



TRANSIENT STABILITY IMPROVEMENT OF BENIN BUS/IKEJA WEST-BENIN TRANSMISSION LINE WITH THE ARTIFICIAL NEURAL NETWORK CONTROLLED VSC- HVDC THROUGH EIGENVALUE ANALYSIS

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ABSTRACT

This work presents the application of Artificial Neural Network Voltage Source Converter for improvement of the transient stability of the Nigerian 330kV transmission system. Enhancement of the dynamic response of generators, within a power system, when subjected to various disturbances, has been a major challenge to power system researchers and engineers for the past decades. The system was modeled in Power System Analysis Toolbox (PSAT) environment and MATLAB software was employed as the tool for the simulations. The eigenvalue analysis of the system buses was performed to determine the critical buses. A three-phase balanced fault was then applied to some of these critical buses and lines of the transmission network in order to establish the existing transient stability situation of the grid through the observation of the dynamic responses of the generators in the case network when the fault was applied. This clearly shows that one of the most critical buses is Benin bus and critical transmission line, Ikeja West – Benin Transmission line within the network. To this effect, the inverter and the converter parameters of the HVDC were controlled by the artificial neural network and were installed along to those critical lines. The results obtained showed that 33.33% transient stability improvement was achieved when the HVDC was controlled with the artificial neural network. The voltage profile result and the damping were improved when the ANN was installed.

KEYWORDS: Transmission Line, Eigenvalue Analysis, Transient Stability, Artificial Neural Network, VSC-HVDC

INTRODUCTION

The demand of electricity has radically increased and a modern power system becomes a difficult network of transmission lines interconnecting the generating stations to the major loads centres in the overall power system in order to support the high demand of consumers. Transmission networks being overloaded, are pushed closer to their stability limits. This is as a result of increasing demand for electricity due to growing industrialization. This could have negative effect on the power system

security. The security of a power system is regarded as the ability of the network to withstand disturbances without breaking down (Khoshnaw, and Saleh, 2005). Stability is determined by the observation of voltage frequency and rotor angle. Transient stability which can be defined as the ability of the power system to maintain certain parameters within limit of occurrence of the transient on power system like sudden load discharge, grid failure or any kind of fault can also be seen as the ability of a power system to regain its normal operating condition after sudden and severe disturbance in system. Those disturbances may be because of the application of faults, clearing of faults, switching on and off surges in EHV system. Transient stability of the system can also be improved by increasing the system voltage. Increase in the voltage profile of the system implies increase in the power transfer ability.

METHODOLOGY

MATLAB/PSAT software was employed as the tool for the simulations. The existing Nigerian 330kV transmission system was modeled in PSAT environment and the system load flow was simulated. The eigenvalue analysis of the system buses was performed to determine the critical buses. A balanced three-phase fault was then applied to some of these critical buses and lines of the transmission network in other establish the existing/current transient stability situation of the grid through the observation of the dynamic responses of the generators in the Nigeria 330-kV grid/network when the fault was applied. This shows clearly that there exist three most critical buses which are Makurdi, Ajaokuta and Benin buses and critical transmission lines (which include Jos - Makurdi Transmission line, Ajaokuta - Benin and Ikeja West – Benin Transmission line) within the network. The performed load flow analysis also revealed that the system losses synchronism when the balanced three-phase fault was applied to these identified critical buses and lines. To this effect, VSC-HVDC was installed along to those critical lines. The inverter and the converter parameters of the HVDC were controlled by the conventional proportional integral (PI) method and artificial neural network. The generalized swing equation for a multi-machine power system was also used. The flowchart is shown in Figure 1.0.

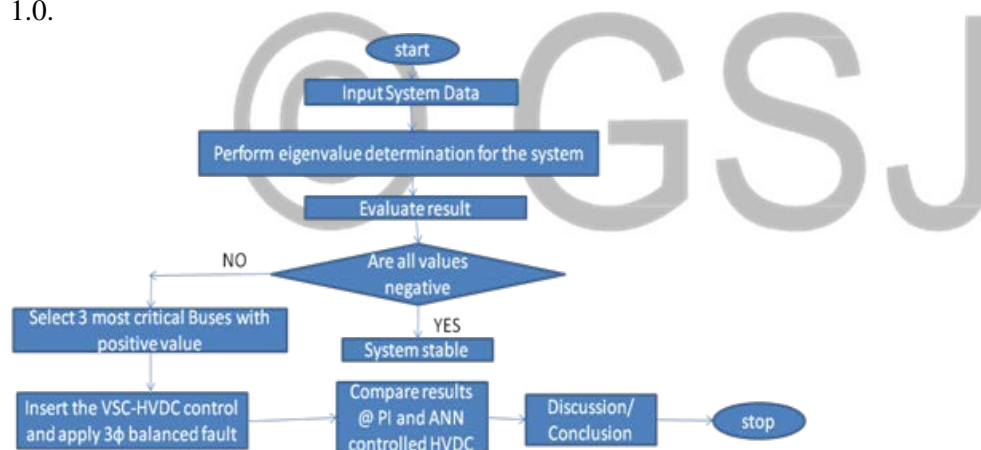


Figure 1.0: Flowchart for determination of Transient stability using Eigenvalue method

Load Flow Equation

Nodal admittance matrix can given as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & & \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & & \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & & \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & & \\ \vdots & \vdots & \vdots & \vdots & \ddots & \\ Y_{n1} & Y_{n2} & Y_{n3} & Y_{n4} & & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ \vdots \\ V_n \end{bmatrix} \quad 1.1$$

Now define complex in a node such as k.

As $S_k = P_k + Q_k$ hence the load schedule at node k is $P_{ks} + Q_{ks}$.

Therefore the current

$$P_k = \sum_j^n Y_{kj} (V_k + V_j) \quad 1.2$$

Where Y_{kj} is the summation of all the admittances connected between node k and j, and V_k and V_j are node voltages in the respective nodes.

Since,

$$I_k = V_k \sum_{j=0}^n Y_{kj} - \sum_{j=1}^n Y_{kj} V_j \quad 1.3$$

Since from the nodal KCL admittance matrix,

$$I_k = Y_{k0} V_k + Y_{k1} (V_k - V_1) + Y_{k2} (V_k - V_2) + \dots + Y_{kn} (V_k - V_n) \quad 3.4$$

$$= (Y_{k0} + Y_{k1} + Y_{k2} \dots Y_{kn})V_k - Y_{k1}V_1 - Y_{k1}V_1 \quad 1.5$$

The real and reactive power at bus k as

$$P_k + jQ_k = V_k + I_k^* \quad 1.6$$

$$\text{Hence, } I_k = \frac{P_k + jQ_k}{V_k} \quad 1.7$$

If we substitute for I_k in equation (3) we have

$$\frac{P_k + jQ_k}{V_k} = \sum_{j=0}^n Y_{kj} V_j - \sum_{j=1}^n Y_{kj} V_j \quad 1.8$$

From equation (4)

$$V_k = \frac{1}{Y_{kk}} \left[\frac{P_k + jQ_k}{V_k} \right] - \sum_{j \neq k}^n Y_{kj} V_j \quad 1.9$$

Power Flow Analysis of Nigeria 330kV Transmission Power System

The Nigeria 330-kV transmission network used as the case study in this dissertation consists of eleven (11) generators, twenty-nine (29) loads, comprising of forty (40) buses and fifty-two (52) transmission lines, which cut across the six (6) Geopolitical zone (South-West, South-South, South-East, North- Central, North-West and North-East Region) of the country with long radial interconnected transmission lines. The line diagram and data of the Nigerian transmission system were sourced from the National Control Centre of Power Holding Company of Nigeria, Osogbo, Nigeria. Power flow analysis of the Nigerian transmission system was performed in Matlab/Psat environment as shown in Figure 2.0

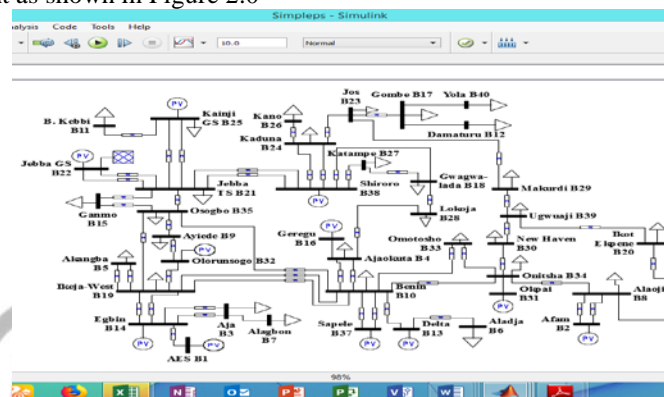


Figure 2.0: PSAT Model of the Nigeria 330kV transmission power system without VSC-HVDC

Mathematical Formulation of Swing Equation for a Multi- Machine Power System

Consider a multi-machine n -bus power network consisting of m number of generators such that $n > m$. At any bus i within the system, the complex voltages (V_i), generators real power (P_{gi}) and the generator reactive power (Q_{gi}) can easily be obtained from the pre-fault load-flow analysis from which the initial machine voltages(E_i) can also be obtained. This relationship can be expressed as

$$E_i = V_i + jX_i \left[\frac{P_{gi} - jQ_{gi}}{V_i^*} \right] \quad 2.1$$

Where;

X_i is the equivalent reactance at bus i . By converting each load bus into its equivalent constant admittance form, we have the load admittance as;

$$Y_{Li} = \frac{P_{Li} - jQ_{Li}}{|V_i|^2} \quad 2.2$$

Where P_{Li} and Q_{Li} are the respective equivalent real and reactive powers at each load buses. The pre-fault bus admittance matrix [$bus Y$] can therefore be formed with the inclusion of generators reactance and the converted load admittance. This can be partitioned as

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \quad 2.3$$

Where Y_{11} , Y_{12} , Y_{21} , and Y_{22} are the sub-matrices of Y_{bus} . Out of these four sub-matrices, Y_{11} , whose dimension is $m \times m$ is the main interest of this work as it contains generators buses only with the load buses eliminated. Equation (2.3) is formulated for the network conditions such as pre-fault, during fault and post-fault. The $bus Y$ for the network is then formulated by eliminating all nodes except the internal generator nodes. The reduction is achieved based on the fact that injections at all load nodes are zero. The nodal equations, in compact form, can therefore be expressed as

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{mm} & Y_{mn} \\ Y_{nm} & Y_{nn} \end{bmatrix} \begin{bmatrix} V_m \\ V_n \end{bmatrix} \quad 2.4$$

By expansion equation (2.4) can be expanded as

$$I_m = Y_{mm} V_m + Y_{mn} V_n \quad 2.5$$

$$\text{and } 0 = Y_{mm} V_m + Y_{mn} V_n \quad 2.6$$

By combining equations (2.5) and (2.6) and some mathematical manipulations, the desired reduced admittance matrix can be obtained as

$$Y_{reduced} = Y_{mm} - Y_{mn} Y_{nn}^{-1} Y_{nm} \quad 2.7$$

$Y_{reduced}$ is the desired reduced matrix with dimension $m \times m$, where m is the number of generators. The electrical power output of each machine can then be written as

$$P_{ei} = E_i^2 Y_{ii} \cos \theta_{ii} + \sum_{j=1}^m |E_i| |E_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad 2.8$$

Equation (2.8) is then used to determine the system during fault $P_{ei}(P_{ei(during-fault)})$ and post-fault $P_{ei}(P_{ei(post-fault)})$ conditions.

The rotor dynamics, representing the swing equation, at any bus i , is given by

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} + D_i \frac{d \delta_i}{dt} = P_{mi} - P_{ei} \quad 2.9$$

All the parameters retain their usual meanings.

Consider a case when there is no damping i.e. $D_i = 0$, equation (2.9) can be re-written as

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} = P_{mi} - \left(E_i^2 Y_{ii} \cos \theta_{ii} + \sum_{j=1}^m |E_i| |E_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \right) \quad 2.10$$

The swing equation for the during-fault condition can easily be expressed as

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} + D_i \frac{d \delta_i}{dt} = P_{mi} - P_{ei(during-fault)} \quad 2.11$$

Similarly, the swing equation for the post fault condition can be written as

$$\frac{H_i}{\pi f_0} \frac{d^2 \delta_i}{dt^2} + D_i \frac{d \delta_i}{dt} = P_{mi} - P_{ei(post-fault)} \quad 2.12$$

EIGENVALUE ANALYSIS

The Eigenvalue analysis investigates the dynamic behavior of a power system under different characteristic frequencies ("modes"). In a power system, it is required that all modes are stable. Moreover, it is desired that all electromechanical oscillations are damped out as quickly as possible. The Eigen value (γ) gives information about the proximity of the system to instability. The participation factor measures the participation of a state variable in a certain mode oscillation. The damping ratio (τ) is an indication of the ability of the system to return to stable state in the event of disturbance. For eigenvalue determination of stability, all the values must have negative real part and will lie on the left side of the S-plane. However, if any of the established eigenvalue lies on the positive right side of the S-plane, thus indicates oscillation in the system hence unstable.

The aim here is to determine the generator buses that are most marginally unstable. In order to demonstrate the effect of the HVDC on transient stability the Nigeria 330kV grid, the buses to be subjected to three phase fault should be the buses that are marginally unstable. To do this, the case study network was designed in Matlab/PSAT environment and simulation procedure and results specific to its parameters were obtained. This enabled this work to explore the peculiarity of the Nigerian power system.

The overall network/load representation comprises a large sparse nodal admittance matrix equation with a structure similar to that of the power-flow problem. The network equation is written in matrix form as:

$$I_L = Y_N V \quad 3.1$$

Where V is the node voltage and I is the node current. The node admittance matrix Y_N is symmetrical, except for dissymmetry introduced by phase-shifting transformers.

This can be represented in steady state-space form as follows:

$$Ax = x \quad 3.2$$

To obtain the solution of equation (3.2), a scalar parameter λ called the eigenvalue is introduced such that equation (3.2) becomes;

$$Ax = \lambda x \quad 3.3$$

Where $A = [a_{ij}]_{n \times n}$ is an $n \times n$ square matrix, where x is $n \times 1$ vector and λ is a number (scalar) parameter. Clearly the solution $x = 0$ for λ is usually not useful and thus is neglected.

For non-trivial solutions i.e. $x \neq 0$, the values of λ are called the eigenvalues and the characteristics values or latent roots of the matrix A and the corresponding solutions of equation (3.3) are called eigenvectors or characteristic vectors of A . Expressed as separate equations we have;

$$A \cdot x - \lambda x = 0 \quad 3.4$$

$$(A - \lambda I)x = 0 \quad 3.5$$

Notice that the unit matrix I was introduced so that λ can be subtracted from matrix A . Now for equation (9) to have a non-trivial solution, determinant of $|A - \lambda I|$ must be equal to zero. Hence

$$|A - \lambda I| = \begin{vmatrix} a_{11} - \lambda & a_{12} & a_{1i} \\ a_{21} & a_{22} - \lambda & a_{2i} \\ \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & a_{ii} - \lambda \end{vmatrix} = 0 \quad 3.6$$

Expansion of equation (3.6) gives the characteristics equation. The n solutions of $\lambda = \lambda_1, \lambda_2, \lambda_3 \dots \lambda_n$ are eigenvalues of A.

The output from the eigenvalue analysis on the PSAT model of the Nigeria 330kV transmission grid is extracted and tabulated in Table 1.0 To ensure that the buses to be used are marginally unstable, the buses selected are buses having eigenvalue that lie on the right side of the S-plane and having lowest value of damping ratio.

Table 1.0 *Extracted output from eigenvalue analysis*

Bus Number	Bus Name	Eigen Value (s)	Damping Ratio (%)	Participation Factor (%)
1	AES	2.7653 ± j8.4192	0.6442	1.0520
2	Afam	-1.9404 ± j4.2813	0.4723	0.6197
3	Aja	-2.1746 ± j6.7011	0.2632	0.7139
4	Aisokuta	1.9640 ± j3.1032	0.0476	2.6122
5	Akangba	2.0367 ± j8.2287	0.5941	0.6122
6	Aladja	-3.4083 ± j6.0053	0.7456	2.4165
7	Alagbon	0.2562 ± j5.7324	0.6745	0.4165
8	Alaoji	-0.4528 ± j4.2183	0.6259	1.0817
9	Ayiede	-2.7653 ± j11.2419	0.4933	0.3021
10	Benin	2.8730 ± j6.1437	0.0219	3.3021
11	Brenin Kebbi	-2.1674 ± j5.1101	1.3511	0.3228
12	Damaturu	1.6064 ± j6.8320	0.8232	3.1297
13	Delta	-2.0367 ± j8.2287	0.7624	1.1096
14	Egbin	3.4083 ± j7.1537	0.8320	0.3176
15	Ganmo	-0.2562 ± j5.7324	0.8031	0.2113
16	Geregui	-0.4528 ± j4.2183	0.2803	0.2113
17	Gombe	-4.6097 ± j7.5635	2.3893	0.3260
18	Gwagwa	2.3576 ± j8.1273	0.3048	1.0640
19	Ikeja-West	-0.5284 ± j3.3182	1.1601	0.2639
20	Ikot Ekpene	4.6097 ± j7.3637	0.5060	0.2680
21	Jebba TS	-1.7356 ± j4.9214	0.0931	4.6422
22	Jebba GS	-1.7653 ± j10.4192	0.1311	0.1422
23	Jos	1.4011 ± j3.1375	0.6534	0.3252
24	Kaduna	-2.1746 ± j6.7011	0.7324	1.9180
25	Kainji GS	-1.9640 ± j5.3208	0.6612	1.2912
26	Kano	2.5376 ± j10.9419	0.3342	1.0768
27	Ketambe	-1.7011 ± j3.1375	0.3442	0.0768
28	Lokoja	-2.1746 ± j6.7011	0.2632	0.7139
29	Makurdi	3.0640 ± j5.3208	0.0564	2.6122
30	New Haven	2.0367 ± j8.2287	0.5941	0.6122
31	Okpai	-3.4083 ± j7.5374	0.7456	5.4165
32	Olorunsogo	-0.2562 ± j4.7324	0.2674	3.4165
33	Omotosho	2.7297 ± j5.5635	0.3284	4.2720
34	Omitsha	0.4528 ± j4.2183	0.6259	0.1817
35	Osogbo	-3.8372 ± j6.3756	0.1842	4.3366
36	Papalanto	-2.7653 ± j11.2419	0.4933	0.3021
37	Sapele	1.7301 ± j3.1375	0.2193	3.3021
38	Shiroro	0.1674 ± j4.1170	0.0925	6.3228
39	Ugwuaji	-1.6064 ± j6.8320	0.8232	3.1297
40	Yola	-2.0367 ± j8.2287	1.7624	1.1096

From the tabulation, it can be seen that the Nigeria 330kV transmission grid network is generally not stable. This is due to the fact that all the eigenvalues are not located on the left side of the S-plane. The Eigenvalues located on the left side of the S-plane are negative whereas eigenvalues located on the right side of the S-plane are positive.

INSTALLATION OF VSC-HVDC TO THE NIGERIA 40 BUS 330KV TRANSMISSION NETWORK FOR TRANSIENT STABILITY IMPROVEMENT DURING OCCURRENCE OF A THREE-PHASE FAULT

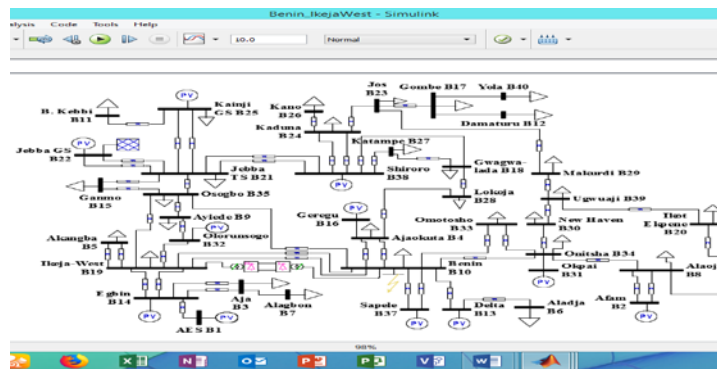


Figure 3.0: PSAT Model of the Nigeria 330kV transmission power system with VSC-HVDC installed along side with Ikeja West- Benin Transmission Line

Figures 3.0 shows the PSAT Model of the Nigeria 330kV transmission power system with VSC-HVDC transmission line installed along side with Benin – Ikeja West, transmission lines respectively. The choice of position for the location of the VSC-HVDC was determined through eigenvalue analysis as its eigenvalue was located on the right side of the S-plane and also is among the three buses that have the lowest damping ratio (as aforementioned).

Response of the Nigeria 40 Bus 330kV Transmission Network to Occurrence of a Three Phase Fault

The results obtained from the simulation are presented in this section. The simulation results are carried out on the MATLAB/PSAT environment. The demonstration for the transient stability analysis on the Nigeria 330-kV grid network, in this work, considered three scenarios as aforementioned. A three phase fault was created on the transmission lines connected to these three buses (very close to the buses) one after the other which forms the three scenarios.

Dynamic Response of the Nigeria 40 Bus 330kV Transmission Network to Occurrence of a Three-Phase Fault without any VSC-HVDC

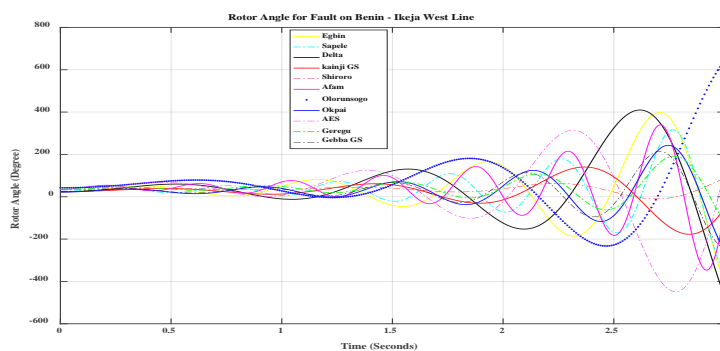


Fig 4.0: Rotor Angle response of the generators for fault clearing time of 0.35sec (without any VSC-HVDC)

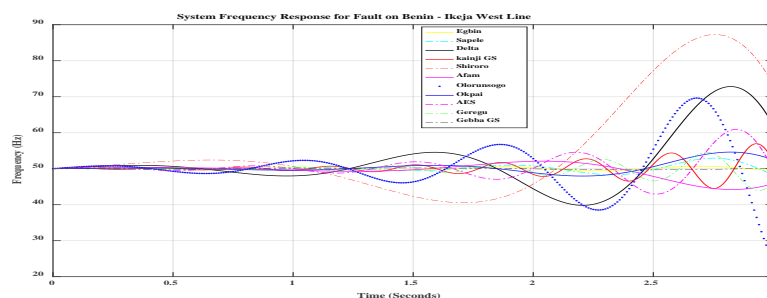


Fig 5.0: Frequency response of the system generators for fault clearing time of 0.35sec (without any VSC-HVDC)

In this Scenerio, It can be observed that virtually all generators in the system at were critically disturbed and all failed to recover after the fault was cleared at 0.3 seconds. So, the system lost synchronism and became unstable as shown in Figures 4.0 and 5.0.

Dynamic Response of the Nigeria 330kV Transmission Grid to Occurrence of a Three-Phase Fault with ANN Controlled VSC-HVDC Installed in the Unstable Buses

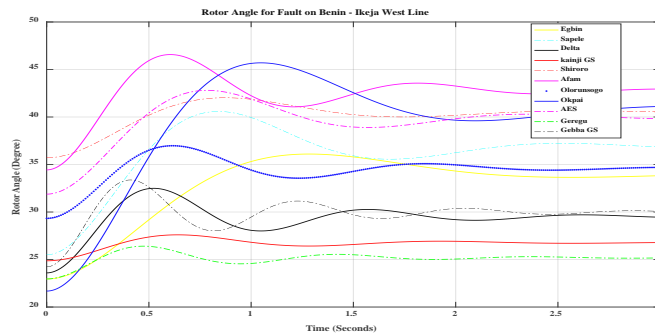


Fig 6.0: Rotor Angle response of the generators for fault clearing time of 0.2sec (with ANN Controlled VSC-HVDC)

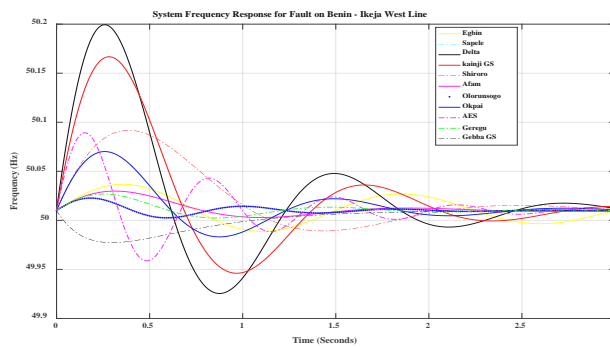


Fig 7.0: Frequency response of the system generators for fault clearing time of 0.2sec (with ANN Controlled VSC-HVDC)

In this Scenario, it can be observed that all the generators in the system which were all critically disturbed during a fault occurrence without VSC-HVDC, have achieved faster damping as shown in figure 6.0 and 7.0 with CCT of 0.2seconds.

Table 2.0: The Simulated Bus Voltage Profile during Occurrence of a Three Phase Fault on Benin Bus with ANN Controlled VSC-HVDC Installed

Bus No	Bus Name	Voltage [p.u.]	Phase Angle [rad]
1	AES	1.000000	0.016368
2	Afam	1.000000	-0.00533
3	Aja	0.998480	0.006284
4	Ajaokuta	0.989621	-0.00676
5	Akangba	0.980541	-0.10014
6	Aladja	0.996952	-0.00231
7	Alagbon	0.984200	-0.03763
8	Alaoji	1.000000	-0.00962
9	Ayiede	0.996654	0.001761
10	Benin	0.995594	-0.00382
11	B. Kebbi	0.955445	-0.04433
12	Damaturu	0.996001	0.001354
13	Delta	1.000000	0.000672
14	Egbin	1.000000	0.007773
15	Ganmo	0.995887	-0.00372

16	Geregu	0.989101	-0.00231
17	Gombe	0.976632	-0.04365
18	Gwagwa-lada	0.953375	-0.03592
19	Ikeja-West	0.996943	0.001354
20	Ikot Ekpene	0.988973	-0.01895
21	Jebba TS	1.000000	0.00456
22	Jebba GS	1.000000	0.00215
23	Jos	0.966434	-0.04046
24	Kaduna	0.971423	-0.03687
25	Kainji GS	1.000000	0.007816
26	Kano	0.982557	-0.20071
27	Katampe	0.973536	-0.03586
28	Lokoja	0.970445	-0.03763
29	Makurdi	0.972167	-0.03443
30	New Haven	0.985259	-0.01984
31	Okpai	0.998001	-0.03763
32	Olorunsogo	0.983565	0.61537
33	Omotosho	0.997725	-0.72907
34	Onitsha	0.992507	-0.01132
35	Osogbo	0.994828	-0.00446
36	Papalanto	0.963279	-0.04365
37	Sapele	1.000000	-0.00019
38	Shiroro	0.998189	-0.90286
39	Ugwuaji	0.981078	-0.02538
40	Yola	0.995245	-0.04763

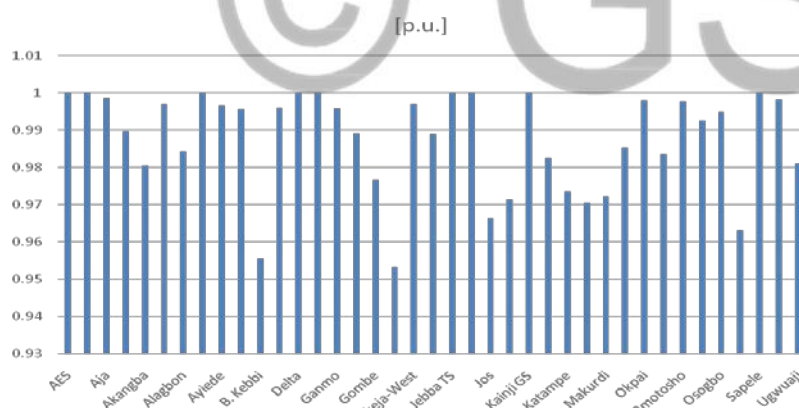


Figure 8.0: Nigeria 330kV Transmission Line Bus Voltage Profile during Occurrence of a Three Phase Fault on Benin Bus with ANN Controlled VSC-HVDC Installed

It can be observed from Table 2 that the voltage violations at buses 1, 2, 13, and 37 were further improved.

CONCLUSION

The results obtained shows that the Nigeria 330-kV transmission network is presently operating on a time-bomb alert state which could lead to total blackout if a 3-phase fault occurs on some strategic buses. The location of a balanced 3-phase fault, at various nodes, were determined based on the most critical buses within the network through eigenvalue analysis and its damping ratio and the dynamic responses for various fault locations were obtained. The result obtained shows that when a 3-phase fault of any duration occurs on Markudi, Ajaokuta and Benin buses, the system losses synchronism immediately. Also, Jos - Markudi, Ajaokuta - Benin and Ikeja West - Benin transmission lines have been identified as critical lines that can excite instability in the power network if removed to clear a 3-

phase fault. The dissertation has successfully demonstrated that the transient stability of the Nigeria 330kV transmission system can be significantly improved by applying an intelligent HVDC to the network.

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