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Optimal Location of VSC-HVDC System in Nigerian 330kV Power Network Using a Short Circuit Voltage Violation Index and Line Loss Technique

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Abstract The capability of a power system to sustain steady and acceptable voltages at all buses after being subjected to disturbance has become a very important issue in any High Voltage Alternating Current (HVAC) transmission system, especially in developing nations like Nigeria. In weak systems, a small disturbance can cause so large deviations in the voltages that the system's operation is jeopardized. Modern approaches favor the deployment of Voltage Source Converter High Voltage Direct Current (VSC-HVDC) systems into the weak areas of the HVAC network as suitable technologies to address this precarious situation. This paper employs a short circuit voltage violation indicator as an alternative to the Short Circuit Ratio (SCR) in locating the weak areas of the power network, with cognizance that high voltage violations occur at the weak buses. This indicator portrays the propagation of voltage dip from the fault location to the entire network by estimating the root-mean-square voltage deviations of all the buses outside the fault location. This violation index was validated by comparing its magnitude at selected locations with that of SCR. Its application on the existing 39-bus Nigerian power grid revealed that the weak areas are located in the Bauchi zone of the power grid. Every transmission line attached directly to a weak bus was subjected to power flow analysis, and considering that voltage enhancement is associated with a reduction in power loss, the line dissipating the highest loss becomes an option for the location of the HVDC system. All the HVDC options were grouped under different configurations, namely: One HVDC System, Two HVDC Systems, and Three HVDC Systems. The insertion of three HVDC systems along the Kaduna – Gombe – Jos – Makurdi transmission routes appeared as the best option since it produced the least value of voltage violation index and was consequently selected as the optimal location for the HVDC systems in the given network. The impact of the selected HVDC systems on the modified power network shows a remarkable reduction in voltage violation at the weak buses. Modifying the Nigerian electricity grid in this way will minimize voltage collapse during fault conditions, and the quality of power delivery will be significantly improved.

Keywords: *HVDC transmission, voltage source converter, voltage violation index, voltage enhancement*

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1. Introduction

Despite the high cost of the VSC-HVDC transmission system in multi-bus high voltage transmission systems, it proves to be a viable technology for improving the system voltage profile [1,2,3]. It eliminates the series and shunt reactance responsible for reactive power flow and minimizes the system's voltage drops [4]. According to recent investigations, its insertion in the Nigerian transmission grid will produce a remarkable improvement in the system voltage profile and enhance the system's power transfer capability [5]. However, its potency in correcting the negative impact of circuit disturbances on the existing power system in terms of voltage instability is another subject of concern. Typical cases of circuit disturbance include loss of load, loss of generation, fault conditions etc. The capability of a power system to sustain steady and acceptable voltages at all buses of the system after being subjected to disturbance is described in many quarters as the strength of the system [6]. It portrays the sensitivity of the system voltages to circuit disturbances. Disturbances in a robust and strong system do not cause any significant change in the system voltage, but in a weak system, even a small disturbance at one location can cause a large deviation of voltage at other locations, thereby jeopardizing the system's operation. Severe disturbances like short circuit faults could even result to voltage collapse, power interruptions and economic waste [7,8]. Apparently, the efficacy of VSC-HVDC systems in mitigating the negative effect of system disturbances in the 330kV Nigerian grid with respect to voltage stability is indisputable [5]. One major challenge is - how many HVDC systems are required to achieve this in the Nigerian power grid. Moreover, which parts of the power grid should they be located in order to reduce the probability of voltage collapse to the barest minimum in the event of a short circuit fault or other serious system disturbances? These are the main issues addressed in this paper.

In order to determine the optimum location of the HVDC lines, [9] employed a Genetic Algorithm (GA) approach to optimize the system voltage profile and identified the weak areas of the grid that require voltage enhancement. The method was applied to IEEE 57-bus test systems to show its validity. Short Circuit Ratio (SCR), has also been adopted by many scientists as a reliable standard for identifying the weak areas of the grid [6,10]. The SCR at a network bus could be determined by calculating the short circuit MVA at that bus using (1).

$$MVA_{SC} = \frac{\left|V_j\right|^2}{Z_F} \quad (1)$$

V_j – voltage at bus j in per unit

Z_F – fault impedance in per unit

The AC grid is a weak grid when SCR < 3, and a very weak grid when SCR < 2, according to the IEEE standard 1204-1997. The short-circuit ratio is widely used in planning HVDC transmissions and inserting the HVDC lines in the weak areas of the power system. The effectiveness of SCR in identifying the over-voltage areas of a power system with a single HVDC in-feed system was analyzed by [11]. However, evaluating the strength of multiple HVDC systems becomes very complex due to the interactions between rectifiers and inverters. The multi-in-feed short circuit ratio (MSCR) was devised by [10] to overcome this problem while [11] derived a power-flow model as the mathematical framework for an analytical equivalent of MSCR, to facilitate the rigorous analysis of voltage/power interactions in multi-infeed HVDC systems. In [12], the limitations of the existing MSCR were discovered; for instance, with a large amount of capacitor-based compensators installed in the system, their impact on system stability becomes insignificant. Due to the complexity of the multi-in-feed HVDC system, research on the improvement of the MSCR is still in progress.

There are other voltage stability indicators for describing the system strength [13-18], but in severe fault conditions, none of these could actually serve as a reliable estimate of the propagation of voltage collapse to the entire network from fault locations. However, certain investigations have revealed that bus voltage violation resulting from the system disturbance is also a good measure of the strength of the system, which was effectively demonstrated in [5,13].

This paper presents, as an alternative to SCR, the use of the root-mean-square voltage violation index to evaluate the strength of the Nigerian electricity grid network under short circuit disturbances and to identify the weak areas of the network where an HVDC System could be inserted to prevent system collapse during any short circuit event. This violation index was validated by comparing its magnitude at selected locations with that of SCR. The bus voltages were computed using the Gauss-Seidel power flow technique and a steady-state mathematical model of HVAC and HVDC systems described in the literature [5,19,20]. All transmission lines linked to the weak buses were considered as possible locations for the intended HVDC system. Different configurations were employed, such as: One HVDC system, Two HVDC systems, and Three HVDC systems, to produce many options for the VSC-HVDC system. The corresponding mean voltage violations and enhancement impacted on the system voltage profile were estimated to determine the best option.

2. The Investigated Network

Figure 1 represents the existing 330KV HVAC power transmission network in Nigeria under investigation, with 39 buses comprising nine generating stations and 47 transmission lines. It is a modified version of the network used in [5] for the assessment of the voltage profile across different sections of the Nigerian power grid. The Egbin power station was chosen as the slack bus in the Power Flow Analysis (PFA) because of its strategic location in the network. The system data comprising the line parameters, shunt capacitor data, transmission station load, and generator data were obtained from the Power Systems Planning, Research, and Development unit of the Transmission Company of Nigeria (TCN) [5,21].
The base values of the ac network are:

$$S_{base} = 100\ MVA \text{ and } V_{base} = 320\ kV.$$

The HVDC parameters are presented in Table 1.

Table 1. Recommended line Parameters for the HVDC system [22]

Cable parameters	Values
Nominal voltage (kV)	600
Proposed line distance, D (km)	160
Line resistance, R_L (Ω/km)	0.029
Line reactance, X_L (Ω/km)	0.25
Line susceptance, γ (S/km)	4.39×10^{-6}
Impedance of Converter Reactor, Z_c (Ω)	10.890+j25.047
Modulation index of converter	1.0

3. Identifying the Weak Areas of the Given Network

The weak areas of the Nigerian power grid were identified in this study by conducting a power flow analysis with a circuit disturbance applied on a certain bus and the voltage violations at other buses evaluated. The extent to which the impact of the circuit disturbance is propagated to other buses across the entire power system forms the criteria for identifying the weak buses in this study. The voltage violation index, H_k, adopted in this paper is the root-mean-square voltage deviations at buses. This is very similar to the standard deviation of voltage magnitudes at all buses while using the nominal system voltage (the base value of voltage, V_{base}) as the central tendency. It measures the degree of impact on the entire power grid by a system disturbance at a given bus whose strength or weakness is being tested. Absolute voltage deviation at bus j,

$$U_j = |1 - V_j| \quad (2)$$

Therefore, the root-mean-square of voltage deviations of the network when a circuit disturbance is applied to a bus, k, becomes

$$H_k = \sqrt{\frac{\sum_{\substack{j \in n \\ j \neq k}} \left(1 - V_j\right)^2}{n-1}} \quad (3)$$

Where $0 < H_k < 1$

n – number of load buses

The voltage at bus 'k' is excluded in the calculation. The bus, k, could be termed as a weak bus if, when subjected to a circuit disturbance, the value of H_k is far from 0 and closer to 1. For the purpose of this study, our benchmark for identifying a weak bus is $H_k > 0.2$. The root-mean-square voltage violation index was validated by comparing its magnitude with that of SCR at selected locations. The two indicators yielded similar results in identifying the weak buses (see Table 2), proving that the voltage violation index is a reliable estimator. To identify the weak buses in the grid network under investigation, steady state PFA was performed with the network subjected to system disturbances such as: Disconnection of 95% of the load, loss of generation at the supply buses and application of three phase-to-ground short circuit fault at the load buses. The loss of generation and load disconnection were implemented by reducing the generated power and load demands as described in (4) and (5) respectively.

$$G'_j = G_j \times 10^{-12} \quad (4)$$

$$P'_j = \left(1 - 0.95\right) P_j \quad (5)$$

The application of a short circuit entails connecting short circuit impedance Z_F between a bus and the ground, which implies updating the diagonal entries of the bus admittance matrix as follows

$$Y'_{kk} = Y_{kk} + 1/Z_F \quad (6)$$

The results presented in Table 2 reveal that the disconnections of load at the selected number of buses do not cause any significant voltage violation. The disconnection of supply in all the generating buses shows similar characteristics in voltage violations. The results imply that these kinds of system disturbances do not cause any significant voltage violation (as all the values are far less than the specified limit). However, considerable levels of voltage violations were observed in the application of three-phase short circuit fault at load buses. Figure 2 shows that when the short circuit fault is injected into buses 28, 30, 31, 32, 36, and 37, the system voltage violation exceeds the acceptable limit of $H_k > 0.2$, implying that they could be considered as the weak buses.

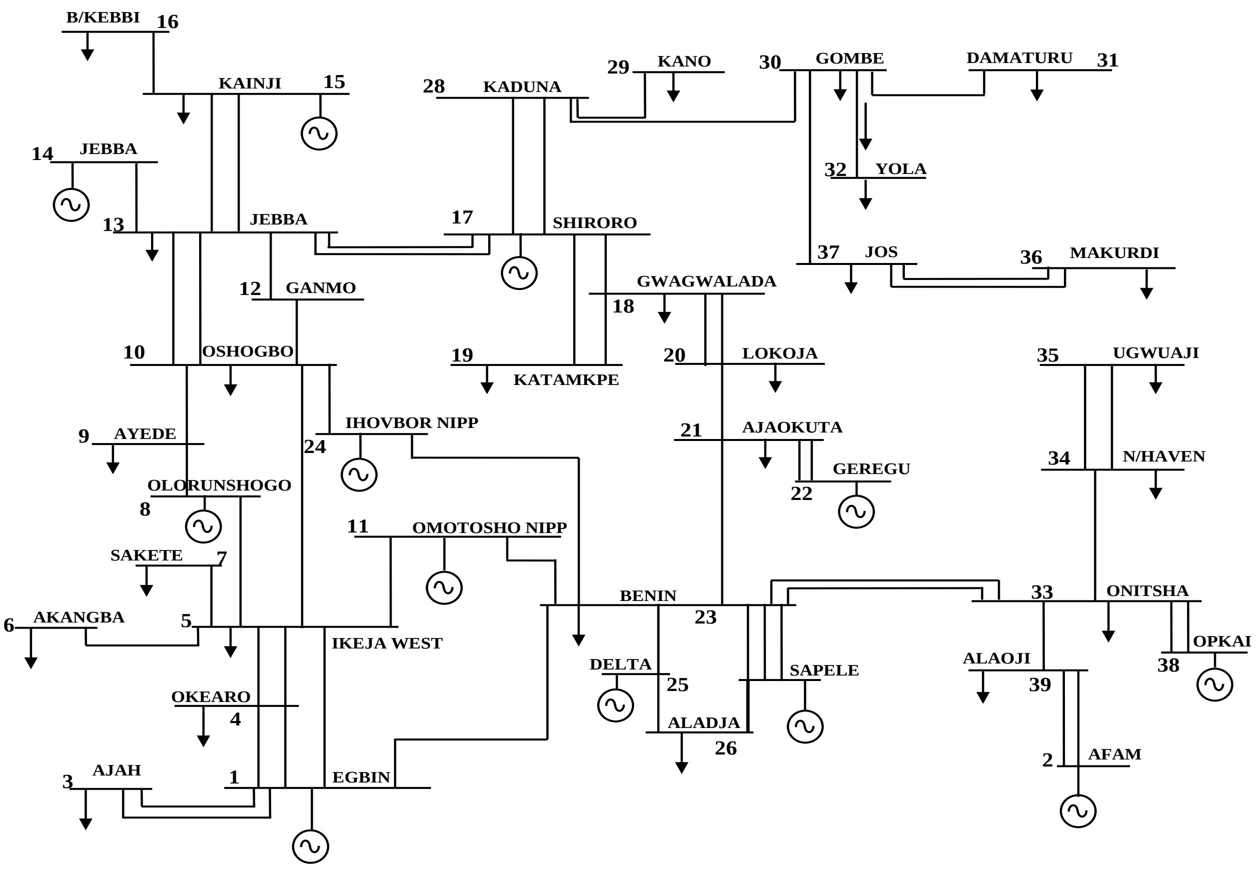

Figure 1. Single-line diagram of the 39-bus Nigerian power grid used as case study

Table 2. Voltage Violations in the HVAC network for selected circuit disturbances

Bus No	Voltage violations, $\mathbf{H}_k$			SCR
	Loss of Generation	Loss of Load	Short Circuit Fault	
1	0.0510	-	-	
2	0.0514	-	-	
3	-	0.0511	0.034	93.0823
4	-	0.0516	0.0335	83.72
5	-	0.054	0.0334	89.36
6	-	0.054	0.0356	75.72
7	-	0.052	0.036	13.17
8	0.0519	0.0519	0.0541	92.74
9	-	0.052	0.0472	58.78
10	-	0.052	0.0392	65.26
11	0.0502	-	-	
12	-	0.0517	0.0399	57.05
13	-	0.0511	0.0511	98.66
14	0.0506	-	-	
15	0.0519	-	-	
16	-	0.0518	0.0540	4.35
17	0.0519	-	-	-
18	-	0.0519	0.0721	44.59
19	-	0.0519	0.0705	36.30
20	-	0.0519	0.0706	45.25
21	-	0.0519	0.063	60.92
22	0.0519	-	-	
23	-	0.0519	0.0539	88.78
24	0.0519	-	-	
25	0.0519	-	-	
26	-	0.0519	0.0541	79.83
27	0.0519	-	-	
28	-	0.0357	0.2833	2.956
29	-	0.0312	0.1939	5.666
30	-	0.0359	0.2316	1.664
31	-	0.0408	0.2678	1.331
32	-	0.039	0.2543	1.012
33	-	0.0519	0.0576	73.52
34	-	0.0519	0.0717	48.79
35	-	0.0519	0.072	46.42
36	-	0.0395	0.2467	2.38
37	-	0.0371	0.2621	1.35
38	0.0519	-	-	
39	-	0.0516	0.0542	81.97

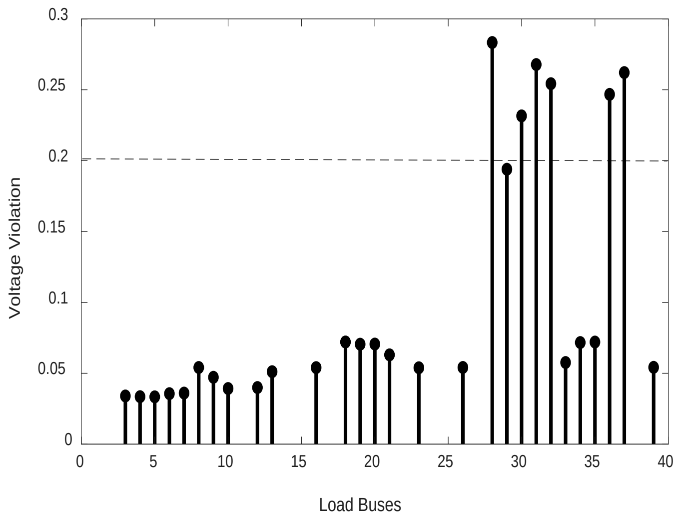

Figure 2. Voltage violations in the HVAC network when short circuit is applied to load buses

Hence, the system voltage profile is highly sensitive to short circuit faults with or without an HVDC transmission line. The injection of fault on other buses failed to produce any significant impact on the system voltage profile as indicated by the values of the voltage violation index at those locations. Three-phase short circuit disturbance which seems to produce the greatest impact among other system disturbances was therefore utilized in the investigation of voltage stability at each load bus.

4. Steady State Mathematical Model of the VSC-HVDC System

A steady state physical model of the VSC-HVDC scheme comprising two VSC stations – VSC1 operating as a rectifier station and VSC2 as an inverter station – connected by a DC transmission link is shown in Figure 3. The direction of power flow considered here is from the rectifier towards the inverter. The mathematical model of the VSC-HVDC system was derived from this simple physical model based on the concept of controlling reactive power by regulating the voltage at the Voltage Source Converter [5]. The HVDC system is connected to the grid through the points of common coupling (PCC) represented by bus '*s*' and bus '*q*' in Figure 4. The VSC could be considered as a three-phase AC controllable voltage source which, by its pulse width modulation activity, imposes either a reduction or incremental factor on its output voltage in order to restore it to the nominal value. This influence of the converter in controlling its output voltage is indicated by means of a modulation index, M_i. The converter ratio, according to [1] is

$$\beta = \frac{V_i}{V_{dc}} = \frac{\sqrt{6}M_i}{2} \tag{7}$$

For balanced phase currents, the value of the modulation index is considered equal at all three phases. The integration of the HVDC parameters in the PFA of the network involves creating an additional bus *i* to represent the voltage control bus introduced by the VSC converter [5,19], and the inclusion of HVDC parameters in the system data necessitates an update in the bus admittance matrix. The primitive impedances around the converter bus are,

$$Z_{si} = Z_c + \beta^2 R_{dc} \tag{8}$$

and $Z_{qi} = Z_c$.

Conversion into the same base voltage requires referring the converter reactor impedance Z_c to the grid side of the network using the voltage ratio, N, of the converter transformer as well as the inclusion of transformer reactance X_T. The above impedances referred to the grid side are respectively.

$$Z_{si}^{'} = jX_T + N^2(Z_c + \beta^2 R_{dc}) \tag{9}$$

$$Z_{qi}^{'} = jX_T + N^2 Z_c \tag{10}$$

This action merges the two converter stations into a single bus *i*, thereby resulting in an entirely HVAC system that could be analyzed with conventional power flow technique. Hence, the PFA considers the insertion of a single HVDC system into the power grid as an extra bus (n+1) introduced into the network, and designated as bus *i* [5]. The line impedances in (9) and (10) will jointly replace the primitive impedance of the weak line in the original HVAC network. The reactive component of the HVDC link is eliminated since it is not considered in any DC system. Supposing the voltage magnitude and angle at the converter bus are fixed at $V_i = 1$, $\delta_i = 0$ respectively. The voltage in per unit at buses *s* and *i* are considered as $V_s = |V_s| e^{j\delta_s}$ and $V_i = |V_i| e^{j\delta_i}$ respectively.

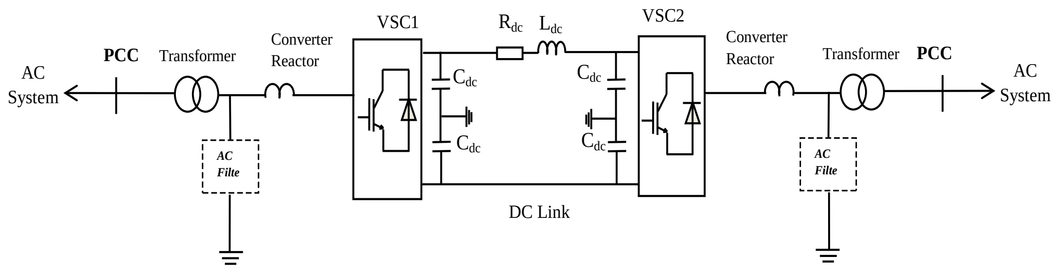

Figure 3. Steady state physical model showing the main components of VSC-HVDC topology [20]

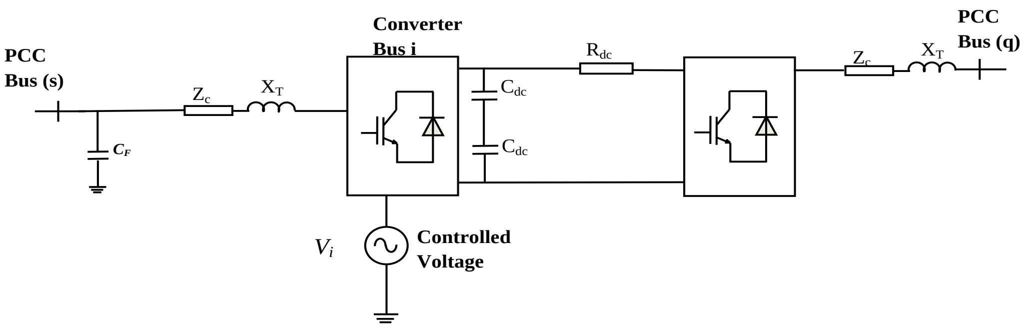

Figure 4. The schematic diagram of the VSC Converter Station with the controller represented as a controllable voltage source [5]

The active and reactive power flowing in from bus s to bus i are

$$P_{si} = |Y_{si}||V_s||V_i|\cos(\delta_s - \delta_i) \qquad (11)$$

$$Q_{si} = |Y_{si}||V_s||V_i|\sin(\delta_s - \delta_i) - |Y_{si}||V_i|^2 \qquad (12)$$

Y_{si} – element at s-th row and i-th column of bus admittance matrix.

The power losses between buses s and i is

$$PL_{si} = |I_{si}|^2 \times R_{si} \times S_{base} \qquad (13)$$

where

$$I_{si} = |Y_c|\, e^{-j\theta_c} (|V_s|\, e^{j\delta_s} - |V_i|) \qquad (14)$$

θ_c – impedance angle of the converter reactor

$$\theta_c = \tan^{-1}\left(\frac{X_c}{R_c + \beta^2 R_{dc}}\right) \qquad (15)$$

and

$$Y_c = \frac{1}{\sqrt{\left(R_c + \beta^2 R_{dc}\right)^2 + X_c^2}} \qquad (16)$$

5. Optimal Location of the VSC-HVDC Line

The detailed procedure for identifying the optimal location of HVDC systems in the network is illustrated in Figure 5. This procedure was translated to a Matlab script and implemented on the power transmission network in Figure 1. Three phase short circuit was employed as the most suitable form of system disturbance in this study due to the colossal impact on bus voltage deviations. Since the load buses where the voltage violation index exceeds the specified limit ($\varepsilon = 0.2$) have been identified as weak buses, the expected location of the HVDC system is within the vicinity of the weak buses. In locating the HVDC line optimally, the focus is to give a fair trial to all the weak buses by considering every transmission line attached to a weak bus as a possible location of the HVDC system, and bearing in mind that reduction in power loss is associated with voltage enhancement. The particular line (designated as Lj) dissipating the highest transmission loss is considered as the weak line among the lines connected directly to a weak bus.

Table 3 contains a summary of the maximum power losses produced by the lines linked to the weak buses. The vector **B** represents the weak buses, while **M** represents the maximum loss dissipating buses corresponding to each of the weak buses. The vector **M** signifies the bus that, when connected to a weak bus, produces the highest power loss among the lines directly connected to the weak bus. The weak lines L_j, therefore, constitute options for the insertion of a single HVDC system into the network. These lines are connections between buses 17-28, 28-30, 30-31, 30-32, 30-37, and 36-37. Hence, there are six options for one HVDC system configuration. Three configurations have been considered: One HVDC system, Two HVDC Systems and Three HVDC Systems. A value, r, representing the number of HVDC systems, was assigned to each configuration. The number of options, α_r , available for each HVDC configuration is dependent on the number of weak buses and the number of HVDC systems to be inserted into the network. This is obtained from the combinatorial expression, ${}^W_rC$, expanded as

$$\alpha_r = \frac{W!}{(W-r)!r!} \qquad (17)$$

W – number of weak buses

For One HVDC System, the number of options corresponds to the number of weak buses. For each option in the r-th configuration, all the possible HVDC line combinations were generated using the Matlab function

$$F = combnk(v, r) \qquad (18)$$

where $v = [1, 2, 3, \ldots, W]$ and $r = 1, 2, 3$

The function, F, produces a matrix with α-rows and r-columns, and each row represents a possible combination of the weak lines taken 'r' at a time (indicated as *z-th* option in Figure 5). Combinations of the weak lines produced fifteen and twenty options for the two and three HVDC system configurations respectively. The HVDC lines in each option are represented by their terminating bus pairs as shown in Table 3. For instance, in the z-th option of a two HVDC System configuration, the bus terminals of each HVDC link are B_x and M_x , B_y and M_y.

The subscripts are selected from the z-th row of the combination matrix F as follows $x= F_{z1}$ and $y= F_{z2}$ $\forall$ $z = 1, 2, 3, ..., \alpha_2$.

Similarly, in the z-th option of a Three HVDC System configuration, the bus terminals of each HVDC link are B_a and M_a , B_d and M_d , B_p and M_p , $a= F_{z1}$, $d= F_{z2}$ and

$$p = F_{z3} \; \forall \; z = 1, 2, 3, ..., \alpha_3,$$

where $\alpha_1 = 6$, $\alpha_2 = 15$ and $\alpha_3 = 20$.

The mean of short circuit voltage violations, at all load buses was computed for each option, and the minimum value was selected as the best option for that configuration. Finally, the most effective HVDC System configuration and the corresponding optimal location for the given network was determined by the least value among the minimum violation of all the HVDC configurations. The mean voltage violations corresponding to all options are also indicated in Table 3, with their minimum values as 0.0589, 0.0500, and 0.0484, respectively. Comparing the mean voltage violations produced by each option with 0.1358 obtained for the HVAC network prior to the insertion of the HVDC system shows a significant enhancement in the voltage profile (see Table 4 and Figure 6). Among the 20 options considered for the insertion of three HVDC systems, the 5th option with a voltage violation index of 0.0484 is the best choice. This option which comprises the transmission lines linking buses 28 – 30, 30 – 37, and 37 – 36, produced a much more voltage enhancement at almost all the load buses than the single HVDC options as shown in Figure 6. However, it is observed that the lines linking buses 30–31 and 30–32 in the Two HVDC Systems configuration seem to be the closest alternative choice, which could be adopted for economic reasons (when the project fund is inadequate).

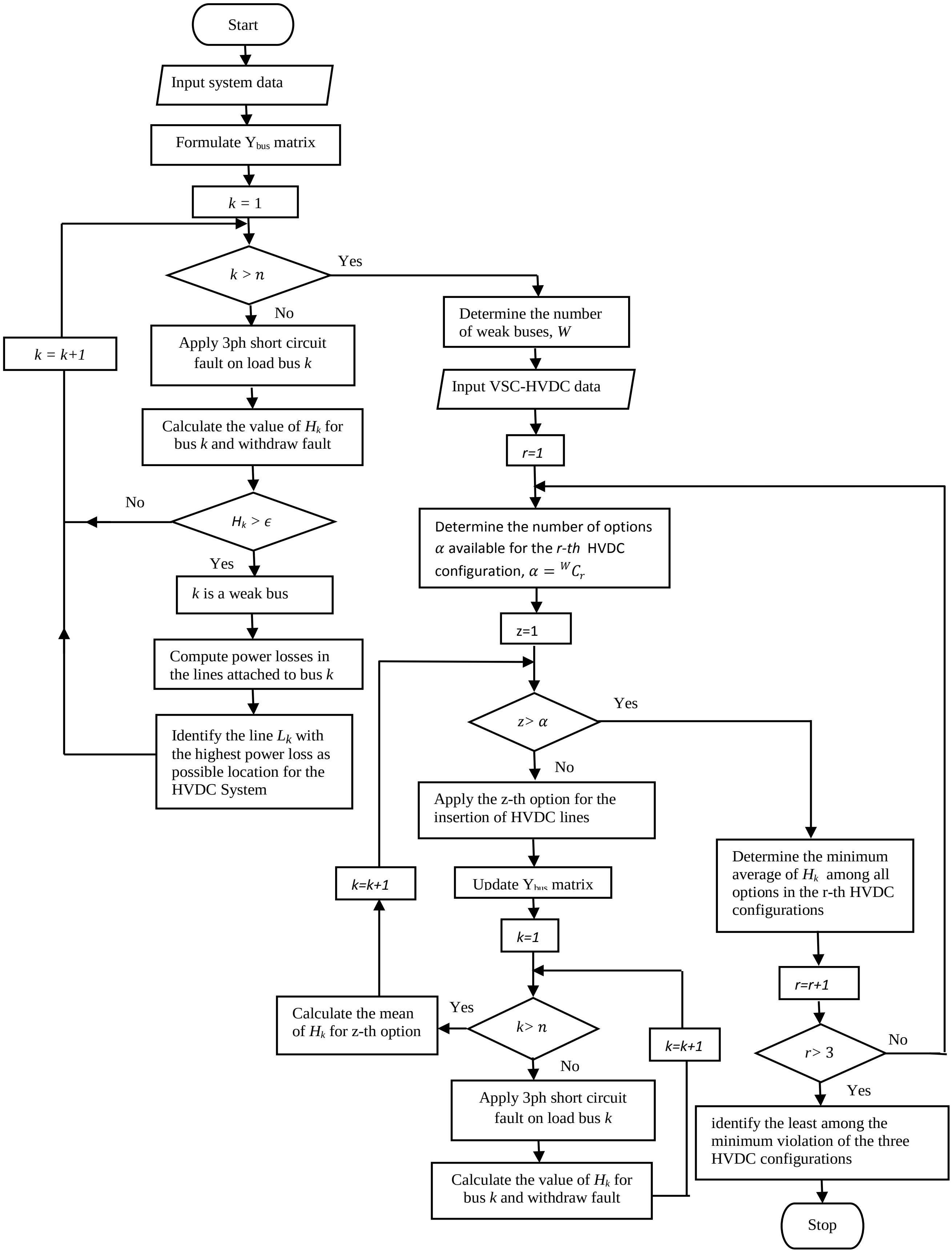

Figure 5. Procedure for the optimal location of the VSC-HVDC system in a power grid

Table 3. Mean Voltage Violations for the Various HVDC Link Options

Options, Z	One HVDC System				Two HVDC Systems					Three HVDC Systems						
	B_j	M_j	Line Loss [MW]	Mean Violation	HVDC LOCATION 1		HVDC LOCATION 2		Mean Violation	HVDC LOCATION 1		HVDC LOCATION 2		HVDC LOCATION 3		Mean Violation
					B_x	M_x	B_y	M_y		B_a	M_a	B_d	M_d	B_p	M_p	
1	28	17	22,71	0.1045	28	17	30	28	0.0826	32	30	36	37	37	30	0.0503
2	30	28	10.82	0.0816	28	17	31	30	0.0603	31	30	36	37	37	30	0.0502
3	31	30	0.22	0.0589	28	17	32	30	0.0604	31	30	32	30	37	30	0.0697
4	32	30	0.67	0.059	28	17	36	37	0.0748	31	30	32	30	36	37	0.0501
5	36	37	0.2	0.0738	28	17	37	30	0.0616	30	28	36	37	37	30	0.0484
6	37	30	2.23	0.0603	30	28	31	30	0.055	30	28	32	30	37	30	0.0489
7					30	28	32	30	0.055	30	28	32	30	36	37	0.0494
8					30	28	36	37	0.0642	30	28	31	30	37	30	0.0486
9					30	28	37	30	0.0561	30	28	31	30	36	37	0.0492
10					31	30	32	30	0.05	30	28	31	30	32	30	0.0489
11					31	30	36	37	0.0539	28	17	36	37	37	30	0.0537
12					31	30	37	30	0.0514	28	17	32	30	37	30	0.0532
13					32	30	36	37	0.0541	28	17	32	30	36	37	0.0542
14					32	30	37	30	0.0517	28	17	31	30	37	30	0.053
15					36	37	37	30	0.0529	28	17	31	30	36	37	0.054
16										28	17	31	30	32	30	0.0515
17										28	17	30	28	37	30	0.0555
18										28	17	30	28	36	37	0.0638
19										28	17	30	28	32	30	0.0544
20										28	17	30	28	31	30	0.0543

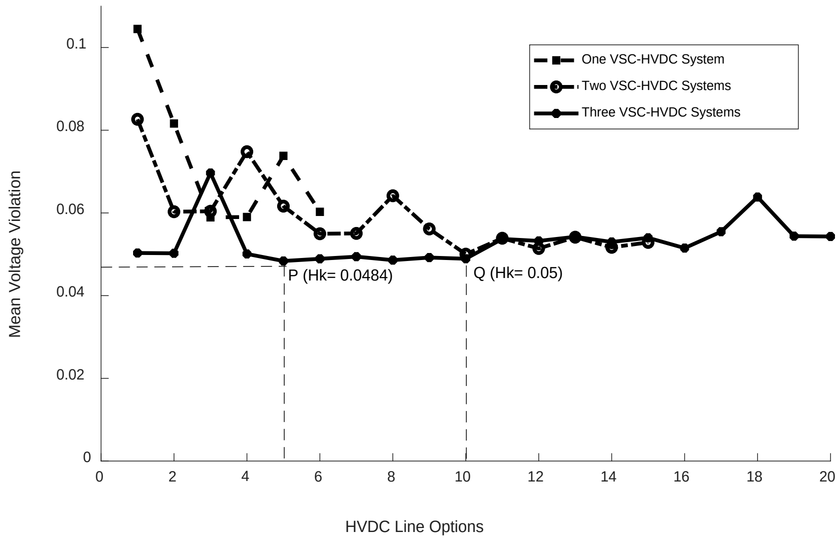

Figure 6. Comparison between Single, Double and Triple HVDC line configurations

When the power network was modified with the VSC-HVDC systems inserted at the selected optimal location, PFA with short circuit fault applied to each of the load buses showed a remarkable improvement in voltage magnitude at buses located within the weak zones of the network. The choice of this location for the VSC-HVDC system is justified by the results in Table 4, which compares the voltage violations in the modified network with the ones obtained in the absence of an HVDC system. There is voltage enhancement at all the weak buses, also affirmed by the overall average of voltage violations, which is 0.0484 for the modified network and less than 0.1358 obtained for the original network. This is a confirmation of an earlier statement in [5] that the inclusion of HVDC lines in the Nigerian power grid will outweighed the use of HVAC lines in terms of reducing the voltage violations. The impact of HVDC inclusion is more pronounced when the fault location moves closer to the HVDC systems. In all the cases, there was no positive impact at the fault location. The insertion of an HVDC system in a power network does not guarantee the total restoration of voltage at the weak buses, but it does restore their voltages to acceptable magnitudes.

Table 4. Short circuit voltage violations of the modified network compared to the HVAC network

Load Bus	Voltage violations $\mathbf{H}_k$			
	No HVDC System	One HVDC Systems	Two HVDC Systems	Three HVDC Systems
20	0.0706	0.0593	0.0585	0.0597
21	0.063	0.0502	0.0495	0.0512
23	0.0539	0.0386	0.038	0.0404
26	0.0541	0.0388	0.0382	0.0407
28	0.2833	0.1041	0.0462	0.0667
29	0.1939	0.052	0.0467	0.0421
30	0.2316	0.1919	0.0936	0.0958
31	0.2678	0.085	0.0593	0.0587
32	0.2543	0.0751	0.0509	0.0516
33	0.0576	0.0435	0.0428	0.0449
34	0.0717	0.0605	0.0597	0.0609
35	0.072	0.0609	0.0601	0.0612
36	0.2467	0.0973	0.0926	0.0355
37	0.2621	0.1249	0.1037	0.0449
39	0.0542	0.039	0.0384	0.0408
Mean Violation	0.1358	0.0589	0.0500	0.0484

6. Conclusion

This paper investigates the criteria for the insertion of VSC-HVDC system into an electricity network in order to prevent voltage collapse during short circuit fault, while using the Nigerian 330kV transmission grid as a case study. A root-mean-square voltage violation index was used to identify of the weak areas of the network where the possibility of voltage collapse is high, and choice of the best location for the VSC-HVDC system was based on the maximum power loss from the weak buses. By the outcome of this investigation, the weakest parts of the Nigerian power grid exist in the Bauchi region.

It is hereby recommended that three HVDC systems inserted in the Kaduna – Gombe, Gombe – Jos, and Jos – Makurdi transmission routes will effectively curb the menace of voltage imbalance in the event of a short circuit or any other type of circuit disturbance. If the results achieved in the study are utilized, the quality of power delivery in the Nigerian electricity grid will be significantly improved, voltage collapse will be minimized, and the network's reliability ensured.

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