and as a result experiences a high rate of instability. In order to improve the system, an evaluation of the 330kV grid network is required to ascertain its ability to withstand disturbance while maintaining quality of service.

1.3 Aims and Objectives of the Study

This research work is aimed at carrying out a stability study of the Nigeria 330kV network, with the following objectives:

1. To determine the most affected generating stations and buses in the network after the occurrence of a three phase (3-θ) fault on Delta-Benin Transmission line
2. To determine whether or not the affected generating stations maintained synchronism with the grid when the fault was cleared.

1.4 Justification of Work

A power system duly analyzed under a given operating state could be said to be stable if it maintains acceptable operating condition under normal and after being subjected to a disturbance. However, the Nigeria 330kV network today are heavily stress and operates closer to its capacity limits due to economic and environmental constraints. According to the report made available by the Federal Government owned Transmission Company of Nigeria (TCN), the 330kV grid network in 2005 recorded a total number of 529 outages out of which 42.53% were forced outages compared to 35.1% in 2004. The inconvenience and economic cost of the occasioned forced outage on the public residence on the affected areas are enormous and unpleasant. With this statistics, the dissertation will investigate the stability limit of the Nigerian 330kV grid before, during and after fault occurrence and make appropriate recommendations to improve the system.

1.5 Scope of Study

The scope of the present research work is limited to Nigerian 330kV grid network to carry out transient stability study.

METHODOLOGY

This chapter describes the various research procedures and techniques adopted in carrying out this research

3.1 Data Collection

The data used in this research work were collected from the transmission company of Nigeria (TCN).

3.2 Materials Used

i. Electrical Transient Analyzer Program (ETAP 12.6)
ii. 350mm^2 ACSR Conductor
iii. HT/GT /ST Synchronous Generators
iv. PT/CT Instrument Transformers
v. High Voltage Circuit Breakers
vi. Relays
vii. Loads
viii. Power Transformers
ix. Capacitor Bank

3.3 Description of the Existing Nigerian 330KV Grid Network

The Nigeria grid consists of about nineteen (19) generating stations, fifty-six (56) buses and eighty (80) transmission lines. The grid network is grouped into three (3) regional control units and a National control centre at Oshogbo. The regional control units are Shiroro for Northern region, Ikeja-West for South-West region and Benin for South-East/South-South region. The National control centre(NCC) is responsible for all grid operations, offering the requisite supervision and control within the transmission network while the regional control centres (RCC) is responsible for monitoring grid operations in all the 330kV and 132kV transmission network under the regional operations coordinating units. Figure 3.1 shows the existing Nigeria 330kV power system network.

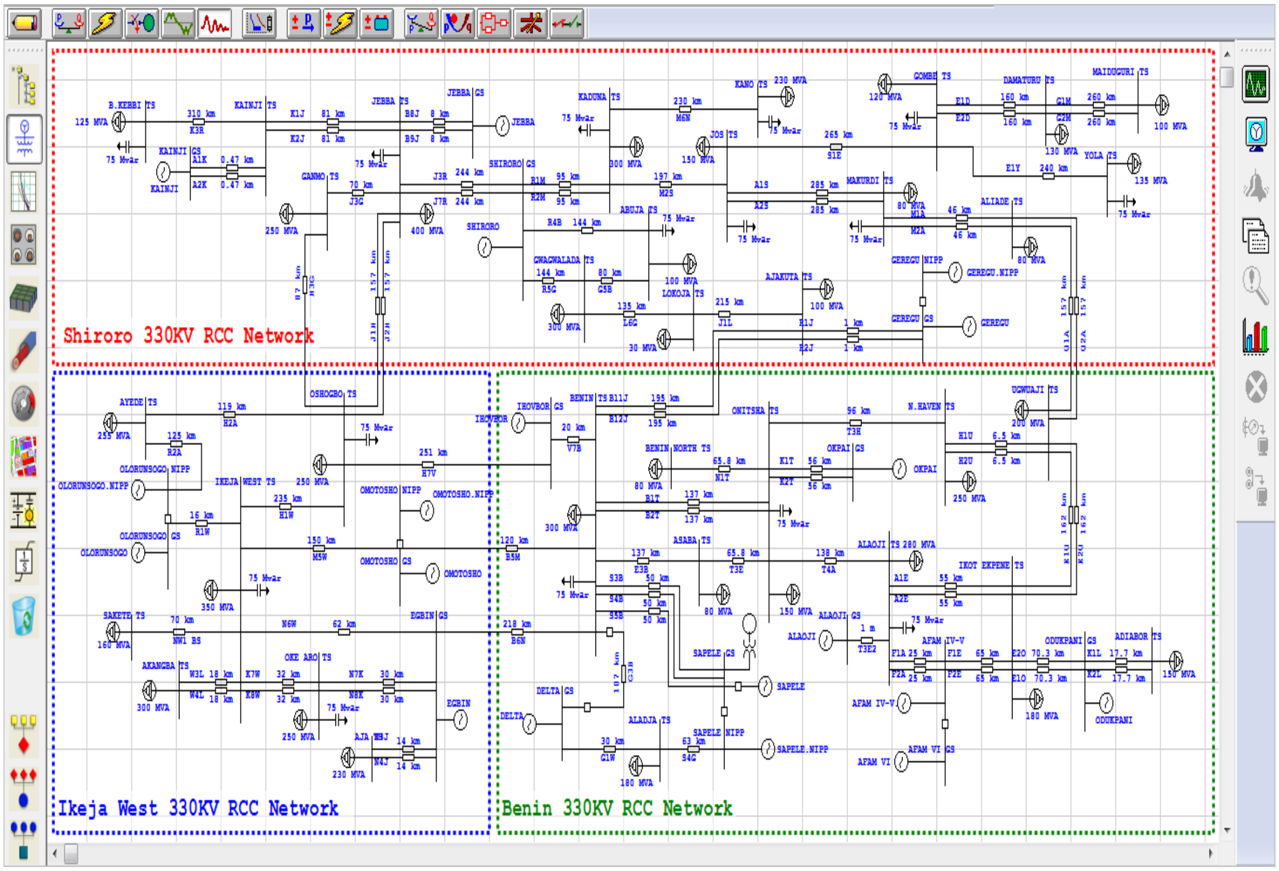

Figure 3.1: Model of the Existing Nigerian 330kV Grid Network before Simulation

Table 3.1: Generator Data

S/n	Generator ID	Operating Mode	Turbine Type	Power (MW)	Nominal Bus kV	Speed (Rpm)	P.F
1	Afam IV-V	Voltage Control	Gas/Steam	110	330	1500	0.85
2	Afam VI	Voltage Control	Gas	650		1500	0.85
3	Alaoji G.S	Voltage Control	Gas	120	330	1500	0.85
4	Delta G.S	Voltage Control	Gas	480	330	1500	0.85
5	Egbin /AESG.S	Swing	Steam	880	330	1500	0.85
6	Geregu G.S	Voltage Control	Gas	290	330	1500	0.85
7	Geregu NIPP	Voltage Control	Gas	435		1500	0.85

8	Ihovbor NIPP	Voltage Control	Gas	113	330	1500	0.85
9	Jebba G.S	Voltage Control	Hydro	450	330	1500	0.85
10	Kainji G.S	Voltage Control	Hydro	206	330	1500	0.85
11	Odukpani G.S	Voltage Control	Gas	500	330	1500	0.85
12	Okpai G.S	Voltage Control	Gas/Steam	450	330	1500	0.85
13	Sapele G.S	Voltage Control	Steam	69	330	1500	0.85
14	Sapele NIPP	Voltage Control	Gas	120		1500	0.85
15	Shiroro G.S	Voltage Control	Hydro	600	330	1500	0.85
16	Olorunsogo Phase 1	Voltage Control	Gas	228	330	1500	0.85
17	Olorunsogo NIPP	Voltage Control	Gas	480		1500	0.85
18	Omotosho Phase 1	Voltage Control	Gas	304	330	1500	0.85
19	Omotosho NIPP	Voltage Control	Gas	480		1500	0.85

Source: TCN

Table 3.2: Bus Data

S/N	Load ID	Rated MVA	Shunt Mvar	S/N	Bus ID	Rated MVA	Shunt Mvar
1	Abuja TS	100	75	18	Ikeja West TS	350	75,75
2	Adiabor TS	150		19	Ikot Ekpene TS	180	
3	Aja TS	230		20	Jebba T.S	300	75, 75
4	Ajaokuta TS	100		21	Jos TS	150	75
5	Akangba TS	300		22	Kaduna TS	300	75
6	Aladja TS	180		23	Kainji TS	150	
7	Alaoji TS	280	75	24	Kano TS	230	75
8	Aliade TS	120		25	Lokoja TS	100	
9	Asaba TS	100		26	Maduguri TS	100	
10	Ayede TS	255		27	Makurdi TS	100	75

11	Benin North TS	80		28	New Heaven TS	200	
12	Benin TS	300	75,75	29	Oke-Aro TS	250	75
13	Birnin-KebbiTS	125	75	30	Onitsha TS	150	75
14	DamaturuTS	130		31	Osogbo TS	250	75
15	Ganmo TS	250		32	Sakete TS	160	
16	Gombe TS	100	50, 50	33	Ugwaji TS	200	
17	Gwagwalada TS	300		34	Yola TS	135	75,75

Source: TCN

Table 3.3: Transmission Line Data

S/N	Circuit Nomenclature	Distance (KM)	Transmission Line		Line Admittance	
			From	To	(Rpu)	(1/2Bpu)
1	A1E & A2E	55	Alaoji TS	Ikot Ekpene TS	1.637-j2.626	0.208
2	A1k &A2K	0.47	Kainji GS	Kainji TS	3.194-j7.555	0.257
3	A1S & A2S	285	Makurdi TS	Jos TS	9.615-j6.129	0.104
4	B11J & B12J	195	Benin TS	Ajaokuta TS	6.494-j3.891	0.257
5	B1T & B2T	137	Benin TS	Onitsha TS	5.848-j4.184	0.208
6	B5M	120	Benin TS	Omotosho GS	2.754-j3.553	0.257
7	B6N	218	Benin TS	Egbin GS	5.284-j5.913	0.239
8	B8J & B9J	8	Jebba G.S	Jebba T.S	5.848-j4.184	0.239
9	D1M	260	DamaturuTS	Maduguri TS	1.508-j9.932	0.208
10	E1D	160	Gombe TS	Damaturu TS	9.615-j1.129	0.104
11	E1O & E2O	70.3	Odukpani GS	Ikot Ekpene TS	2.754-j3.553	0.524
12	E1U, E2U	162	Ikot Ekpene TS	Ugwuaji TS	6.494-j3.891	0.308
13	E1Y	240	Gombe TS	Yola TS	6.494-j3.891	0.308
14	E3B	137	Benin TS	Asaba TS	5.848-j4.184	0.104
15	F1A & F2A	25	Afam GS	Alaoji TS	2.754-j3.553	0.104
16	F1E & F2E	65	Afam GS	Ikot Ekpene TS	6.494-j3.891	0.104
17	G1W	30	Delta GS	Aladja TS	6.129-j9.615	0.454
18	G3B	107	Delta GS	Benin TS	4.545-j3.247	0.437
19	G5B	80	Gwagwalada TS	Abuja TS	1.235-j0.478	0.521
20	H1U & H2U	6.5	New Heaven TS	Ugwaji TS	1.637-j2.626	0.437
21	H1W	235	Osogbo TS	Ikeja West TS	3.846-j2.739	0.208
22	H2A	119	Osogbo TS	Ayede TS	5.848-j4.184	0.257
23	H3G	87	Osogbo TS	Ganmo TS	1.508-j2.932	0.208
24	H7V	251	Osogbo TS	Ihovbor GS	2.823-j3.771	0.257
25	J1H & J2H	157	JebbaTS	Osogbo TS	8.652-j4.808	0.257
26	J1L & J2L	215	Ajaokuta TS	Lokoja TS	5.848-j4.184	0.065
27	J3G	70	Jebba TS	Ganmo TS	3.846-j2.739	0.239

28	J3R & J7R	244	Jebba TS	Shiroro GS	8.232-j4.808	0.437
29	K1J & K2J	81	Kainji TS	JebbaTS	6.494-j3.891	0.308
30	K1L & K2L	17.7	Odukpani GS	Adiabor TS	1.192-j0.848	0.239
31	K1T & K2T	56	Okpai GS	Onitsha TS	1.192-j0.848	0.524
32	K3R	310	Kainji TS	Birnin-KebbiTS	3.241-j4.808	0.257
33	K7W & K8W	32	Oke-Aro TS	Ikeja West TS	5.142-j4.808	0.308
34	L6G & L7G	135	Lokoja TS	Gwagwalada TS	7.308+j7.142	0.257
35	M1A & M2A	46	Makurdi TS	Aliade TS	5.848-j4.184	0.208
36	M2S	197	Kaduna TS	Jos TS	5.848-j4.184	0.257
37	M5W	150	Omotosho GS	Ikeja West TS	5.848-j4.184	0.308
38	M6N	230	Kaduna TS	Kano TS	2.615-j1.919	0.239
39	N1T	65.8	Benin North TS	Onitsha TS	1.923-j6.456	0.954
40	N3J & N4J	14	Egbin GS	Aja TS	1.391-j2.999	0.521
41	N6W	62	Egbin GS	Ikeja West TS	6.494-j3.891	0.208
42	N7K & N8K	30	Egbin GS	Oke-Aro TS	6.494-j3.891	0.239
43	NW1BS	70	Ikeja West TS	Sakete TS	2.695-j1.919	0.365
44	R1J& R2J	1	Geregu GS	Ajaokuta TS	2.695-j1.919	0.208
45	R1M & R2M	95	Shiroro GS	Kaduna TS	2.695-j1.919	0.208
46	R1W	16	Olorunsogo GS	Ikeja West TS	5.848-j4.184	1.178
47	R2A	125	Olorunsogo GS	Ayede TS	2.615-j1.919	1.178
48	R4B	144	Shiroro GS	Abuja TS	1.923-j6.456	0.208
49	R5G	144	Shiroro GS	Gwagwalada TS	1.391-j2.999	0.208
50	S3B & S4B	50	Sapele GS	Benin TS	6.494-j3.891	0.257
51	S5B	50	Sapele GS	Benin TS	6.494-j3.891	0.257
52	S4G	63	Sapele GS	Aladja TS	6.494-j3.891	0.239
53	S5B	50	Sapele GS	Benin TS	2.695-j1.919	0.239
54	SIE	265	Jos TS	Gombe TS	2.695-j1.919	0.239
55	T3E	65.8	Asaba TS	Onitsha TS	2.695-j1.919	0.239
56	T3H	96	Onitsha TS	New Haven TS	0.246-j3.092	1.013
57	T4A	138	Onitsha TS	Alaoji TS	2.695-j1.919	0.257
58	U1A & U2A	157	Ugwuaji TS	Aliade TS	6.494-j3.891	0.208
59	V7B	20	Ihovbor GS	Benin TS	3.846-j2.739	0.257
60	W3L & W4L	18	Ikeja West TS	Akangba TS	5.848-j4.184	0.521

Source: TCN

3.4 Methods of Analyzing Transient Stability

(i) Equal area criterion
(ii) Point by point method
(iii) Euler method

(iv) Lianupuv's direct method
(v) Modified Euler method
(vi) Runge-Kutta method
For this research, modified Euler's method was used to solve the swing equation because it is one of the easiest methods to program for solution of differential using digital computer. Its techniques is simple and requires less computation time.

3.5. Formulation of Swing Equation

The swing equation is used to describe the behavior of a synchronous machine during transient. It is a differential equation that relates the angular momentum M, the accelerating power P_a and the rotor angle δ of the machine.
The kinetic energy of the rotor is given by

$$J = mr^2 \quad (3.1)$$

$$K_e = \frac{1}{2}J\omega^2 \quad (3.2)$$

$$M = J\omega \quad (3.3)$$

$$K_e = \frac{1}{2}M\omega \quad (3.4)$$

H Constant is the kinetic energy stored in the rotating parts of the machine at synchronous speed per unit MVA.

$$H = \frac{K_e}{G} \quad (3.5)$$

Substituting K_e from (3.4) into (3.5)

$$H = \frac{M\omega}{2G} \quad (3.6)$$

$$M = \frac{GH}{\pi f} = \frac{GH}{180f} \quad (3.7)$$

Rotor angular displacement and acceleration is given by

$$\omega = \frac{d\delta}{dt} \quad (3.8)$$

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\delta}{dt^2} \quad (3.9)$$

Generator accelerating toque and power is given by

$$T_a = J\alpha = \frac{M\alpha}{\omega} \quad (3.10)$$

$$P_a = \omega T_a \quad (3.11)$$

$$P_a = M\alpha \quad (3.12)$$

Substituting α from (3.9) into (3.12)

$$P_a = M\frac{d^2\delta}{dt^2} \quad (3.13)$$

$$P_a = P_{m-}P_e \quad (3.14)$$

$$M\frac{d^2\delta}{dt^2} = P_s - P_e \text{ or } \frac{d^2\delta}{dt^2} = \frac{180f}{H}(P_m - P_e) \quad (3.15)$$

Where
r= radius of gyration in kg-m^2
m= mass of rotor in kg
ω= synchronous speed of the rotor in rad/s
J= moment of inertia of the rotor in kg-m^2

M= angular momentum of the rotor in MJs/elect radian or degree
K_e= kinetic energy of the rotor in MJ
G= Generator rating in MVA
H= Inertia Constant in MJ/MVA
f= Frequency in H_z
P_m= Mechanical power in Watts
P_e= Electrical power in Watts

3.6Determination of Generator Internal Current and Voltage

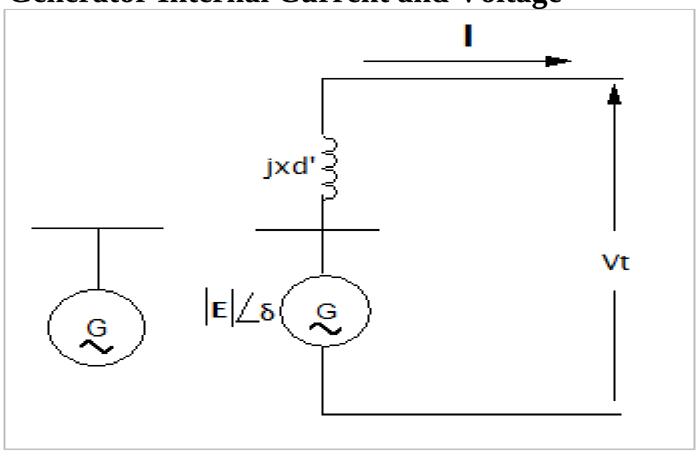

Figure 3.2: Synchronous Machine Model

Figure 3.2 show the equivalent circuit of a synchronous machine. From the power equation the internal current and voltage of the generator can be obtained.

$V_t I^* = P_g + jQ_g$ (3.16)

$I = \frac{P_g + jQ_g}{V_t^*}$ (3.17)

$E = V_t + (jX'_d)I$ (3.18)

$=|E'|\angle\delta$

Where
Pg= generator real power
Qg= generator reactive power
Vt=conjugate of terminal voltage from load flow analysis
Xd'=transient reactance of the generator
$|E'|$ = absolute value of the internal voltage
$\angle\delta$=initial rotor angle

3.7Determination of Load Admittance Matrix

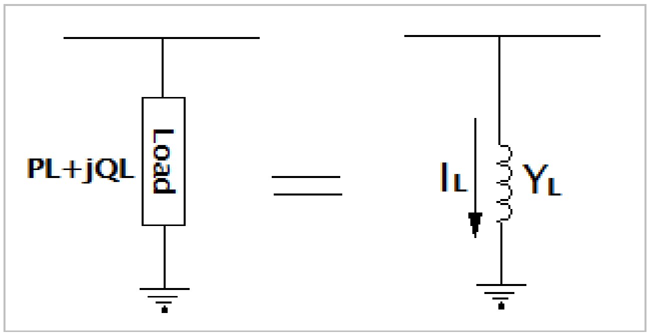

Figure 3.3: Static Load Model

Figure3.3. shows static load which can be represented by admittance connected between the bus and the ground. The admittance is added to their corresponding diagonal elements in the bus admittance matrix.

$$P_L + jQ_L = V_L I_L^* \quad (3.18)$$

$$= V_L (V_L^* Y_L^*) \quad (3.19)$$

$$= |V_L|^2 Y_L \quad (3.20)$$

$$Y_L = \frac{P_L - jQ_L}{|V_L|^2} \quad (3.21)$$

Where

P_L= Load real power

Q_L= Load reactive power

$|V_L|$= absolute value of the load terminal voltage from power flow

3.8Formation of Bus Admittance Matrix

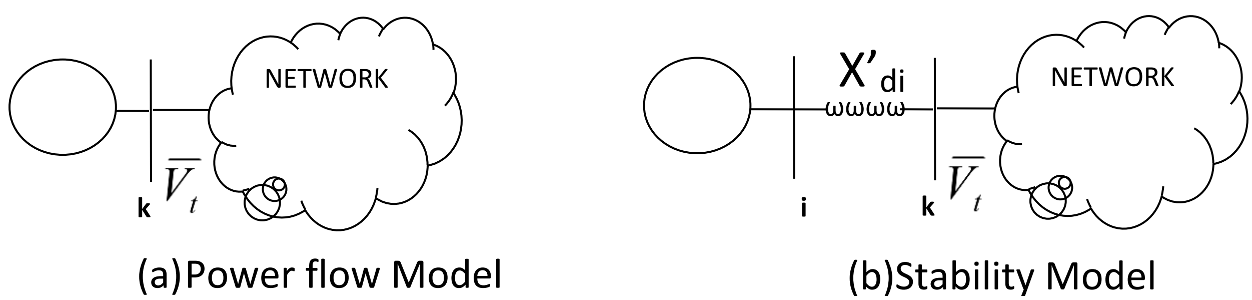

Figure 3.4: Network Representation

Relative to the power flow model, for each generator connected to the system an extended network is formed by adding a new generator bus between E and the terminal voltage bus k. Consequently the dimension of Y-bus admittance matrix is increased by adding a new row and column for each node i with diagonal element $Y_{ii}=y_{ik}=-j/X'_{di}$ and off-diagonal elements all zero except for $Y_{ik}=Y_{ki}=-y_{ik}=j/X'_{di}$.

Considering a network system with n generator buses and r load buses. Then the Y-admittance matrix can be written as

$$\begin{vmatrix} I_n \\ I_r \end{vmatrix} = \begin{vmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{vmatrix} \begin{vmatrix} E_n \\ E_r \end{vmatrix} \quad (3.22)$$

Where
Y_{nn}, Y_{rr} =the diagonal elements of the admittance matrix
Y_{nr}, Y_{rn} = the off-diagonal elements of the admittance matrix
I_n= the injected current at the generator bus
I_r= the injected current at the load bus
E_n= Internal generator Voltage
E_r= Internal Load Voltage

3.9Reduction of Bus Admittance Matrix

Kron's reduction techniques is performed to reduce the bus admittance matrix (3.22) by eliminating the internal load voltage E_r since there are zero injection current at the load buses. Therefore equation (3.22) can be written as

$$\begin{vmatrix} I_n \\ I_0 \end{vmatrix} = \begin{vmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{vmatrix} \begin{vmatrix} E_n \\ E_r \end{vmatrix} \quad (3.23)$$

$$|I_n| = |Y_{nn} - Y_{nr} Y_{rr}^{-1} Y_{rn}^{T}||E_n| \quad (3.24)$$

Where
I_n= the injected current at the generator bus
E_n= Internal generator Voltage
Y_{nn}=the diagonal elements of the admittance matrix
Y_{rr}^{-1}= inverse of the diagonal matrix
Y_{rn}^{T}= transposition of the off-diagonal matrix

The kron's network reduction technique in (3.24)is used only when loads are considered as constant impedances else the identity of the load buses must be retained.

3.10 Determination of Power Output

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{n=1 \\ n \neq i}}^{m} |E_i||E_n||Y_{in}| \cos(\delta_{in} - \theta_{in}) \quad (3.25)$$

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{n=1 \\ n \neq i}}^{m} |E_i||E_n||Y_{in}| \sin(\delta_i - \theta_{in} + 90^{\circ}) \quad (3.26)$$

Where

E_i = the internal generator voltage at bus i

G_{ii}= the real element of the diagonal matrix at bus i

$|Y_{in}|$= absolute value of the off-diagonal element at bus i

θ_{in}= angle of the off-diagonal element at bus i

δ_i= initial rotor angle at bus i

3.11Solution of Swing Equation Using Modified Euler's Methods

The swing curve is a graph of rotor power angle with time and can be obtained by solving the swing equation. The curve is useful in determining the adequacy of relay protection in power system with regards to fault clearing. From (3.15)

$$\frac{d^2\delta}{dt^2} = \frac{180f}{H}(P_m - P_e)$$

The second order swing differential equation can be written as two first order differential equation and solution obtained using Modified Euler's method.

3.11.1 Predictor Step

Let δ_0 and $\omega_0$be the initial point and Δt the increment in time

$$\frac{d\delta}{dt}|_0 = D_1 = \omega_0 \quad (3.27)$$

$$\frac{d\omega}{dt}|_0 = D_2 = \frac{180f}{H}(P_m - P_{max}\sin\delta_0) \quad (3.28)$$

The approximate value of δ and ω denoted as δ^p and$\omega^p$are calculated asfollows:

$$\delta^p = \delta_0 + D_1\Delta t \quad (3.29)$$

$$\omega^p = \omega_0 + D_2\Delta t \quad (3.30)$$

3.11.2 Corrector Step

With the new value of δ^p and ω^pobtained in the predictor step, the value of $P_e$is updated.

$$\frac{d\delta}{dt}|_p = D_{1p} = \omega^p \quad (3.31)$$

$$\frac{d\omega}{dt}|_p = D_{2p} = \frac{180f}{H}(P_m - P_{max}\sin\delta^p) \quad (3.32)$$

With the above new derivative values obtained, the final value of δ and ω at p denoted as δ_1 and ω_1 are calculated as

$$\delta_1 = \delta_0 + \left(\frac{D_1 + D_{1p}}{2}\right) * \Delta t \quad (3.33)$$

$$\omega_1 = \omega_0 + \left(\frac{D_2 + D_{2p}}{2}\right) * \Delta t \quad (3.34)$$

Proceeding further, for calculating δ and ω at 2p, the initial pointsδ_0 and $\omega_0$are replaced by δ_1 and ω_1 respectively.

3.12 Algorithm for Transient Stability

Step1. Prepare data for the given system. This includes the lines, transformers and shunt capacitors data.

Step2. Formulate the Y_{bus} admittance matrix.

Step3. Solve the initial load flow.

Step4. Reads generator data.

Step5. Modify Ybus by adding the generator and load admittances.

Step6. Compute the pre-fault admittance matrix by eliminating all nodes except the internal generator nodes.

Step7. Solve the generator swing equation for the pre-fault period.

Step8. Set t = 0.2s and t=0.25s the time a three-phase fault occurs and was cleared.**Step9.**Compute the admittance matrix during fault.

Step10. Solve the swing equation for the fault period.

Step11. Isolate the line which fault occurred.

Step12. Compute the post-fault system admittance matrix.

Step13. Solve the swing equation for the post fault period.

Step14. Plots the swing curves for all generators.

3.13 Transient stability Calculation for a Multi-Machine System

Figure 3.5 shows a five bus model of the Nigeria 330kV network. The model will be used as a prototype for analyzing transient stability in a multi-machine system.

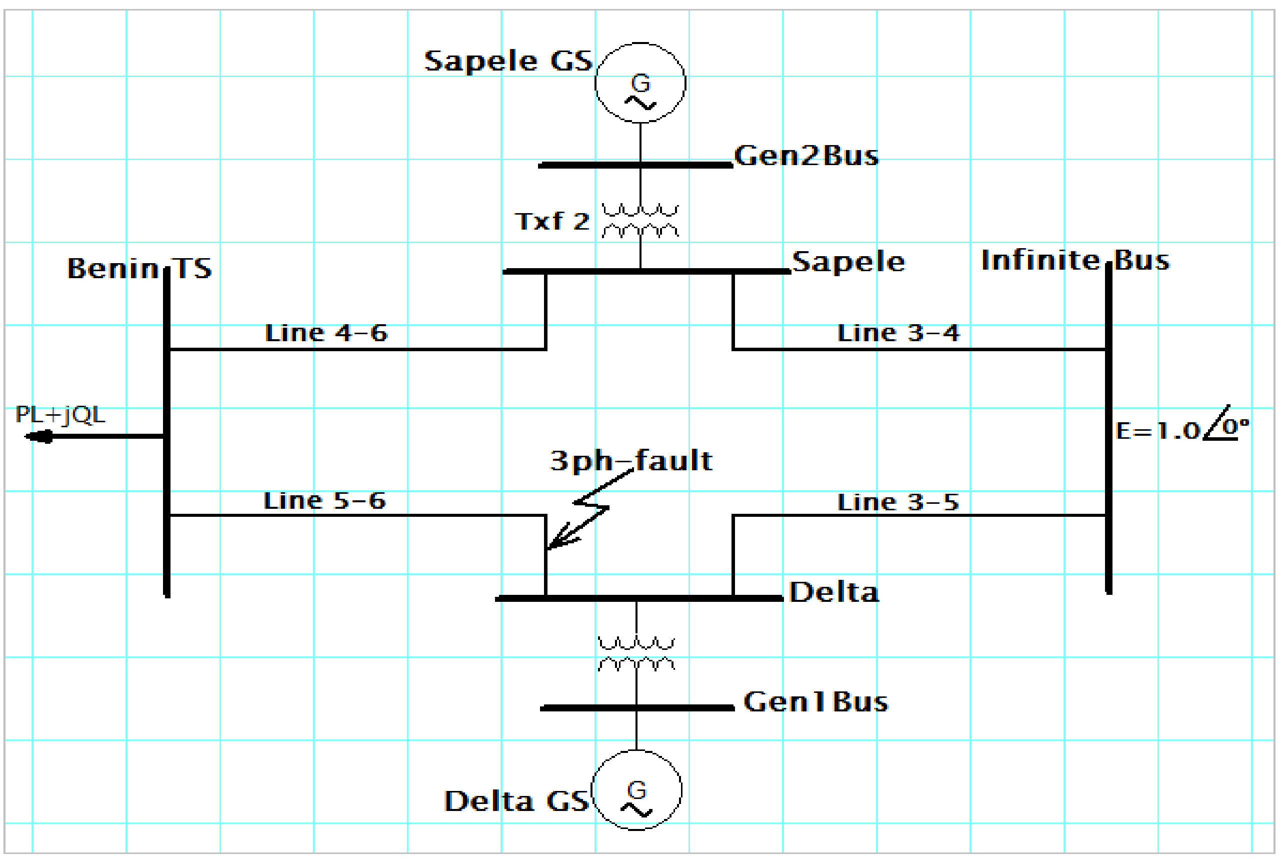

Figure 3.5:Network Model of Nigeria 330kV Grid

3.13.1 Pre-Fault Load Flow Analysis

Table 3.4 and 3.5 shows the line and bus data of the network shown in figure 3.2
Table 3.6 shows the pre-fault power values of the network in figure 3.2 performed with the aid of a software.

Table: 3.4 Line Data of Network Model

Bus to bus	**Impedance(Z)**		**Shunt (Y)**
	R	**X**	**(B)**
Txf 1-5	-	0.125	-
Txf 2-4	-	0.125	-
Line 3-4	0.020	0.040	0.040
Line 3-5	0.013	0.025	0.022
Line 4-6	0.018	0.047	0.040
Line 5-6	0.010	0.030	0.047

Table: 3.5 Bus Data of Network Model

Bus ID	**Generation**				**Load**	
	H	Xd^I	MW	Mvar	MW	Mvar
Bus 1	11.2	0.30	-	-	-	-
Bus 2	8.0	0.28	2.00	-	-	-
Bus 3	-	-	-	-	-	-
Bus 4	-	-	-	-	-	-
Bus 5	-	-	-	-	-	-
Bus 6	-	-	-	-	-4.0	-2.0

Table: 3.6 Pre-Fault Load Flow Values

Bus ID	**PU Voltage**		**Generation**		**Load**	
	Mag	Angle	MW	Mvar	MW	Mvar
Bus 1	1.02	0.00	-5.98	-1.49	-	-
Bus 2	1.01	0.94	2.00	-15.66	-	-
Bus 3	1.00	0.00	-	-	-	-
Bus 4	1.02	0.55	-	-	-	-
Bus 5	1.02	0.41	-	-	-	-
Bus 6	1.02	0.48			-4.0	-2.0

3.13.2Determination of Generators Internal Current and Voltages

```
% THE DATA OBTAINED FROM PRE-FAULT LOAD FLOW CALCULATION
% Generator Real(pg), and Reactive power(qg)
pg1=-5.98; qg1=-1.49i;
pg2=2.00;  qg2=-15.66i;
% Load Real(pl), and Reactive power(ql)
pl=-4.0;ql=-2.0;
%Bus voltage
v1=1.0200;
```

```
v2=1.0100+0.9400i;
v3=1.0000;
v4=1.0200+0.5500i;
v5=1.0200+0.4100i;
v6=1.0200+0.4800i;
% Reactance of the generators
xd1=0.3i;
xd2=0.28i;
%Inertia constant of the generators
h1=11.2;
h2=8.0;
% DETERMINATION OF GENERATORS INTERNAL CURRENT AND VOLTAGES
i1=(p1-q1)/conj(v1)
e1=v1+(xd1*i1)
i2=(p2-q2)/conj(v2)
e2=v2+(xd2*i2)

i1 =
  -5.8627 + 1.4608i
i2 =
  -6.6714 + 9.2959i

e1 =
   0.5818 - 1.7588i or 1.8525∠ − 71.6868
e2 =
  -1.5929 - 0.9280i or  1.8435∠ − 149.7561
>>
```

3.13.3 Determination of Bus Admittance Matrix of the Network

```
% Transformer reactance(X)
z15=0.125i;
z24=0.125i;
% Line Impedance(Z)
z34=0.02+0.04i;
z35=0.013+0.025i;
z46=0.018+0.047i;
z56=0.01+0.03i;
% Line Shunt(B)
b34=0.04;
b35=0.022;
b46=0.04;
b56=0.047;
% Effective Line shunt
b33=(b34+b35)/2;
```

```
b44=(b34+b46)/2;
b55=(b34+b56)/2;
b66=(b46+b56)/2;
% Line Admittance
y15=inv(z15);
y24=inv(z24);
y34=inv(z34);
y35=inv(z35);
y46=inv(z46);
y56=inv(z56);
y12=0; y21=y12;
y13=0; y31=y13;
y14=0; y41=y14;
y16=0; y61=y16;
y23=0; y32=y23;
y25=0; y52=y25;
y26=0; y62=y26;
y36=0; y63=y36;
y45=0; y54=y45;
% Mutual Admittance
y15=-y15; y51=y15;
y24=-y24; y42=y24;
y34=-y34; y43=y34;
y35=-y35; y53=y35;
y46=-y46; y64=y46;
y56=-y56; y65=y56;
% Self Admittance
y11=-y15;
y22=-y24;
y33=-(y34+y35)+b33;
y44=-(y42+y43+y46)+b44;
y55=-(y51+y52+y53+y56);
y66=-(y64+y65)+b66;
% ybus admittance matrix
ybus=[y11 y12 y13 y14 y15 y16; y21 y22 y23 y24 y25 y26; y31 y32 y33 y34 y35 y36; y41 y42
y43 y44 y45 y46; y51 y52 y53 y54 y55 56;y61 y62 y63 y64 y65 y66]
```

The initial bus admittance matrix obtained from power flow calculation is

Ybus =

0-8.0000i	0	0	0	0+8.0000i0	
0	0-8.0000i	0	0+8.0000i	0	0

0 0 26.4038-51.4861i -10.0000+20.0000i -16.3728+31.4861i 0
0 0+8.0000i -10.0000+20.0000i 17.1462-46.5551i 0 -7.1062+18.5551i
0+8.0000i 0 -16.3728+31.4861i 0 26.3728-69.4861i -10.0000+30.0000i
0 0 0 -7.1062+18.5551i -10.0000+30.0000i 17.1497-48.5551i

3.13.4Updating Ybus Matrix to Determine the Value at Pre-Fault Condition

Step1: Generator Bus
Remove the admittance of the transformer Ybus(1,5) and Ybus (2,4) .
Add the series admittance of generator and transformer toYbus(1,5) and Ybus (2,4)
Step2: Load Bus
Add load admittance to Ybus (6,6)
The bus admittance matrix corresponding to pre-fault condition is
Ybus1 =

0-2.3529i0 0 0 0+2.3529i 0
0 0-2.3529i 0 0+2.3529i 0 0
0 0 26.4038-51.4861i -10.0000+20.0000i -16.3728+31.4861i 0
0 0+2.3529i -10.0000+20.0000i 17.1462-46.5551i 0 -7.1062+18.5551i
0+2.3529i 0 -16.3728+31.4861i 0 26.3728-69.4861i -10.0000+30.0000i
0 0 0 -7.1062+18.5551i -10.0000+30.0000i14.0021-46.9813i

3.13.5 Determination of Bus Admittance Matrix During-Fault Condition

A 3-phase fault occurred on Line 5-6 (Benin-Delta transmission line) as shown in figure3.5. During the fault, bus 5 (Delta) is short circuited to the ground. Consequently the row 5 and column 5 in the bus admittance matrix obtained during pre-fault condition will disappear because node 5 is merged with the reference node. However, the new row 5 and column 5 (previous node 6) are eliminated using Kron's reduction techniques (3.42). The resulting bus admittance matrix when bus 5 is grounded is

Ybus2 =

0-2.3529i 0 0 0 0
0 0-2.4691i 0 0+2.4691i 0
0 0 26.4038-51.4861i -10.0000+20.0000i 0
0 0+2.4691i -10.0000+20.0000i 17.1462-46.5551i -7.1062+18.5551i
0 0 0 -7.1062+18.5551i 13.3050-46.6327i

Applying Kron's reduction techniques Ybus matrix during fault condition is further reduced to

Ybus2 =

0-2.3529i 0 0
0 0.0438 - 2.2272i -0.1614 + 1.2545i
0 -0.1614 + 1.2545i 19.7002 - 41.5089i

In polar form
$2.3529\angle-89.9883$ 0 0
$02.2277\angle-88.86081.2648\angle-97.3192$
$01.2646\angle-97.319345.9466\angle-64.6025$

3.13.6 Determination of Bus Admittance Matrix During Post-Fault Condition

Opening line 5-6 (Delta –Benin Transmission line) by the circuit breaker cleared the fault on the system. However, the bus admittance matrix at post fault condition can be obtained by subtracting the admittance of line 5-6 and half line charging admittance from the diagonal and off-diagonal matrix of line 5-6 in the pre-fault bus admittance matrix. Kron's reduction techniques is further applied to eliminate node 4, 5 and 6.The resulting bus admittance matrix when line 5-6 is opened

Ybus3 =

0-2.3529i0 0 0 0+2.3529i 0
0 0-2.3529i 0 0+2.3529i 0 0
0 0 26.4038-51.4861i -10.0000+20.0000i -16.3728+31.4861i 0
0 0+2.3529i -10.0000+20.0000i 17.1462-46.5551i 0 -7.1062+18.5551i
0+2.3529i 0 -16.3728+31.4861i 0 16.3728-39.5096i 0
0 0 0 -7.1062+18.5551i 0 4.0021-17.0048

Applying Kron's reduction techniques Ybus matrix during post-fault condition is further reduced to

ybus3 =
-0.0720-2.4913i 0 0-2.3529i
0 0.0463-2.1567i -0.4405+1.8646i
0-2.3529i -0.4405+1.8646i 31.1075-68.9946i

In polar form
$2.4923\angle-91.6428$ 0 $2.3529\angle-89.9883$
$02.1572\angle-88.75891.9160\angle-103.2782$
$2.3539\angle-89.98831.9160\angle-103.278275.6831\angle-65.7224$

3.13.7 Determination of Power Output

```
% During Fault Condition when bus 5 is short circuited
E1=1.8525; E2=1.8435; E3=1.0;
G11=0.0438; y21=0; y23=1.2648;
```
θ_{23}=-97.3192;
Pe1=0;
Pe2=0.1489+2.3317$\sin(\delta_2 + 187.3192)$

```
% During Post-Fault Condition when Line 5-6 is opened
E1=1.8525; E2=1.8435;
G11=-0.0720; G22=0.0463;
y13=2.3529; y23=1.9160;
```
θ_{13}=-89.9883;θ_{23}=-103.2782;

Pe1=-0.2471+4.3587$\sin(\delta_1 + 179.9883)$
Pe2=0.1574+3.5321$\sin(\delta_2 + 193.2782)$

3.13.8 Solution of Swing Equation by Modified Euler's Method

```
Pm=2.0;
f=50;
H=8.0;
a0=-2.6137;
w0=2*pi*f;
for dt=0.00:0.02:0.14;
D1=w0;
D2=pi*f/H*(Pm-(0.1574+3.5321*sin(a0-0.2318)));
ap=(a0-0.2318)+D1*dt;
wp=w0+D2*dt;
D1p=wp;
D2p=180*f/H*(Pm-(0.1574+3.5321*sin(ap)));
a1=(a0-0.2318)+dt*(D1+D1p)/2
w1=w0+dt*(D2+D2p)/2
```

RESULT AND DISCUSSION

4.1 Presentation and Discussion of Results

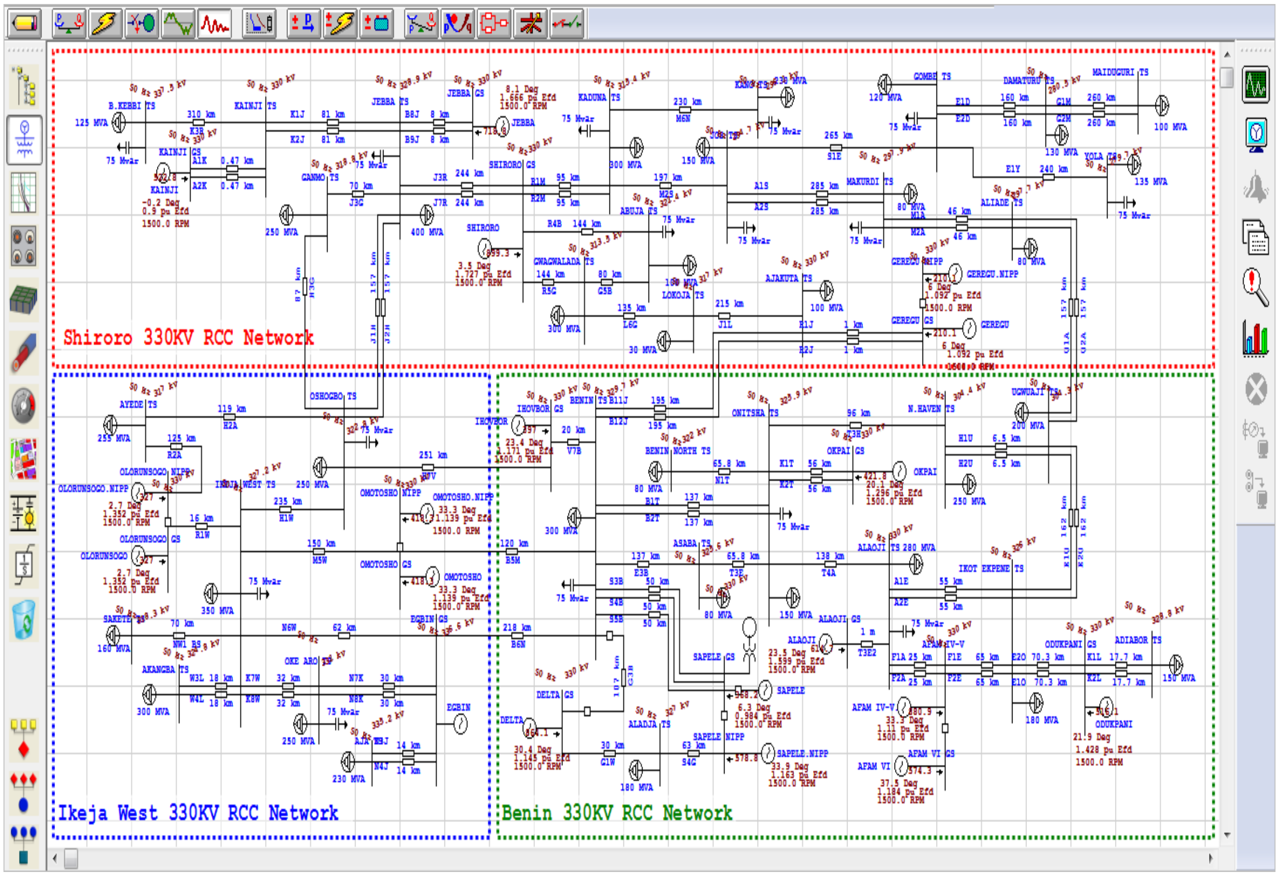

Figure 4.1: Model of the Existing Nigeria 330kV Network after Simulation

Figure 4.1 shows the performance of the Nigerian 330kV power system network. The generation, load and voltage profile of the existing network is shown in the above figure. Egbin power station is used as the swing bus since it has the largest generating capacity. A simulation time step of 0.001 was used in Etap software to increase the calculation. Also a fault time was set at 0.2 second for a three phase-fault to occur at80% of Benin-Delta transmission line and a clearing time was set at 0.25 seconds. The simulation lasted for 20seconds

Table 4.1: Bus Voltage (kV)

SN	Bus ID	Bus Type	Nominal	Pre-Fault	During-Fault	Post-Fault
1	Abuja TS	Load	330	316.3	279.6	315.1
2	Adiabor TS	Load	330	328.9	297.3	328.2
3	Afam IV-V	Gen.	330	330.1	294.3	329.3
4	Afam VI GS	Gen.	330	330.1	294.3	329.3
5	Aja TS	Load	330	335.4	279.8	334.2
6	Ajakuta TS	Load	330	330.1	226.2	326.0
7	Akangba TS	Load	330	323.9	269.8	322.5
8	Aladja TS	Load	330	327.0	171.9	317.6

9	Alaoji TS	Load	330	330.1	291.5	329.2
10	Alaoji GS	Gen.	330	330.1	291.5	329.2
11	Aliade TS	Load	330	315.8	245.3	313.5
12	Asaba TS	Load	330	325.0	195.2	321.0
13	Ayede TS	Load	330	315.4	265.5	313.9
14	B.Kebbi TS	Load	330	318.2	290.3	313.9
15	Benin North TS	Load	330	321.4	217.1	318.1
16	Benin TS	Load	330	329.4	147.1	323.9
17	Damaturu TS	Load	330	328.1	228.8	324.9
18	Delta GS	Gen.	330	330.1	170.5	320.1
19	Egbin GS	Swing	330	336.8	281.0	335.6
20	Ganmo TS	Load	330	317.6	278.3	316.4
21	Geregu GS	Gen.	330	330.1	226.5	326.0
22	Geregu NIPP	Gen.	330	330.1	226.5	326.0
23	Gombe TS	Load	330	325.0	274.1	316.2
24	Gwagwalada TS	Load	330	325.3	270.6	319.0
25	Ihovbor GS	Gen.	330	330.1	173.1	325.0
26	Ikeja West TS	Load	330	326.3	271.7	324.8
27	Ikot Ekpene TS	Load	330	326.9	288.0	325.9
28	Jebba GS	Gen.	330	330.1	299.8	329.2
29	Jebba TS	Load	330	328.6	297.6	327.6
30	Jos TS	Load	330	315.1	251.9	313.9
31	Kaduna TS	Load	330	320.3	279.7	317.6
32	Kainji GS	Gen.	330	313.5	307.0	329.2
33	Kainji TS	Load	330	330.1	306.9	329.2
34	Kano TS	Load	330	316.3	248.8	313.5
35	Lokoja TS	Load	330	319.3	254.1	317.1
36	Makurdi TS	Load	330	315.0	246.3	314.5
37	Maiduguri	Load	330	326.4	234.8	319.9
38	N.Haven TS	Load	330	318.0	245.0	313.8
39	Odukpani GS	Gen.	330	330.1	298.4	329.4
40	Oke Aro TS	Load	330	329.7	274.8	328.5
41	Okpai GS	Gen.	330	330.1	239.9	327.0
42	Olorunsogo GS	Gen.	330	330.1	279.8	328.7
43	Olorunsogo NIPP	Gen.	330	330.1	279.8	328.7
44	Omotosho GS	Gen.	330	330.1	228.4	326.9

45	Omotosho NIPP	Gen.	330	330.1	228.4	326.9
46	Onitsha TS	Load	330	325.3	219.7	322.0
47	Oshogbo TS	Load	330	320.6	268.8	319.0
48	Sakete TS	Load	330	317.4	264.3	316.0
49	Sapele GS	Gen.	330	330.1	182.2	322.9
50	Sapele NIPP	Gen.	330	330.1	182.2	322.9
51	Shiroro GS	Gen.	330	330.1	300.6	329.3
52	Ugwuaji TS	Load	330	328.0	245.0	325.3
53	Yola TS	Load	330	324.1	228.8	316.1

Table 4.1 shows the bus voltages at pre-fault, during fault and post-fault condition. It was observed that the bus voltages were deviating from the statutory limit of 313.45 kV-346.5 kV when fault occurred. However, the oscillation was damped after the fault was cleared.The buses that were mostly affected by the fault are Sapele GS,Delta GS, Ihovbor GS, Okpai GS, Omotosho GS, GereguGS, Benin TS, Aladja TS, Asaba TS, Onitsha TS and Benin North TS.

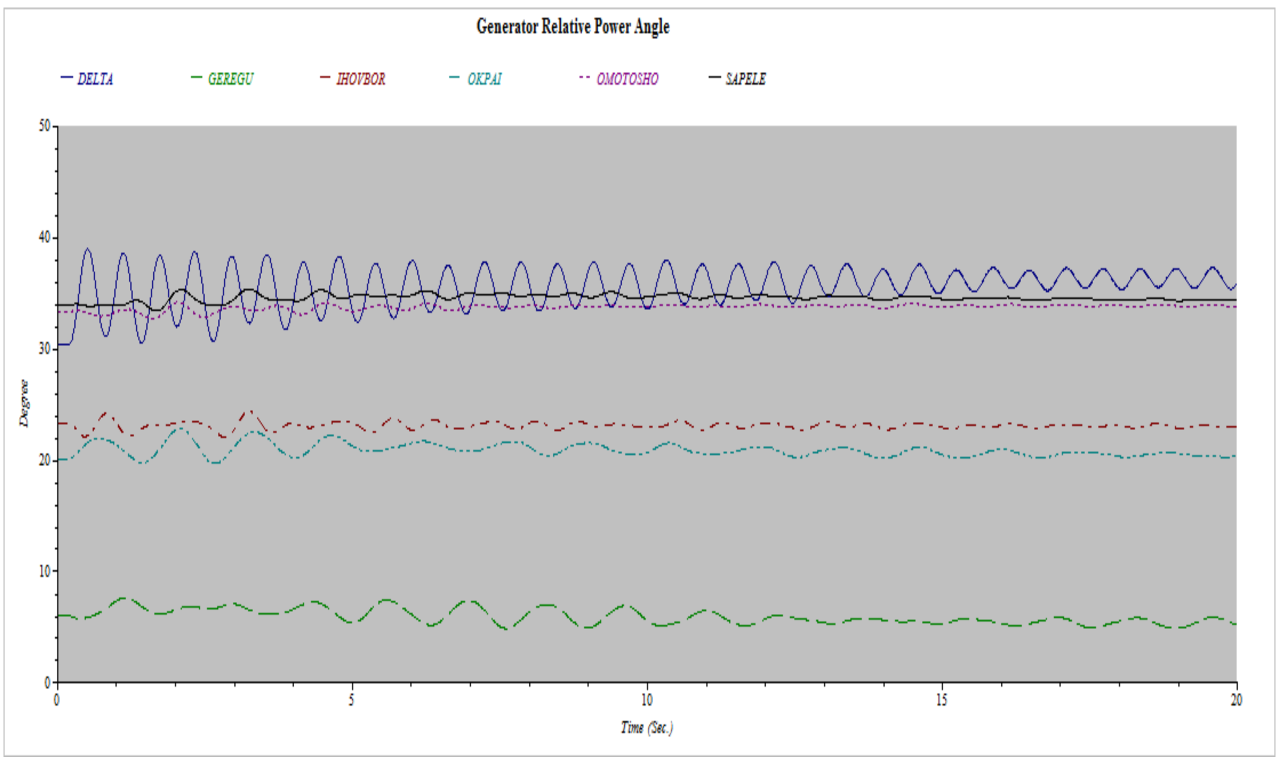

Figure 4.2: Plot of Generator Relative Power Angle with Time

Figure 4.2 shows the graph of relative power (rotor) angle with time. The graph is an indicator of the generator's stability. Looking at the profile, at 0.00-0.19 second there were no power oscillations in the output which shows that the generators were running at synchronous speed. At 0.20-0.24 seconds it was observed that due to the fault, the generators experienced a power swing and now operates in a new power angles. At 0.25 seconds after the fault was cleared, it oscillated and was damped gradually though will attain stability after a period as the oscillation decays away with time. Based on this behavior, we can say that the generators maintained synchronism with the grid.

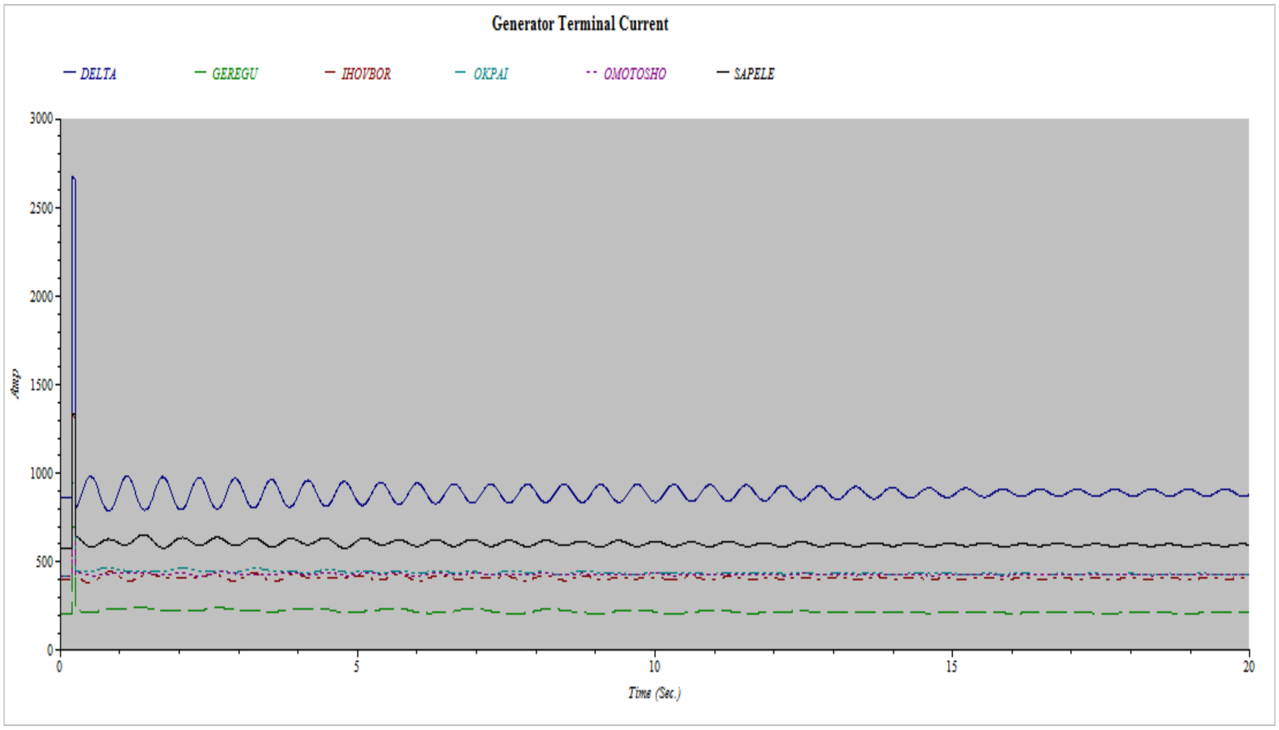

Figure 4.3: Plot of Generator Terminal Current with Time

Figure 4.3 shows the plot of generator terminal current with time. From the profile a sudden rise in generator's terminal current was observed during fault period. After the fault was cleared the oscillations in the terminal current reduced gradually and the system reaches a stable operating condition. Based on this behavior, we can say that the generators maintained synchronism with the grid.

SUMMARY AND CONCLUSION

5.1 Summary and Conclusion

The study was carried out to examine the capacity of the existing Nigeria 330kV power system network to withstand disturbance while quality of service is maintained. The swing equation was solved using Modified Euler's method and Electrical Transient Analyzer Program (ETAP12.6) software was used to model the network to examine the impact a three phase fault created along

Delta–Benin transmission line. Transient stability was improved through the use of high speed circuit breakers to open faulty areas without collapse of the system.

5.2Contribution to Knowledge

The study is valuable to the transmission company of Nigeria for proper planning of Nigerian national grid. Also serves as a guide to the power system engineers to set their relays and circuit breakers operating time to act at 0.04 seconds or less in the occurrence of a three phase fault to enable the system regain its power stability as quick as possible to avoid system collapse.

5.3 Recommendation

Based on the findings, the following recommendations are highlighted as a measure to improve transient stability for optimum performance and reliability the power system.

1. More loops are to be created in the transmission sub-network to increase reliability and stability during disturbances.
2. The deployment of faster auto-reclosure mechanisms to facilitate the swinging synchronous generators to develop restoring torque and accentuate the stability limit of the system. Manual reclosure have been considered too sluggish to have any significant impact on the stability limit

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