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Enhancement of Transmission Efficiency and Voltage Profile in the Bauchi Axis of Nigerian Power Grid Using a VSC-HVDC System

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Abstract Increasing electricity demand occasioned by increased population and advancement in economic activities makes it mandatory to upgrade the Nigerian power grid. The ongoing construction of a new hydropower plant at Mambila Plateau in Taraba State of Nigerian is a response to this call. Performance evaluation of the Nigerian power grid expanded to include the new power plant has revealed the occurrence of poor voltage profile accompanied by colossal power losses mostly in the Bauchi region. This paper explores the techniques for addressing this challenge by the integration of voltage source controlled high voltage direct current (VSC-HVDC) transmission system into the expanded Nigerian 41- bus 330kV transmission grid network at the weakest areas. The HVDC converter is introduced into the power grid as an extra bus, and all impedance elements in the HVDC system transformed to the grid side. This action merges the two converter stations into a single bus to produce an entirely high voltage alternating current (HVAC) system, thereby making it possible to apply conventional power flow techniques. This model was verified by the simulation of the modified network in Matlab Simulink environment. Performance evaluation of the expanded network prior to the connection of HVDC system identified the transmission line between the Jalingo bus and the Mambila power plant as the weakest area, which was consequently selected as the optimal location for the proposed VSC-HVDC system. Power flow analysis of the modified network with the inclusion of HVDC system revealed a remarkable improvement in voltage magnitude at the weak buses, and minimized power losses in the system. This implies that such a project is worth undertaking. Therefore, the enhancement of voltage profile using the VSC-HVDC transmission system is a panacea for curbing the expected line losses that may arise while evacuating power from the proposed Mambila plant.

Keywords: *HVDC transmission, voltage source converter, voltage enhancement, line losses, Nigerian grid, power flow analysis*

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1. Introduction

Investigations conducted on Nigeria’s electricity supply prospect reveal that the power demand far outstrips the supply [1]. Only about 40% of the nation’s population, predominantly the city dwellers have access to the national power grid. The rural level which constitutes about 70% of the population suffers from an acute shortage of electricity supply [2]. This could be attributed to insufficient power generation and under-utilization of electricity supply infrastructure [3,4,5]. Presently, the Nigerian electricity grid consists of three hydroelectric power stations located in the country’s North Central region, six thermal stations located mainly in the southern part of the country, and several Independent Power Producers (IPPs) scattered all over the regions. The total installed capacity of these power stations is estimated at 7,876 MW, and coupled with the average daily power generation of 4,000 MW is far below the peak load forecast of 8,900MW for the currently existing infrastructure [6]. The involvement of IPPs in the Nigerian electricity industry was expected to boost the actual generating capacity, but unfortunately, neither the state-owned nor private-owned IPPs have met their mandates in this regard [7]. Hence, the old thermal plants located at Egbin, Afam, Sapele and Ugheli are constrained to operate at maximum capacity rendering them inefficient. In economic interest, it has become necessary to expand the national grid much further to include additional generating stations, but the projected capacity required to close the generation deficit is estimated at 10,000MW, and this is expected to come from the proposed Mambila hydropower station intended for 2700MW installed capacity [6,8].

Many researchers have questioned the feasibility of this project based on the likelihood of poor voltage profile occurring in most parts of the northern region especially the Bauchi axis as a result of shortage of reactive power support [9]. Kano, Kaduna, Jos, Gombe and Katampe substations were identified as the most affected buses [10,11,12]. The challenge now is, how stable will the grid remain when the new generating plant comes on-stream, and what measures could be devised to avert the possibility of voltage instability and high transmission losses? Power flow analysis (PFA) of the existing 39-bus and expanded 41-bus Nigerian 330 kV electrical network has confirmed that without any major upgrade of the transmission system, there will be widespread under-voltages throughout the system accompanied by colossal power losses, when the new power plant comes on. Various line compensation techniques producing a substantial voltage enhancement at the weak buses have been recommended for the Nigerian power grid [13,14], but the application of VSC- HVDC system to the Nigerian grid was very recently conceived as the appropriate respite [15,16]. The use of the VSC-HVDC system eliminates the presence of series and shunt reactance which are responsible for the flow of reactive power and consequently minimizes voltage drops in the system. It also reduces the resistance of line conductors by eliminating the skin effect of AC on conductors [17]. However, another challenge is to obtain a suitable model of VSC-HVDC system for the power flow analysis. These are the concerns being addressed in this paper.

The paper investigates the efficacy of applying the VSC-HVDC system to correct the voltage instability problem and line losses to be encountered when the Mambila hydropower plant is connected to the Nigerian 330kV transmission grid. It employs the bus voltage violations, line losses and transmission efficiency obtained from PFA of the expanded Nigerian 330kV, 41-bus transmission grid as indices to determine that efficacy. The main objective is to compare the values of these quantities computed before the inclusion of the Mambila hydropower station with their counterparts after the connection of the new power plant, and assess the level of improvement achieved. Secondly, the paper sets out to formulate appropriate modeling technique for the VSC-HVDC system which can adapt to conventional power flow techniques.

2. Materials and Methods

A power flow analysis of the multi-bus system is an effective way of investigating the performance of the power system in steady-state. It reveals the power flows, voltage violations and transmission losses at peak loads. In this section, power flow calculations are performed on the Nigerian power grid to determine the voltage profile of the power system and also identify the weak areas which will guide us in deciding on the appropriate locations of the HVDC transmission links.


[redacted]

Figure 1. Nigerian Map showing the existing, on-going and proposed TCN/NIPP/IPP projects [16]

2.1. Description of the Nigerian Electricity Grid

The map in Figure 1 represents the existing transmission network in Nigeria used as the case study. It is entirely a HVAC network; the blue lines represent the 330kV transmission lines. The single-line diagram of the existing 330KV Nigeria transmission network in Figure 3 was developed from the map. There are 39 existing buses comprising nine generating stations and 47 transmission lines, but two extra buses are included to represent the expansion of the network to 41 buses when the new power plant comes on-stream. The Egbin power station was chosen as the slack bus in the PFA because of its strategic location in the network. Jalingo substation is considered as the possible connection point for the transmission line linking the hydropower plant to be located on the Mambila Plateau. The dotted lines represent the additional transmission lines required to link the proposed power plant to the grid. The Jalingo – Mambila route is split into two sections in accordance with the report of German Consultants engaged by the Nigerian government on the Mambila power project [10]. The first section (about 120 km) follows the existing Bali-Jalingo road while the second section follows the Mambila Plateau road shown in Figure 2, which passes several villages before climbing up to Mambila Plateau.

Figure 2. Scenic view of Mambilla Plateau Road [10]

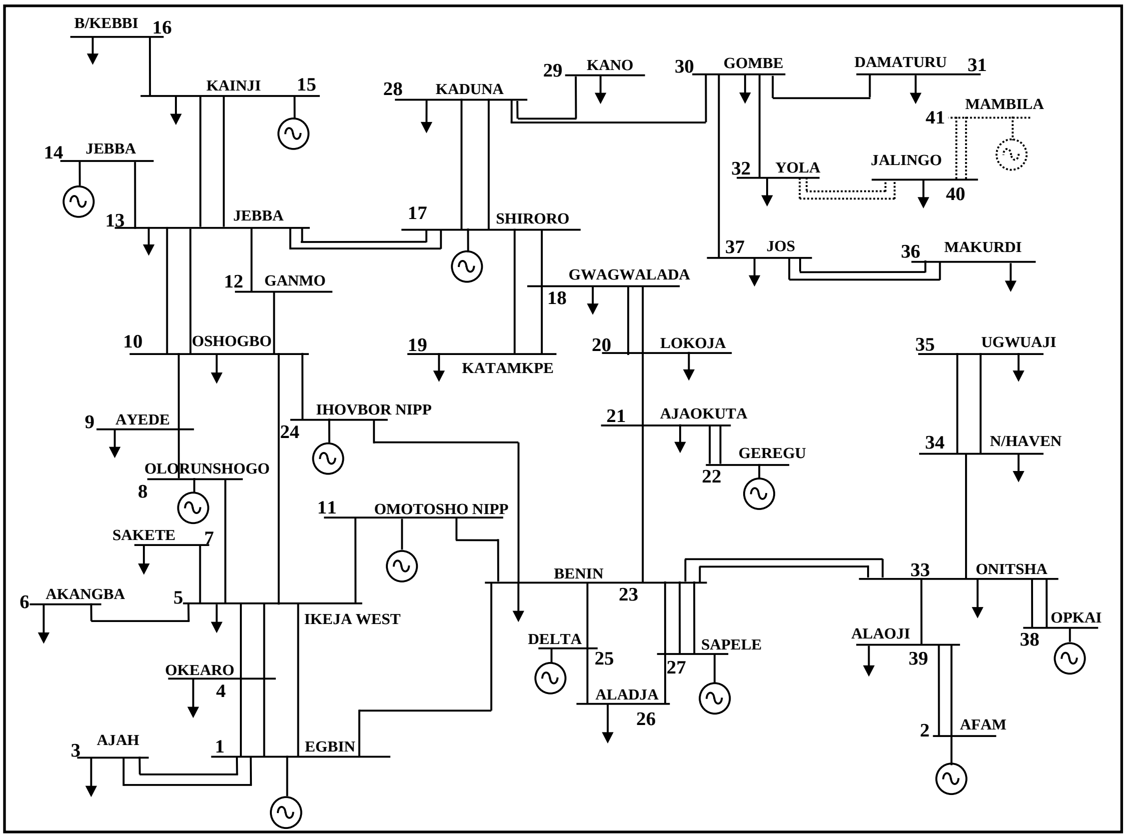

Figure 3. Single-line diagram of the expanded Nigerian 330kV, 41-bus Transmission grid

2.2. System Data

The system data were obtained from the reports of Power Systems Planning, Research and Development unit of Transmission Company of Nigeria (TCN) [18]. These data comprising the line parameters, shunt capacitor data, transmission station load and generator data were utilized in computing the network elements needed for the power flow analysis. The bus data showing scheduled power of Generating Stations (G.S.) and Transmission Station (T.S.) load demands are presented in Table 1, while the line data were translated to the equivalent values of series impedance and shunt susceptance both in per unit. The calculations were done according to equations (1) and (2).

Table 1. Bus Data for the 330kV Nigerian Grid Showing the Scheduled Power of generators and Load Demands

Bus No	Name	Status	Max. Power (MW)	Max. Load	
				MW	MW
1	Egbin	G.S	1320	-	-
2	Afam	G.S	550	-	-
3	Ajah	T.S	-	220	103
4	Okearo	T.S	-	75	50
5	Ikeja West	T.S	-	510	321
6	Akangba	T.S	-	471	228
7	Sakete	T.S	-	145	70
8	Olorunshogo	G.S	335	-	-
9	Ayede	T.S	-	270	130
10	Oshogbo	T.S	-	235	189
11	Omotosho	G.S	335	-	-
12	Ganmo	T.S	-	270	130
13	Jebba	T.S	-	412	349
14	Jebba	G.S	578	-	-
15	Kainji	G.S	650	-	-
16	Birnin Kebbi	T.S	-	112	84
17	Shiroro	G.S	600	-	-
18	Gwagwalada	T.S	-	75	50
19	Katampe	T.S	-	300	127
20	Lokoja	T.S	-	75	50
21	Ajaokuta	T.S	-	96	46
22	Geregu	G.S	414	-	-
23	Benin	T.S	-	298	219
24	Ihovbor	G.S	113	-	-
25	Delta	G.S	300	-	-
26	Aladja	T.S	-	167	81
27	Sapele	G.S	550	-	-
28	kaduna	T.S	-	275	208
29	Kano	T.S	-	250	196
30	Gombe	T.S	-	180	87
31	Damaturu	T.S	-	75	50
32	Yola	T.S	-	112	54
33	Onitsha	T.S	-	162	79
34	New Haven	T.S	-	235	110
35	Ugwuaji	T.S	-	75	50
36	Makurdi	T.S	-	75	50
37	Jos	T.S	-	141	68
38	Okpai	G.S	412	-	-
39	Alaoji	T.S	-	266	124
40	Jalingo	T.S	-	75	50
41	Mambila	G.S	2700	-	-

Series impedance in per unit,

$$Z = \frac{(R + jX)D}{N_{ph} Z_{base}} \quad (1)$$

while the Half-line charging susceptance in p.u. is

$$B/2 = \frac{\gamma D Z_{base}}{2} \quad (2)$$

where $Z_{base} = \frac{V_{base}^2}{S_{base}}$

N_{ph} – number of conductors per phase, S_{base} =100 MVA and V_{base} = 330kV.

The impact of tap changing transformers on the line impedances was neglected in the study. The recommendation of the German consultants [10] was adopted for configuration of the HVDC Jalingo – Mambila line. They recommended a 600 kV line, using a Single Circuit with 5-bundle Bison conductors. The parameters including those of the HVDC converter stations are presented in Table 2.

Table 2. Line Parameters of the Grid Recommended by the German Consultants for Linking the Mambila Power Plant to Taraba Substation [10]

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

2.3. Formulation of a mathematical Model for the Voltage Source Converter

A steady state model of the VSC-HVDC scheme used in transmitting power through the HVDC is shown by the point-to-point station in Figure 4 with the relevant parameters indicated. It consists of two VSC stations: VSC1 operating as a rectifier station and VSC2 as an inverter station. The two stations are linked together by a DC transmission link. The direction of power flow considered here is from the rectifier towards the inverter. For the purpose of PFA, a more detailed representation of the converter station is presented in Figure 5 showing the parameters of the converter reactor and its transformer. The two buses represented as point of common coupling (PCC) serve as connecting point between the AC and DC systems at both ends.

A mathematical model for the VSC-HVDC system is formulated in this study based on the concept of controlling reactive power by regulating the voltage at the nodes where the HVDC terminals are connected. The voltages are measured and compared with a specified reference value. The difference acts as the input command of the voltage controller which is expected to keep the voltage at the converter terminal constant and equal to the reference voltage regardless of the power flow changes

[19,20]. Hence, the voltage source converter could be considered as a three-phase AC controllable voltage source producing a fundamental frequency voltage output, and harmonic content. The converter station, 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. Only the fundamental frequency component is utilized since all harmonic content of the AC side voltage are removed by the filter unit. This influence of the converter in controlling its output voltage is indicated by means of a modulation index, M_i. The ratio between the maximum fundamental peak phase voltage and the DC total voltage for a modulation index of 1 is $\sqrt{2}/\sqrt{3}$.

$$\frac{\sqrt{2}V_i}{\sqrt{3}} = \frac{M_i V_{dc}}{2} \tag{3}$$

while the Converter voltage ratio is

$$\beta = \frac{V_i}{V_{dc}} = \frac{\sqrt{6}M_i}{2} \tag{4}$$

In practice the converter is not 100% efficient, and M_i is assumed the same for all the three phases. Considering the fact that the AC side voltage of the converter is kept constant by a voltage control mechanism, a simplified steady state physical model of the Source Converter is achieved as shown in Figure 6, and this was applied in all the power flow analysis in this study. The HVDC system is connected between two PCC buses *s* and *q*. These buses represent the Jalingo and the hydropower stations respectively. The PFA considers the connection of HVDC converter into the power grid as an extra bus (*n*+1) introduced into the network, and designated as bus *i*. The primitive impedances around the converter bus are

$$Z_{si} = Z_c + \beta^2 R_{dc} \tag{5}$$

and $Z_{qi} = Z_c$

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

$$Z'_{si} = jX_T + \alpha^2(Z_c + \beta^2 R_{dc}) \tag{6}$$

$$Z'_{qi} = jX_T + \alpha^2 Z_c \tag{7}$$

The transformation of the DC resistance to the AC side of the converter merges the two converter stations into a single bus *i*, thereby resulting in an entirely AC system that could be analyzed with conventional power flow technique. It is pertinent to note that the reactive component of the HVDC link is eliminated since it is not considered in any DC system.

2.4. Comparative Power Flow Analysis of the Nigerian Power Grid

Power flow analysis was conducted to evaluate the system voltage and power losses and identify the weakest areas in the system. This power flow analysis was performed using the single line diagram of the expanded 41-bus 330kV Nigeria transmission grid shown in Figure 3. The purpose is to evaluate the bus voltages at the load centres as well as the power flows and losses along the transmission lines. Three cases were considered in isolation during the comparative power flow analysis:

Case I: PFA of the existing 39-bus HVAC 330kV network was conducted prior to the connection of the Mambila plant.

Case II: PFA of the 330kV HVAC network expanded to include the Mambila generating station and Jalingo transmitting station bringing the number of buses to 41. The buses and transmission lines adversely affected by the injection of the new hydropower plant were identified. The weak buses and the line with the highest transmission losses determine the appropriate location for the VSC-HVDC system.

Case III: PFA of the expanded 330kV network with the Mambila – Jalingo HVAC line replaced with a single VSC-HVDC system. The insertion of HVDC system involves the creation of additional bus to make a total of 42 and updating of the Y_{bus} matrix by the inclusion of HVDC parameters in the system data.

The analysis was conducted according to the above procedure and implemented with matlab script applying the Gauss-Seidel method and the simplified mathematical model of VSC-HVDC system developed in section 2.3. In the matlab script, the active and reactive power flow to the converter bus *i* were evaluated using (8) and (9). The voltage magnitude at that point is fixed at $V_i = 1$ while the voltage angle, $\delta_i = 0$. 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.

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

$$P_{si} = |Y_{si}||V_s||V_i|\cos(\delta_s - \delta_i) \tag{8}$$

$$Q_{si} = |Y_{si}||V_s||V_i|\sin(\delta_s - \delta_i) - |Y_{si}||V_i|^2 \tag{9}$$

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

The power losses between buses *s* and *i* is

$$PL_{si} = |I_{si}|^2 \times R_{si} \times S_{base} \tag{10}$$

This study also introduces a voltage violation index defined in terms of the per unit voltage V_b at each bus *b*.

% Voltage violation,

$$V_{vio} = |V_b - 1| \times 100 \tag{11}$$

The transmission efficiency was calculated as follows

$$\eta = \frac{|P_{si}|}{|P_{si}| + PL_{si}} \tag{12}$$

The voltage violations, power flow results and transmission efficiency were compared for the three cases. The buses where the voltage violation exceeds the specified limit, ε, are considered as ‘weak’. The voltage violation limit adopted for identification of weak buses in this paper is $\varepsilon = 10\%$.

2.5. Model Verification

The efficacy of the proposed VSC-HVDC model formulated in the previous section was verified using the Matlab Simulink as simulation software. The Simulink model diagram of the expanded 42-bus Nigerian power grid was drawn with the Mambila power station in place and the Simulink model of VSC-HVDC system inserted between it and Jalingo substation as shown in Figure 7. Simulation was then carried out for five seconds and bus voltages at selected load centres in the Bauchi region were recorded as well as the power flow along the Jalingo – Mambila transmission line. The bus voltages obtained from Simulink simulation were compared with results of matlab script for Case II and case III.

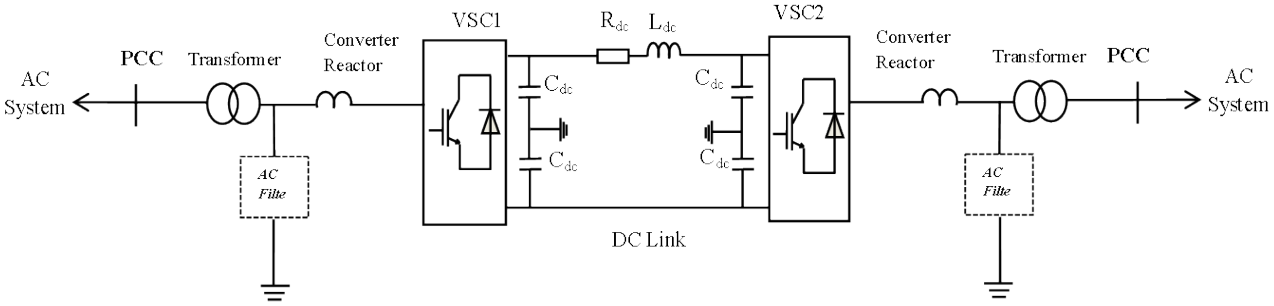

Figure 4. Schematic diagram of steady state physical model showing the main components of VSC-HVDC topology [21]

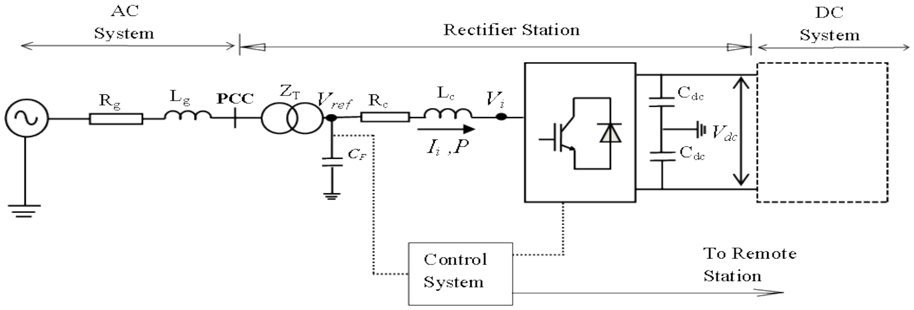

Figure 5. Steady state physical model of left half of a VSC-HVDC system showing the rectifier source converter [22]

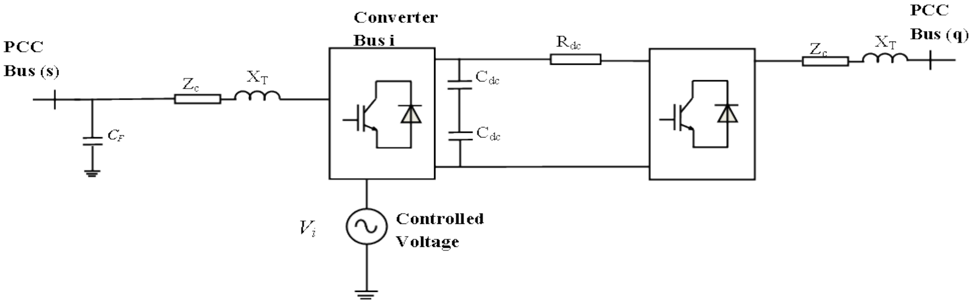

Figure 6. The proposed AC side model of the VSC with the controller represented as a controllable voltage source

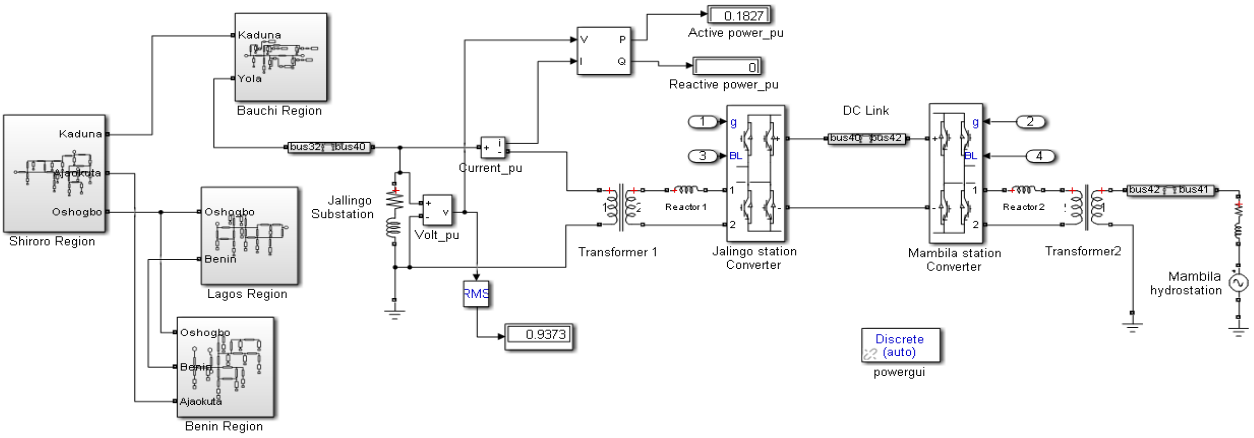

Figure 7. Simulation diagram of Nigerian 330kV, 41-bus Transmission grid with the HVDC System inserted between Jalingo and Mambila stations and different sections of the network represented with model blocks

3. Results and Discussions

The results of the comparative power flow analysis of the grid network revealed that the existing 39-bus HVAC system in the absence of Mambila power plant is a very strong power system with good voltage profile. There were no serious voltage violations except in bus 29 representing the Kano Transmitting Station where the voltage magnitude falls below the nominal value with a voltage violation of 12% (see Figure 10 and Figure 11). The situation became different when the Mambila hydropower plant was linked with a HVAC overhead line. The nature of the voltage profile is displayed in Figure 8, with voltage magnitudes represented by the height of the stems. Serious voltage violations occurred at Yola T.S. (48%), Jalingo T.S. (50%), Damaturu T.S. (20%) and Gombe T.S. (19%) respectively as observed in Figure 11. The greatest voltage dip occurs at bus 32 which is Yola T.S., and could be attributed to the increase in the flow of reactive power around this region.

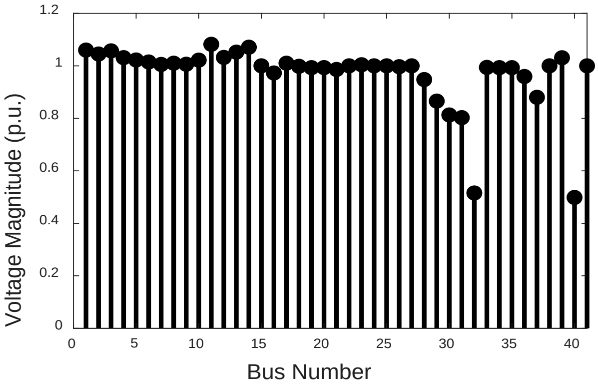

Figure 8. Voltage profile of the 330kV HVAC power grid after the commissioning of Mambila power station

The inclusion of the Mambila power plant also resulted in colossal power transmission losses along different sections of the power grid as stated in Table 3. The table indicates only the most affected transmission lines. The active power flow from Gombe to Yola increased to 662.4 MW at a lower transmission efficiency of 89.5%. A total of 2700MW of active power was injected into the grid by the new plant out which 1249MW was lost along the transmission line. Additional losses amounting to 77.8MW was also incurred in the transmission between Yola and Gobe transmission stations. The Yola – Jalingo line recorded about 279.8 MW power losses. The Jalingo – Mambila line recorded the greatest loss amounting to 1249 MW and the lowest transmission efficiency of 56.7%. This worrisome situation could actually jeopardize the feasibility of having the new power plant in place if no palliative measures are applied. This result justifies the decision in this study to use HVDC transmission system. When the power flow analysis was conducted on the 330kV Nigeria grid with the Jalingo – Mambila transmission line replaced with a VSC-HVDC transmission system, the voltage profile improved as shown in Figure 9. There were significant improvement in voltages at bus 32 (Yola) and bus 40 (Jalingo). This is also illustrated in Figure 11, showing a significant enhancement in the voltage profile of the given power system at the affected areas. The voltage violations were reduced from 48% to 2% and 50% to 1% respectively with the insertion of HVDC system. The transmission losses were drastically reduced as shown in Table 3. The line losses decreased from 77.8MW to 1MW between Gombe and Yola; the line losses along the Yola – Jalingo route also decreased from 279.8MW to 2MW. The greatest impact occurs at Mambila – Jalingo line where the loss reduced from 1249MW to 4MW. It is hereby established that the application of HVDC transmission system between Mambila and Jalingo on the expanded 330kV Nigerian grid minimizes line losses in the process of evacuating power from the proposed Mambila power plant.

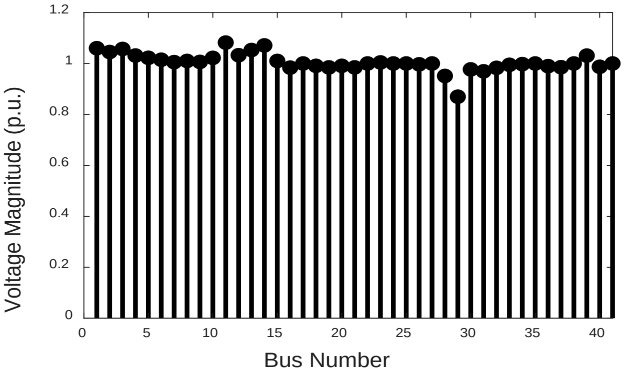

Figure 9. Voltage profile of the expanded 330kV power grid with the Mambila power plant and HVDC transmission system in place

Table 3. Active power flows, line losses and transmission efficiency computed at selected areas of the Nigeria power grid

Lines		Case II			Case III		
Bus	Bus	P (MW)	Losses (MW)	Eff. (%)	P (MW)	Losses (MW)	Eff. (%)
1	**4**	3928.4	145.5	96.4	3928	145	96.4
1	5	129.7	96.4	3507	130	96.4	129.7
5	11	-1223	41.7	96.7	-1223	42	96.7
13	14	-5712	44.5	99.2	-5721	44	99.2
13	15	-4420	303.1	93.6	-4396	295	93.7
23	27	-4067	168.5	96.0	-4066	168	96.0
30	32	662.6	77.8	89.5	-137	1	99.3
36	37	-93.7	2.2	97.7	-42	0	100
32	40	1198.5	279.8	81.1	-249	2	99.2
40	41	1636	1249.4	56.7	-249	4	98.4

The inclusion of HVDC line in the given network has therefore outweighed the use of HVAC line in terms of reducing the voltage violation, but it did not guarantee total restoration of voltage magnitude and total elimination of line losses all over the grid as could be seen from the results. Nevertheless, it did reduce the voltage violations at buses 32 and 40 below the acceptable standard limit of 5% as seen in Figure 11. It was observed that buses located far from the HVDC system could not experience the impact of restoration in voltage magnitude as was the case in buses 10 – 12. The impact of HVDC inclusion is more pronounced when the bus location is closer to the HVDC system. However, if the insertion of two VSC – HVDC systems is attempted, it may certainly show more remarkable improvement in voltage magnitude especially at the weak buses. This investigation reveals that the insertion of HVDC line in a power system does not guarantee the total restoration of voltage at all the buses. The information displayed in Figure 10 is sufficient in affirming the efficacy of the proposed VSC-HVDC model in the power flow analysis. The chart compares the bus voltages of selected load centres with the values obtained from simulink simulation. It is observed that the two set of values are closely matched indicating that the voltage profile obtained with the proposed model compares favourably with its simulink counterpart. The results indicated by the use of the proposed VSC-HVDC model in PFA gives a better picture of the voltage enhancement impacted on the network by the application of VSC-HVDC system.

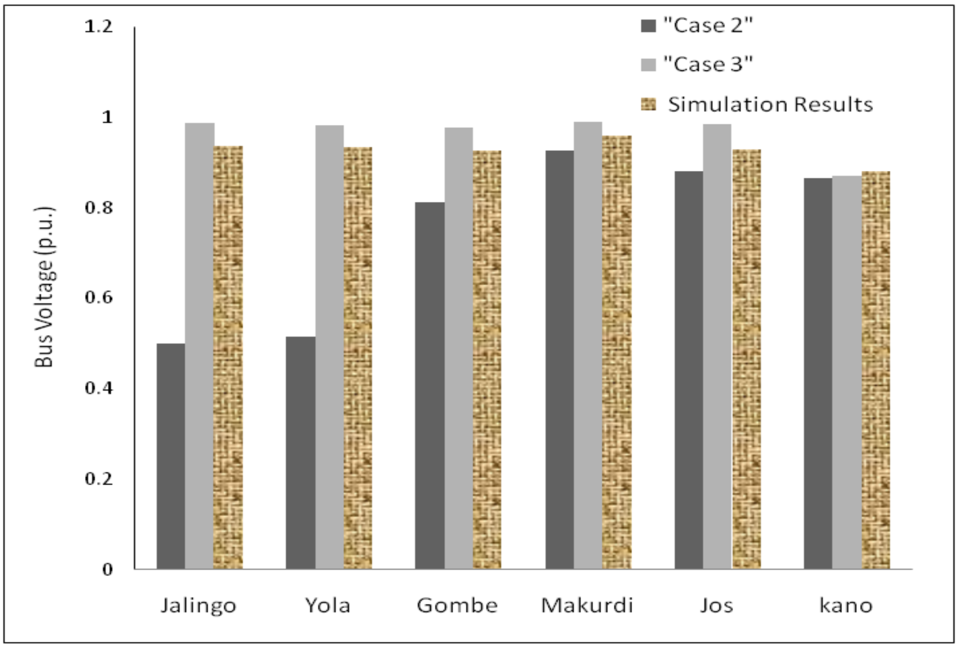

Figure 10. Voltage magnitudes of selected buses obtained with the proposed method and compared with those from simulation results.

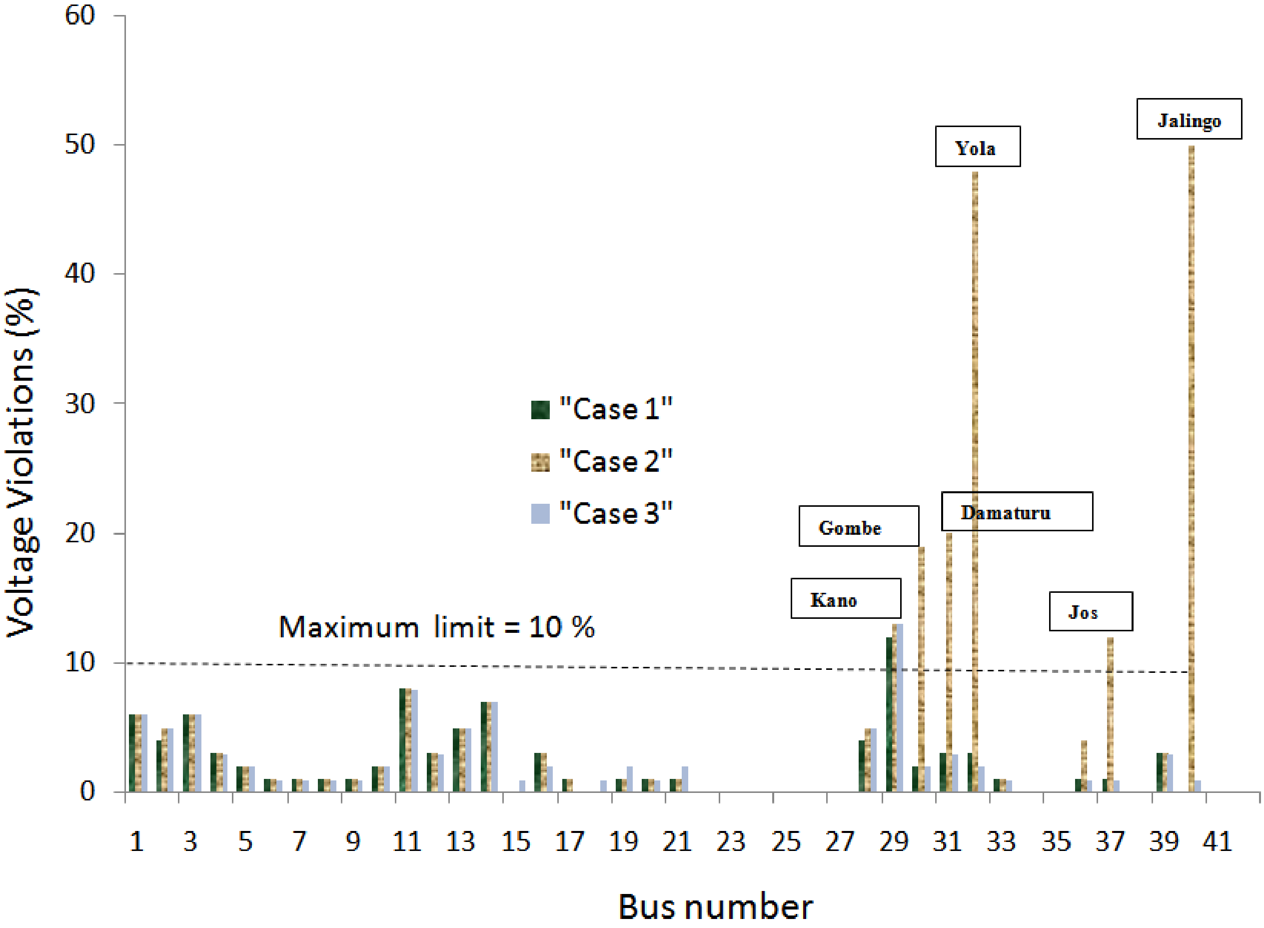

Figure 11. Comparison between the three cases for voltage violations at the network buses

4. Conclusion

The results of the comparative power flow analysis in terms of voltage violations and system losses have actually justified the use of VSC-HVDC system as a viable alternative to HVAC transmission for efficient evacuation of power from the new Mambila power plant in the Nigerian power grid. The simplified model of the VSC-HVDC formulated in this paper suffices for a steady state characterization of HVDC system such that the relevant physical parameters still remain visible. Hence, project funding could be minimized by just installing voltage source converters at Mambila and Jalingo stations. This is the only system upgrade recommended in this paper to enable the new power plant serve the interest of the power consumers.

The developed approach could be adopted in further investigation of the Nigerian power grid as the expansion work progresses. Since it was observed that buses located far from the HVDC system could not experience the impact of restoration in voltage magnitude, it will be a sound judgment to include a second HVDC system to run from Jalingo – Yola or any other part of the network that seem appropriate if the required funds are available. Further investigations could be carried out on the factors that determine the buses where the voltages are restored and the extent of voltage improvement achieved.

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