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VOLTAGE STABILITY CONTROL THROUGH REACTIVE POWER REGULATION IN THE NIGERIAN 330KV GRID

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Abstract— **In this paper, the voltage stability problem of Nigerian national grid is investigated. A method of voltage limit violation correction, with simultaneous reduction in the grid active power losses, by properly dispatching the various var compensators in the power system is proposed. The feasibility and effectiveness of the proposed technique on the Nigeria power system for the entire 37-bus network is simulated using PowerWorld simulating machine and a drop of 48.41% in the grid system active power loss was achieved.**

I. Introduction

In the cause of its operation, power systems may experience both over-voltage and under-voltage violations that can be overcome by voltage/var control. By controlling the production, adsorption and flow of reactive power at all levels in the system, voltage/var control can maintain the voltage profile within acceptable limits and reduce transmission losses [12].

Real and reactive power losses are minimized for economic reasons. Both active and reactive losses depend on power transfer and voltage, as shown in equation 1

$$P_{loss} = \frac{(P^2-Q^2)R}{V^2} \text{ and } = \frac{(P^2-Q^2)X}{V^2} \qquad (1)$$

Thus to minimize losses at constant active power, reactive power transfer has to be minimized and voltage kept high.

A. Power Flow Solution Model

The variables in power system behave in a non-linear manner. Bus powers are calculated from the relationship between node voltages, network admittances and branch

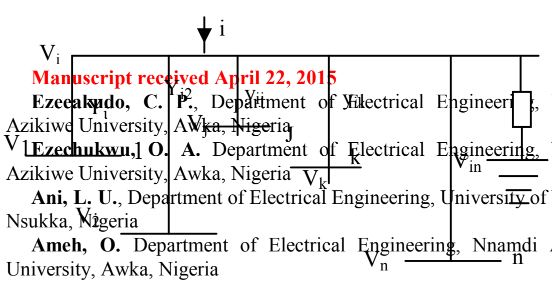

Fig 1: An n-bus power

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currents. The bus power equations developed have non-linear characteristics and their solutions have quadratic convergence which can be achieved by the numerical iteration of the various independent system variables, such as the current, voltage or impedance and can be derived from figure 1.

From the above, the equation for current, I, entering from any bus, i, to the system buses 1, 2, ..., j, k, ..., n is given by:

.

$$I_i = Y_{i1}V_{i} + Y_{i2}(V_i - V_2) + \cdots + Y_{ij}(V_i - V_j) + Y_{ik}(V_i - V_k) + \cdots + Y_{in}(V_i - V_n)$$

$$= (Y_{i0} + Y_{i1} + Y_{i2} + \cdots + Y_{in})V_i - Y_{i1}V_1 - Y_{i2}V_2 - \cdots - Y_{ij}V_j - Y_{ik}V_k - \cdots - Y_{in}V_n \qquad (2)$$

In summation form

$$I_i = V_i \sum_{j=0}^{n} |Y_{ij}| - \sum_{j=0}^{n} |Y_{ij}| V_j \text{ for } j \neq i$$

$$Or\ I_i = \sum_{j=0}^{n} |Y_{ij}| V_j \quad for\ i = 0,1,2,\ldots,n \qquad (3)$$

Generally in polar coordinate form,

$$V_i = \angle\delta_i = V_i e^{j\delta} \text{ then } V_i^* = \angle -\delta_i = V_i e^{-j\delta} \text{ and } V_j = V_j \angle\delta_i = V_i e^{j\delta} \text{ and } Y_{ij} = Y_{ij} e^{-j\theta ij}$$

Where δ is the phase angle of bus voltage and θ_{ij} is the admittance angle.

The complex power injected in the ith bus of a power system is given as

$$S_i = P_i + JQ_i = V_i I_i^* \quad for\ i = 1,2,3,\ldots,n \qquad (4)$$

Where V_i is the voltage of the ith bus with respect to ground and I_i^* is the complex conjugate of source current I_i injected into the bus. Using I_i instead of the complex conjugate I_i^* and substituting equation 3 into equation 4 with all the defined variables V_i^*, V_i and Y_{ij} in equation 3, then

$$S_i^* = P_i - JQ_i = V_i^* I_i = V_i^* \sum_{j=0}^{n} Y_{ij} V_{ij} \quad for\ I = 0,1,2,\ldots,n$$

$$= \sum_{j=0}^{n} V_i V_j Y_{ij} e^{-j(\theta_{ij} + \delta_i + \delta_{ij})} \qquad (5)$$

Separating into real and imaginary parts of the power

$$P_i = Real - V_i^* \sum_{j=0}^{n} V_i Y_{ij} = \sum_{j=0}^{n} V_i V_{ij} Y_{ij} \cos(\theta_{ij} + \delta_i - \delta_{ij})$$

$= V_i V_{ij} Y_{ij} \cos\theta_{ij} + \sum_{j=0}^{n} V_i V_{ij} Y_{ij} \cos(\theta_{ij} + \delta_i - \delta_{ij})$

$Or\ P_i =$

$\sum_{j=0}^{n} |V_i||V_{ij}||Y_{ij}|\cos(\theta_{ij} + \delta_i - \delta_{ij}) \qquad (6)$

And

$Q_i = Imaginary - V_i^* \sum_{j=0}^{n} V_i Y_{ij} = \sum_{j=0}^{n} V_i V_{ij} Y_{ij} \sin(\theta_{ij} + \delta_i - \delta_{ij})$

$- V_i V_{ij} Y_{ij} \sin\theta_{ij} + \sum_{j=0}^{n} V_{ij} Y_{ij} - \sum_{j=0, j\neq i}^{n} V_i V_{ij} Y_{ij} \sin(\theta_{ij} + \delta_i - \delta_{ij})$

$Or\ Q_i =$

$-\sum_{j=0}^{n} |V_i||V_{ij}||Y_{ij}|\sin(\theta_{ij} + \delta_i - \delta_{ij}) \qquad (7)$

Equations 6 and 7 constitute a set of non-linear algebraic equation in terms of independent variables |V| p.u. and δ radians. These are called the bus power equations.

Each load (PQ) bus has two of such equations representing the active and reactive powers given by equations 6 and 7 and one equation for each generator (PV) bus given by equation 7 for calculating reactive power mismatch ΔQ and their levels of violations.

The effect of impedance of a power system is very important in the study of power systems, whether contingency analysis or fault analysis. To this end, the use of bus impedance matrix comes very handy due to the ease of computations. The analysis is based on the assumption that loads are treated as constant current injections into the various system busses. Obviously, manipulation of the bus admittance [Y_{bus}] matrix in a large power system is computationally more efficient and simpler than the use of [Z_{bus}] due to its sparsity. However, the diagonal elements of Z_{bus} matrix provide important characteristics of the power system and facilitate the use of Thevenin's equivalent impedance at designated busses.

The formulation of a bus impedance [Z_{bus}] matrix using Thevenin's theorem can be demonstrated as below:

Let a power system network be represented as in figure 2. The busses are projected as shown and numbered 1 to n. The 1st bus being the reference bus and numbered (1, 2, 3, ..., i, ..., j, ..., n). The reference voltages at these busses are V_{10}, V_{20}, V_{30}, ..., V_{i0}, ..., V_{j0}, ..., V_{n0}) which are assumed initial values. Assuming bus j to be fed by a current source ΔI_j(p.u.), the initial voltages can be mathematically denoted as:

$[V_0] = [Z_{bus} I_0] \qquad (8)$

The injected current, ΔI will cause bus voltage change, ΔV and the new vector equation becomes:

$[V] = [Z_{bus}|I_0 + \Delta I|] = [Z_{bus}|I_0|] + [Z_{bus}|\Delta I|]$

$= [V_0] + [\Delta V] \qquad (9)$

From equation 8,

$[\Delta V] = [Z_{bus}|\Delta I|] \qquad (10)$

So in matrix form, changes in bus voltages and currents are:

$$[\Delta V] = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_i \\ \Delta V_j \\ \vdots \\ \Delta V_n \end{bmatrix};\ [\Delta I] = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \Delta I_i \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad (11)$$

Since ΔI_j is the only injected current in bus j, equation 11 can be re-written as:

$$[\Delta V] = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_j \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} Z_{12} & \cdots & Z_{1j} & \cdots & Z_{1n} \\ Z_{22} & \cdots & Z_{2j} & \cdots & Z_{2n} \\ \vdots & & \vdots & & \vdots \\ Z_{j2} & \cdots & Z_{jj} & \cdots & Z_{jn} \\ \vdots & & \vdots & & \vdots \\ Z_{n2} & \cdots & Z_{nj} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \Delta I_j \\ \vdots \\ 0 \end{bmatrix} \qquad (12)$$

The only non-zero quantity is ΔI_j at bus j, hence equation 12 is re-written as:

$$[\Delta V] = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_j \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} Z_{12} \\ Z_{22} \\ \vdots \\ \Delta I_j \\ \vdots \\ Z_{n2} \end{bmatrix} \qquad (13)$$

Since V_{j0} is the initial j_{th} bus voltage when the current is ΔI_j, we now write the new j_{th} bus voltage as

$V_j = V_{j0} + Z_{jj}\Delta I_j \qquad (14)$

Z_{jj} can be interpreted as the Thevenin's impedance at bus j, hence, $Z_{jj} = Z_{th}$. It is obvious that Z_{jj} is the diagonal entry in the jth row and also the driving point impedance of bus j and from equation 14 we have

$\Delta V_j = V_j - V_{j0} = Z_{jj}\Delta I_j \qquad (15)$

The same procedure can be applied to finding the Thevenin's impedance between multiple busses, i and j, for instance.

From the multi-bus power network of equation 13, we assume current injections ΔI_i and ΔI_j at busses i and j so that the bus voltages V_{10}, V_{20}, ..., V_{i0}, V_{j0}, ..., V_{n0} change to ΔV_1, ΔV_2, ..., ΔV_i, ΔV_j, ..., ΔV_n. Since ΔV = [Z_{bus}][ΔI], then;

$$[\Delta V] = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_i \\ \Delta V_j \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} Z_{11} Z_{12} \cdots Z_{1j} Z_{1j} \cdots Z_{1n} \\ Z_{21} Z_{22} \cdots Z_{2j} Z_{2j} \cdots Z_{2n} \\ \vdots \\ Z_{i1} Z_{i2} \cdots Z_{ii} Z_{ij} \cdots Z_{in} \\ Z_{j1} Z_{j2} \quad Z_{ji} Z_{jj} \quad Z_{jn} \\ \vdots \\ Z_{n1} Z_{n2} \cdots Z_{ni} Z_{nj} \cdots Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ \Delta I_i \\ \Delta I_j \\ \vdots \\ 0 \end{bmatrix} =$$

$$\begin{bmatrix} Z_i\Delta I_i + Z_j\Delta I_j \\ \vdots \\ Z_{ii}\Delta I_i + Z_{jj}\Delta I_j \\ \vdots \\ Z_{ni}\Delta I_i + Z_{nj}\Delta I_j \end{bmatrix} \qquad (16)$$

From the bus matrix equation of equation 16, we have for rows i and j that

$\Delta V_i = Z_{ii}\Delta I_i + Z_{ij}\Delta I_j$

$and\ \Delta V_j = Z_{ji}\Delta I_i + Z_{ji}\Delta I_j$

Since $\Delta V_i = V_i - V_{i0}\ and\ \Delta V_j = V_j - V_{j0}$, we then write

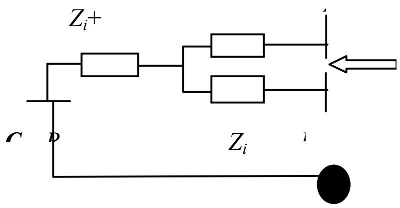
$V_i = V_{i0} + Z_{ij} I_i + Z_{ij}\Delta I_i\ and\ V_j = V_{j0} + Z_{ji} I_j + Z_{ji}\Delta I_j \qquad (17)$

Then, adding and subtracting $Z_{ij}\Delta I_i$ in V_i and $Z_{ji}\Delta I_j$ in V_j, we get

$V_i = V_{i0} + (Z_{ii} - Z_{ij})\Delta I_i + Z_{ij}(\Delta I_i + \Delta I_j)\ and\ V_j = V_{j0} + Z_{ji}(\Delta I_i + \Delta I_j) - (Z_{jj} - Z_{ji})\Delta I_j \qquad (18)$

Since in this analysis we made use of symmetrical bus, we can write $Z_{ij} = Z_{ji}$.

The Thevenin equivalent impedance circuit for equation 17 is shown in figure 2.



Looking into bus terminals i and j, the Thevenin's equivalent impedance is

$Z_{th} = Z_i + Z_j = 2Z_i = 2Z_j$ (Assume $Z_i = Z_j$ (19)

Assuming a line impedance, Z_L is introduced in-between busses i and j, from the concept of circuit theory, it is deduced that

$$I_i \text{ (Current through } Z_i) = \frac{V_{i0} - V_{j0}}{Z_{th} + Z_l} \qquad (20)$$

Where Z_L is a line impedance.

Similarly, if a var compensator is installed between busses i and j, the change in bus voltage, ΔV, will be

$$\Delta V_i = V_{i0} + (Z_i' - Z_j')\Delta I_i + Z_j'(\Delta I_i + \Delta I_j) \text{ and } \Delta V_j = V_{j0} + Z_j'(\Delta I_i + \Delta I_j) - (Z_j' - Z_i')\Delta I_j \quad (21)$$

where $Z_i' = Z_i + Z_x$ and $Z_j' = Z_j + Z_x$

$Z' = \Delta Z_{bus}$ after installation of a var compensator.

and $Z_x = Z_C + Z_L$

where Z_C = Impedance of the capacitor bank

and Z_L = Impedance of the reactor.

From the above, Thevenin's theorem has been used to solve the new bus voltage without developing the bus impedance, Z_{bus} when a line with impedance Z_L in series with the Thevenin's equivalent impedance Z_{th} as represented in equation 21 is added to any bus of a power system.

II. SIMULATION RESULTS AND ANALYSIS

A. Base Case

The following tables show the bus records, indicating voltages at various nodes of the grid network and the line flows for the grid. This is without compensation of any sort and the active and reactive load demands used is the average demand recorded for each area as supplied by

Table 1: Bus records for base case.

Bus Nos.	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen MW	Gen Mvar	Shunts
1	Kainji	13.8	1.05	14.49	1.15			480	187.58	
2	Kainji Ts	330	0.98253	324.236	-14.67					
3	Kebbi	330	0.92285	304.541	-25.1	180	75			
4	Jebba	330	0.96911	319.806	-16.79	120	58			0
5	Jebba Gs	330	0.97076	320.35	-16.49					
6	Jebba Ps	13.8	1.05	14.49	-2.52			420	193.46	
7	Shiroro Ts	330	0.81868	270.166	-33.13	240	108			
8	Shiroro Gs	13.8	1.05	14.49	-15.27			450	485.2	
9	Kaduna	330	0.7446	245.72	-40.57	180	98			
10	Katampe	330	0.79534	262.462	-37.97	250	80			
11	Oshogbo	330	0.98836	326.159	-16.32	180	90			
12	Aiyede	330	0.96917	319.827	-18.74	120	58			
13	Ikeja West	330	0.97495	321.733	-15.92	420	168			
14	Benin	330	1.00377	331.244	-8.63	200	75			0
15	Ajaokuta	330	1.01572	335.186	2.13	90	38			
16	Onitsha	330	0.98868	326.264	-0.54	180	98			
17	New Haven	330	0.96982	320.042	-3.07	180	65			
18	Okpai	330	1.00933	333.078	4.73					
19	Okpai Gs	13.8	1.05	14.49	19.14			450	129.76	
20	Alaoji	330	0.98957	326.557	5.62	120	65			
21	Omoku	13.8	1.05	14.49	9.91			120	86.57	
22	Afam	330	0.98932	326.476	6.1	150	90			
23	Afam Gs	13.8	1.05	14.49	21.81			480	174.95	
24	Sapele	330	1.00708	332.335	-8.25	75	38			
25	Sapele Gs	13.8	1.05	14.49	-3.49			150	83.16	
26	Aladja	330	1.00438	331.444	-7.57	77	34			
27	Delta	330	1.0061	332.013	-6.82	90	35			
28	Delta Gs	13.8	1.05	14.49	7.21			437	132.43	
29	Akangba	330	0.9716	320.627	-16.36	290	97			
30	Egbin	330	0.97966	323.287	-14.24	167	89			
31	Egbin	13.8	1.05	14.49	0			431.65	179.94	
32	Aja	330	0.9751	321.784	-14.68	184	82			

33	Jos	330	0.69188	228.321	-50.28	149.95	49.98			
34	Calabar	330	1.00392	331.294	6.09	80	36			
35	AES	13.8	1.05	14.49	-7.04			220	139.88	
36	Kano	330	0.60797	200.63	-56.73	229.91	100.59			0
37	Geregu	13.8	1.05	14.49	15.31			415	109.38	

Table 2: Line records for base case.

From	To	Circuit	Device Type	MW Loss	Mvar Loss	Mvar To
Kainji	Kainji Ts	1	Transformer	0	141.16	-46.419
Kainji Ts	Kebbi	1	Line	4.23	-75.74	-75
Kainji Ts	Jebba	1	Line	0.7	-24.31	-47.887
Kainji Ts	Jebba	2	Line	0.7	-24.31	-47.887
Jebba Gs	Jebba	1	Line	0.14	-1.77	-41.674
Jebba Gs	Jebba	2	Line	0.14	-1.77	-41.674
Jebba	Shiroro Ts	1	Line	13.58	39.28	-119.914
Jebba	Shiroro Ts	2	Line	13.58	39.28	-119.914
Jebba	Oshogbo	1	Line	0.11	-58.22	7.532
Jebba	Oshogbo	2	Line	0.11	-58.22	7.532
Jebba	Oshogbo	3	Line	0.11	-58.22	7.532
Jebba Ps	Jebba Gs	1	Transformer	0	113.65	-79.803
Shiroro Gs	Shiroro Ts	1	Transformer	0	232.76	-252.438
Kaduna	Shiroro Ts	1	Line	6.28	30.24	178.625
From	To	Circuit	Device Type	MW Loss	Mvar Loss	Mvar To
Shiroro Ts	Katampe	1	Line	1.34	-26.49	-40
Shiroro Ts	Katampe	2	Line	1.34	-26.49	-40
Kaduna	Jos	1	Line	3.41	-10.92	-49.983
Kaduna	Kano	1	Line	10.96	59.13	-100.583
Oshogbo	Aiyede	1	Line	0.69	-37.41	-58
Oshogbo	Ikeja West	1	Line	0.03	-95.54	-65.316
Oshogbo	Ikeja West	2	Line	0.03	-95.54	-65.316
Oshogbo	Benin	1	Line	2.76	-74.56	-38.19
Oshogbo	Benin	2	Line	2.76	-74.56	-38.19
Ikeja West	Benin	1	Line	3.26	-47.2	-1.167
Ikeja West	Benin	2	Line	3.26	-47.2	-1.167
Ikeja West	Akangba	1	Line	0.15	-5.05	-48.5
Ikeja West	Akangba	2	Line	0.15	-5.05	-48.5
Ikeja West	Egbin	1	Line	0.52	-18.79	-2.684
Ikeja West	Egbin	2	Line	0.52	-18.79	-2.684
Ajaokuta	Benin	1	Line	7.06	-17.94	8.586
Benin	Onitsha	1	Line	5.57	-5.98	-77.281
Benin	Sapele	1	Line	0.04	-19.48	6.791
Benin	Sapele	2	Line	0.04	-19.48	6.791
Benin	Sapele	3	Line	0.04	-19.48	6.791
Benin	Delta	1	Line	0.78	-13.22	-15.852
Ajaokuta	Geregu	1	Transformer	0	97.9	109.376
New Haven	Onitsha	1	Line	1.06	-21.08	43.915
Onitsha	Okpai	1	Line	2.48	-32.63	6.587
Onitsha	Okpai	2	Line	2.48	-32.63	6.587
Onitsha	Alaoji	1	Line	3.13	-26.39	-40.192
Jos	New Haven	2	Line	0	0	0
Jos	New Haven	1	Line	0	0	0
Okpai	Okpai Gs	1	Transformer	0	116.58	129.756
Alaoji	Afam	1	Line	0.16	-4.79	-26.892
Alaoji	Afam	2	Line	0.16	-4.79	-26.892
Alaoji	Calabar	1	Line	0.13	-30.08	38.935
Omoku	Calabar	1	Transformer	0	11.64	-74.935
Afam	Afam Gs	1	Transformer	0	138.73	174.945
Sapele	Sapele Gs	1	Transformer	0	15.63	83.157

Sapele	Aladja	1	Line	0.09	-24.22	-33.367
Aladja	Delta	1	Line	0.22	1.82	2.455
Delta	Delta Gs	1	Transformer	0	110.83	132.428
Egbin	Egbin Gs	1	Transformer	0	116.24	179.939
Egbin	Aja	1	Line	0.21	1.82	-82
Egbin	AES	1	Transformer	0	36.13	139.881
Total				100.79	174.72	

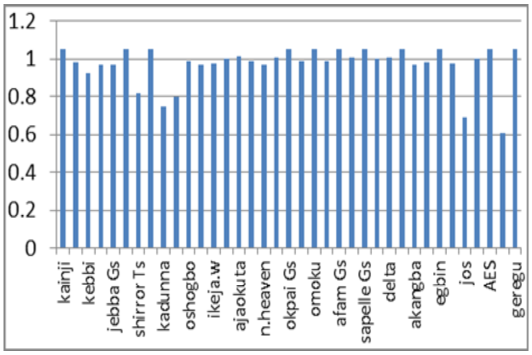
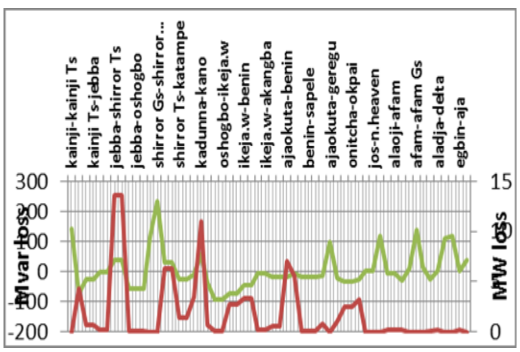


Fig. 3: Bar chart showing voltage magnitudes at the various bus nodes. Fig. 5: Active and reactive power losses.



Legend: Upper trace – Reactive power loss
Lower trace - Active power loss
Fig. 4: Active and reactive power loss

From the results, it can be observed that the voltage magnitudes at busses 3 (Kebbi), 7 (Shiroro), 9 (Kaduna), 10 (Katampe), 33 (Jos) and 36 (Kano) are lower than the acceptable limit of ±5% for the Nigerian 330kV grid system [4], the worse points being busses 36 (Kano) and 33 (Jos) which are below the voltage stability limits. Moreso, apart from the generator busses, only busses 14 (Benin), 15 (Ajaokuta), 24 (Sapele), 26 (Aladja), 27 (Delta) and 34 (Calabar) had voltages with magnitudes around 1.0pu. Furthermore, the grid system has a very high active power loss of 100.79MW, which is unacceptable by all standards.

To correct these voltage lapses and reduce the very high active power losses of the grid network to the barest minimum, several approaches were adopted in this work, which is divided into three: short term, medium term and long term solutions to this problem. The results of these approaches are discussed below.

II. SHORT TERM CORRECTIVE MEASURES

A. Influence of OLTC Adjustment on Voltage Stability

The OLTC transformer tap positions at the various generator busses were adjusted in a bid to correct the poor voltage profile, while keeping the various line loads constant. Several results were obtained with each tap adjustment which cannot all be discussed here due to space restraint but the most feasible result, which was obtained when the OLTC transformer at Shiroro GS was adjusted, is discussed below in Tables 3 and 4.

Table 3: Bus records with OLTC transformer adjustment at Shiroro.

Bus Nos.	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen. MW	Gen. Mvar	Shunts
1	Kainji	13.8	1.05	14.49	1.13			480	71.59	
2	Kainji Ts	330	1.04497	344.839	-13.73					
3	Kebbi	330	1.00019	330.063	-22.81	180	75			
4	Jebba	330	1.04094	343.51	-15.64	120	58			0
5	Jebba Gs	330	1.04118	343.588	-15.37					
6	Jebba Ps	13.8	1.05	14.49	-2.36			420	63.71	
7	Shiroro Ts	330	0.98669	325.608	-28.55	240	108			
8	Shiroro Gs	13.8	1.05	14.49	-14.74			450	309.29	
9	Kaduna	330	0.94891	313.141	-33.54	180	98			
10	Katampe	330	0.97254	320.938	-31.85	250	80			
11	Oshogbo	330	1.04212	343.9	-15.24	180	90			
12	Aiyede	330	1.02491	338.221	-17.41	120	58			
13	Ikeja West	330	1.00386	331.273	-14.97	420	168			
14	Benin	330	1.02767	339.132	-7.97	200	75			0
15	Ajaokuta	330	1.02843	339.382	2.48	90	38			
16	Onitsha	330	1.00207	330.682	-0.11	180	98			
17	New Haven	330	0.98361	324.59	-2.56	180	65			

18	Okpai	330	1.01947	336.425	5.07					
19	Okpai Gs	13.8	1.05	14.49	19.33			450	111	
20	Alaoji	330	0.99614	328.727	5.98	120	65			
21	Omoku	13.8	1.05	14.49	10.26			120	78.15	
22	Afam	330	0.99566	328.569	6.45	150	90			
23	Afam Gs	13.8	1.05	14.49	22.06			480	163.15	
24	Sapele	330	1.0289	339.536	-7.6	75	38			
25	Sapele Gs	13.8	1.05	14.49	-2.94			150	43.93	
26	Aladja	330	1.02512	338.291	-6.94	77	34			
27	Delta	330	1.02618	338.641	-6.21	90	35			
28	Delta Gs	13.8	1.05	14.49	7.54			437	95.36	
29	Akangba	330	1.00061	330.203	-15.38	290	97			
30	Egbin	330	1.0022	330.727	-13.41	167	89			
31	Egbin Gs	13.8	1.05	14.49	0			416.35	134.57	
32	Aja	330	0.99775	329.258	-13.83	184	82			
33	Jos	330	0.92182	304.202	-39.31	150	50			
34	Calabar	330	1.00861	332.842	6.45	80	36			
35	AES	13.8	1.05	14.49	-6.37			220	99.17	
36	Kano	330	0.86713	286.154	-42.81	240	105			0
37	Geregu	13.8	1.05	14.49	15.49			415	85.99	

Table 4: Line flows with OLTC transformer adjustment at Shiroro

From	To	Circuit	Status	Device Type	Transformer	Mvar To	MW Loss	Mvar Loss
Kainji	Kainji Ts	1	Closed	Transformer	YES	53.602	0	125.19
Kainji Ts	Kebbi	1	Closed	Line	NO	-74.998	3.6	-98.26
Kainji Ts	Jebba	1	Closed	Line	NO	-14.449	0.58	-29.62
Kainji Ts	Jebba	2	Closed	Line	NO	-14.449	0.58	-29.62
Jebba Gs	Jebba	1	Closed	Line	NO	13.699	0.12	-2.41
Jebba Gs	Jebba	2	Closed	Line	NO	13.699	0.12	-2.41
Jebba	Shiroro Ts	1	Closed	Line	NO	-48.058	8.59	-25.21
Jebba	Shiroro Ts	2	Closed	Line	NO	-48.058	8.59	-25.21
Jebba	Oshogbo	1	Closed	Line	NO	-32.753	0.01	-66.84
Jebba	Oshogbo	2	Closed	Line	NO	-32.753	0.01	-66.84
Jebba	Oshogbo	3	Closed	Line	NO	-32.753	0.01	-66.84
Jebba Ps	Jebba Gs	1	Closed	Transformer	YES	32.217	0	95.92
Shiroro Gs	Shiroro Ts	1	Closed	Transformer	YES	-169.98	0	139.31
Kaduna	Shiroro Ts	1	Closed	Line	NO	87.415	3.4	-6.41
Kaduna	Shiroro Ts	2	Closed	Line	NO	87.415	3.4	-6.41
Shiroro Ts	Katampe	1	Closed	Line	NO	-39.987	0.88	-48.34
Shiroro Ts	Katampe	2	Closed	Line	NO	-39.987	0.88	-48.34
Kaduna	Jos	1	Closed	Line	NO	-49.968	1.86	-51.93
Kaduna	Kano	1	Closed	Line	NO	-104.962	5.67	-13.32
Oshogbo	Aiyede	1	Closed	Line	NO	-57.999	0.61	-43.06
Oshogbo	Ikeja West	1	Closed	Line	NO	-100.96	0.23	-102.17
Oshogbo	Ikeja West	2	Closed	Line	NO	-100.96	0.23	-102.17
Oshogbo	Benin	1	Closed	Line	NO	-81.128	2.66	-83.26
Oshogbo	Benin	2	Closed	Line	NO	-81.128	2.66	-83.26
Ikeja West	Benin	1	Closed	Line	NO	-11.184	3.11	-52.51
Ikeja West	Benin	2	Closed	Line	NO	-11.184	3.11	-52.51
Ikeja West	Akangba	1	Closed	Line	NO	-48.5	0.14	-5.51
Ikeja West	Akangba	2	Closed	Line	NO	-48.5	0.14	-5.51
Ikeja West	Egbin	1	Closed	Line	NO	-35.853	0.46	-20.55
Ikeja West	Egbin	2	Closed	Line	NO	-35.853	0.46	-20.55
Ajaokuta	Benin	1	Closed	Line	NO	25.135	6.87	-22.35
Benin	Onitsha	1	Closed	Line	NO	-104.316	5.59	-7.81
Benin	Sapele	1	Closed	Line	NO	-7.244	0.03	-20.44
Benin	Sapele	2	Closed	Line	NO	-7.244	0.03	-20.44

Benin	Sapele	3	Closed	Line	NO	-7.244	0.03	-20.44
Benin	Delta	1	Closed	Line	NO	-41.787	0.76	-14.21
Ajaokuta	Geregu	1	Closed	Transformer	YES	85.988	0	95.47
New Haven	Onitsha	1	Closed	Line	NO	42.813	1.03	-22.19
Onitsha	Okpai	1	Closed	Line	NO	-1.592	2.4	-34.5
Onitsha	Okpai	2	Closed	Line	NO	-1.592	2.4	-34.5
Onitsha	Alaoji	1	Closed	Line	NO	-56.839	3.12	-27.52
Jos	New Haven	1	Open	Line	NO	0	0	0
Jos	New Haven	2	Open	Line	NO	0	0	0
Okpai	Okpai Gs	1	Closed	Transformer	YES	110.998	0	114.18
Alaoji	Afam	1	Closed	Line	NO	-31.732	0.16	-4.88
Alaoji	Afam	2	Closed	Line	NO	-31.732	0.16	-4.88
Alaoji	Calabar	1	Closed	Line	NO	31.248	0.11	-30.63
Omoku	Calabar	1	Closed	Transformer	YES	-67.248	0	10.9
Afam	Afam Gs	1	Closed	Transformer	YES	163.146	0	136.61
Sapele	Sapele Gs	1	Closed	Transformer	YES	43.926	0	12.99
Sapele	Aladja	1	Closed	Line	NO	-39.94	0.09	-25.27
Aladja	Delta	1	Closed	Line	NO	-4.191	0.21	1.75
Delta	Delta Gs	1	Closed	Transformer	YES	95.36	0	106.34
Egbin	Egbin Gs	1	Closed	Transformer	YES	134.575	0	101.76
Egbin	Aja	1	Closed	Line	NO	-82	0.2	1.74
Egbin	AES	1	Closed	Transformer	YES	99.172	0	30.95
Total							75.3	-476.02

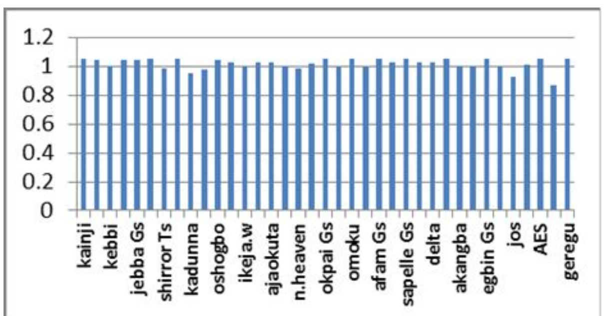
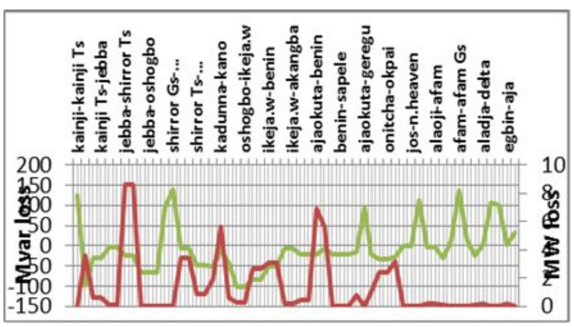


Fig. 5: Bar chart showing bus voltage at the various nodes



Legend: Upper trace – Reactive power loss
Lowe trace - Active power loss

Fig. 6: Active and reactive power loss

From the above tables, it is observed that the voltage profile of all the busses improved and lower limit violations were observed only at busses 33 (Jos) and 36 (Kano) which are 0.92182pu and 0.86713pu respectively but this is a large improvement from the previous base case where they were 0.69188pu and 0.60797pu respectively. Busses 2 (Kainji), 4 (Jebba) and 11 (Oshogbo) had voltages close to the upper voltage limit of 1.05pu. Active power losses reduced by 25.29% to 75.30MW.

Above tables and figures confirmed that OLTC transformer has a huge impact on voltage stability. Regulation of voltage is done by changing the tap ratio of the primary side of the OLTC transformer if the secondary side is too low or too high. Also, the maximum load limit for a system with OLTC transformer is much smaller than that for a system without OLTC transformer. It is so because the OLTC transformer gives additional reactance to the system reactance thus, the reactive power losses are higher and for every additional load, the system needs higher reactive power support to keep the voltage on the desirable level.

III MEDIUM TERM CORRECTIVE MEASURES

A. Influence of Var Compensation on Voltage Stability

One of such corrective measure explored in this work is the installation of a shunt capacitor of 68MVar at node 36 (Kano) and a shunt reactor of 157MVar at node 4 (Jebba). The results are discussed below.

Table 5: Bus records with var compensating devices installed.

Bus Nos.	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen MW	Gen Mvar	Shunts
1	Kainji	13.8	1.05	14.49	1.5			480	98.37	
2	Kainji Ts	330	1.03053	340.074	-13.57					
3	Kebbi	330	0.98252	324.232	-22.93	180	75			
4	Jebba	330	1.02427	338.01	-15.53	120	58			-157.37
5	Jebba Gs	330	1.02484	338.197	-15.25					

6	Jebba Ps	13.8	1.05	14.49	-2.02			420	93.76	
7	Shiroro Ts	330	1.0027	330.891	-28.6	240	108			
8	Shiroro Gs	13.8	1.05	14.49	-15.01			450	277.77	
9	Kaduna	330	0.98046	323.553	-33.43	180	98			
10	Katampe	330	0.98927	326.458	-31.8	250	80			
11	Oshogbo	330	1.02976	339.82	-15.16	180	90			
12	Aiyede	330	1.01211	333.996	-17.38	120	58			
13	Ikeja West	330	0.99733	329.118	-14.94	420	168			
14	Benin	330	1.02222	337.334	-7.84	200	75			0
15	Ajaokuta	330	1.02554	338.427	2.67	90	38			
16	Onitsha	330	0.99902	329.676	0.07	180	98			
17	New Haven	330	0.98047	323.556	-2.4	180	65			
18	Okpai	330	1.01716	335.664	5.26					
19	Okpai Gs	13.8	1.05	14.49	19.56			450	115.26	
20	Alaoji	330	0.99465	328.233	6.17	120	65			
Bus Nos.	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen MW	Gen Mvar	Shunts
21	Omoku	13.8	1.05	14.49	10.46			120	80.06	
22	Afam	330	0.99422	328.093	6.65	150	90			
23	Afam Gs	13.8	1.05	14.49	22.28			480	165.83	
24	Sapele	330	1.02392	337.895	-7.48	75	38			
25	Sapele Gs	13.8	1.05	14.49	-2.79			150	52.86	
26	Aladja	330	1.0204	336.731	-6.81	77	34			
27	Delta	330	1.02161	337.131	-6.07	90	35			
28	Delta Gs	13.8	1.05	14.49	7.74			437	103.8	
29	Akangba	330	0.99406	328.04	-15.36	290	97			
30	Egbin	330	0.99718	329.07	-13.39	167	89			
31	Egbin Gs	13.8	1.05	14.49	0			413.76	143.21	
32	Aja	330	0.99271	327.594	-13.82	184	82			
33	Jos	330	0.95618	315.54	-38.83	150	50			
34	Calabar	330	1.00754	332.49	6.64	80	36			
35	AES	13.8	1.05	14.49	-6.32			220	108.23	
36	Kano	330	0.95077	313.753	-41.91	240	105			67.8
37	Geregu	13.8	1.05	14.49	15.73			415	91.31	

Table 6: Line flows with var compensators installed.

From	To	Circuit	Status	Device Type	Transformer	Mvar To	MW Loss	Mvar Loss
Kainji	Kainji Ts	1	Closed	Transformer	YES	29.239	0	127.61
Kainji Ts	Kebbi	1	Closed	Line	NO	-75.002	3.73	-93.11
Kainji Ts	Jebba	1	Closed	Line	NO	-22.871	0.6	-28.43
Kainji Ts	Jebba	2	Closed	Line	NO	-22.871	0.6	-28.43
Jebba Gs	Jebba	1	Closed	Line	NO	0.062	0.12	-2.28
Jebba Gs	Jebba	2	Closed	Line	NO	0.062	0.12	-2.28
Jebba	Shiroro Ts	1	Closed	Line	NO	-5.308	8.41	-26.62
Jebba	Shiroro Ts	2	Closed	Line	NO	-5.308	8.41	-26.62
Jebba	Oshogbo	1	Closed	Line	NO	-22.576	0.02	-64.95
Jebba	Oshogbo	2	Closed	Line	NO	-22.576	0.02	-64.95
Jebba	Oshogbo	3	Closed	Line	NO	-22.576	0.02	-64.95
Jebba Ps	Jebba Gs	1	Closed	Transformer	YES	4.676	0	98.43
Shiroro Gs	Shiroro Ts	1	Closed	Transformer	YES	-147.129	0	130.64
Kaduna	Shiroro Ts	1	Closed	Line	NO	35.356	2.99	-11.66
Kaduna	Shiroro Ts	2	Closed	Line	NO	35.356	2.99	-11.66
Shiroro Ts	Katampe	1	Closed	Line	NO	-40	0.85	-50.48
Shiroro Ts	Katampe	2	Closed	Line	NO	-40	0.85	-50.48
Kaduna	Jos	1	Closed	Line	NO	-49.998	1.73	-57.97
Kaduna	Kano	1	Closed	Line	NO	-37.197	4.28	-33.19
Oshogbo	Aiyede	1	Closed	Line	NO	-58.001	0.63	-41.75
Oshogbo	Ikeja West	1	Closed	Line	NO	-92.232	0.16	-100.8

Oshogbo	Ikeja West	2	Closed	Line	NO	-92.232	0.16	-100.8
Oshogbo	Benin	1	Closed	Line	NO	-71.04	2.62	-81.74
Oshogbo	Benin	2	Closed	Line	NO	-71.04	2.62	-81.74
Ikeja West	Benin	1	Closed	Line	NO	-8.958	3.18	-51.04
Ikeja West	Benin	2	Closed	Line	NO	-8.958	3.18	-51.04
Ikeja West	Akangba	1	Closed	Line	NO	-48.5	0.14	-5.41
Ikeja West	Akangba	2	Closed	Line	NO	-48.5	0.14	-5.41
Ikeja West	Egbin	1	Closed	Line	NO	-27.581	0.45	-20.36
Ikeja West	Egbin	2	Closed	Line	NO	-27.581	0.45	-20.36
Ajaokuta	Benin	1	Closed	Line	NO	21.279	6.91	-21.38
Benin	Onitsha	1	Closed	Line	NO	-98.087	5.58	-7.44
Benin	Sapele	1	Closed	Line	NO	-3.99	0.04	-20.23
Benin	Sapele	2	Closed	Line	NO	-3.99	0.04	-20.23
Benin	Sapele	3	Closed	Line	NO	-3.99	0.04	-20.23
Benin	Delta	1	Closed	Line	NO	-35.779	0.76	-14
Ajaokuta	Geregu	1	Closed	Transformer	YES	91.31	0	95.97
New Haven	Onitsha	1	Closed	Line	NO	43.064	1.04	-21.94
From	To	Circuit	Status	Device Type	Transformer	Mvar To	MW Loss	Mvar Loss
Onitsha	Okpai	1	Closed	Line	NO	0.284	2.42	-34.08
Onitsha	Okpai	2	Closed	Line	NO	0.284	2.42	-34.08
Onitsha	Alaoji	1	Closed	Line	NO	-53.032	3.12	-27.28
Jos	New Haven	1	Open	Line	NO	0	0	0
Jos	New Haven	2	Open	Line	NO	0	0	0
Okpai	Okpai Gs	1	Closed	Transformer	YES	115.264	0	114.69
Alaoji	Afam	1	Closed	Line	NO	-30.625	0.16	-4.86
Alaoji	Afam	2	Closed	Line	NO	-30.625	0.16	-4.86
Alaoji	Calabar	1	Closed	Line	NO	33.003	0.11	-30.5
Omoku	Calabar	1	Closed	Transformer	YES	-69.003	0	11.06
Afam	Afam Gs	1	Closed	Transformer	YES	165.828	0	137.08
Sapele	Sapele Gs	1	Closed	Transformer	YES	52.864	0	13.44
Sapele	Aladja	1	Closed	Line	NO	-38.416	0.09	-25.03
Aladja	Delta	1	Closed	Line	NO	-2.651	0.21	1.76
Delta	Delta Gs	1	Closed	Transformer	YES	103.801	0	107.23
Egbin	Egbin Gs	1	Closed	Transformer	YES	143.205	0	101.89
Egbin	Aja	1	Closed	Line	NO	-82	0.21	1.75
Egbin	AES	1	Closed	Transformer	YES	108.235	0	31.95
Total							72.78	-491.15

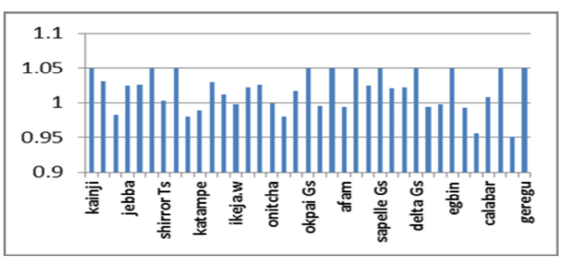
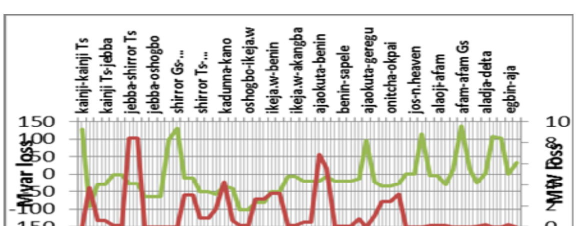


Fig. 7: Bar chart showing bus voltages with var compensating devices installed.



Legend: Upper trace – Reactive power loss
Lowe trace - Active power loss

Fig. 8: Active and reactive power loss

Observe that the voltage magnitude at all nodes of the network has been brought within limits. Active power losses also reduced marginally to 72.78MW.

IV. LONG TERM SOLUTION

A. Effect of Adding a Double Circuit Line from Jos to New-Haven

A lightly loaded transmission line has a capacitive effect and helps to boost voltage magnitudes at the receiving end. Since the voltage magnitude violations we have tend towards the lower limit, we added a double circuit line from Jos to New Haven, to complete the grid network loop and to see the effect on the voltage magnitude. This was done without var compensation of any sort and the OLTC transformer tap positions were kept at 1.0pu.

Table 7: Bus records with a double circuit line added from Jos to New Haven

Bus Nos.	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen. MW	Gen. Mvar	Shunts

1	Kainji	13.8	1.05	14.49	5.84			480	17.04	
2	Kainji Ts	330	1.07442	354.559	-8.6					
3	Kebbi	330	1.03588	341.839	-17.15	180	75			
4	Jebba	330	1.07501	354.755	-10.43	120	58			0
5	Jebba Gs	330	1.07458	354.61	-10.17					
6	Jebba Ps	13.8	1.05	14.49	2.43			420	2.33	
7	Shiroro Ts	330	1.03881	342.807	-17.4	240	108			
8	Shiroro Gs	13.8	1.05	14.49	-3.41			450	75.27	
9	Kaduna	330	1.02472	338.159	-19.94	180	98			
10	Katampe	330	1.02693	338.887	-20.38	250	80			
11	Oshogbo	330	1.07448	354.578	-12.14	180	90			
12	Aiyede	330	1.05838	349.264	-14.18	120	58			
13	Ikeja West	330	1.02749	339.073	-13.82	420	168			
14	Benin	330	1.05389	347.785	-8.42	200	75			0
15	Ajaokuta	330	1.04234	343.972	1.71	90	38			
16	Onitsha	330	1.03959	343.065	-6.58	180	98			
17	New Haven	330	1.04565	345.064	-12.21	180	65			
18	Okpai	330	1.04786	345.795	-1.68					
19	Okpai Gs	13.8	1.05	14.49	12.19			450	58.55	
20	Alaoji	330	1.01453	334.796	-0.7	120	65			
21	Omoku	13.8	1.05	14.49	3.55			120	54.59	
22	Afam	330	1.0134	334.421	-0.24	150	90			
23	Afam Gs	13.8	1.05	14.49	15.09			480	130.18	
24	Sapele	330	1.05283	347.435	-8.06	75	38			
25	Sapele Gs	13.8	1.05	14.49	-3.5			150	0.9	
26	Aladja	330	1.04787	345.796	-7.42	77	34			
27	Delta	330	1.0482	345.906	-6.71	90	35			
28	Delta Gs	13.8	1.05	14.49	6.74			437	54.77	
29	Akangba	330	1.02434	338.031	-14.21	290	97			
30	Egbin	330	1.02069	336.828	-12.41	167	89			
31	Egbin Gs	13.8	1.05	14.49	0			393.09	95.26	
32	Aja	330	1.01632	335.386	-12.82	184	82			
33	Jos	330	1.05305	347.505	-17.1	150	50			
34	Calabar	330	1.02173	337.172	-0.21	80	36			
35	AES	13.8	1.05	14.49	-5.5			220	65.8	
36	Kano	330	0.95591	315.452	-27.74	240	105			0
37	Geregu	13.8	1.05	14.49	14.55			415	60.42	

Table 8: Line flows with a double circuit line added from Jos to New Haven

From	To	Circuit	Status	Device Type	Transformer	Mvar to	MW Loss	Mvar Loss
Kainji	Kainji Ts	1	Closed	Transformer	YES	105.578	0	122.62
Kainji Ts	Kebbi	1	Closed	Line	NO	-75	3.37	-108.67
Kainji Ts	Jebba	1	Closed	Line	NO	3.998	0.56	-31.95
Kainji Ts	Jebba	2	Closed	Line	NO	3.998	0.56	-31.95
Jebba Gs	Jebba	1	Closed	Line	NO	43.059	0.12	-2.66
Jebba Gs	Jebba	2	Closed	Line	NO	43.059	0.12	-2.66
Jebba	Shiroro Ts	1	Closed	Line	NO	-70.248	2.79	-83.59
Jebba	Shiroro Ts	2	Closed	Line	NO	-70.248	2.79	-83.59
Jebba	Oshogbo	1	Closed	Line	NO	-27.34	0.25	-69.15
Jebba	Oshogbo	2	Closed	Line	NO	-27.34	0.25	-69.15
Jebba	Oshogbo	3	Closed	Line	NO	-27.34	0.25	-69.15
Jebba Ps	Jebba Gs	1	Closed	Transformer	YES	91.435	0	93.76
Shiroro Gs	Shiroro Ts	1	Closed	Transformer	YES	35.377	0	110.64
Kaduna	Shiroro Ts	1	Closed	Line	NO	13.935	0.91	-32.35
Kaduna	Shiroro Ts	2	Closed	Line	NO	13.935	0.91	-32.35
Shiroro Ts	Katampe	1	Closed	Line	NO	-40	0.78	-55.37
Shiroro Ts	Katampe	2	Closed	Line	NO	-40	0.78	-55.37
Kaduna	Jos	1	Closed	Line	NO	-1.666	0.67	-77.98

Kaduna	Kano	1	Closed	Line	NO	-105	4.6	-34.12
Oshogbo	Aiyede	1	Closed	Line	NO	-58	0.57	-46.54
Oshogbo	Ikeja West	1	Closed	Line	NO	-109.947	0.48	-105.79
Oshogbo	Ikeja West	2	Closed	Line	NO	-109.947	0.48	-105.79
Oshogbo	Benin	1	Closed	Line	NO	-91.494	0.79	-105.37
Oshogbo	Benin	2	Closed	Line	NO	-91.494	0.79	-105.37
Ikeja West	Benin	1	Closed	Line	NO	-7.84	2.02	-65.86
From	To	Circuit	Status	Device Type	Transformer	Mvar to	MW Loss	Mvar Loss
Ikeja West	Benin	2	Closed	Line	NO	-7.84	2.02	-65.86
Ikeja West	Akangba	1	Closed	Line	NO	-48.5	0.13	-5.88
Ikeja West	Akangba	2	Closed	Line	NO	-48.5	0.13	-5.88
Ikeja West	Egbin	1	Closed	Line	NO	-63.3	0.42	-21.94
Ikeja West	Egbin	2	Closed	Line	NO	-63.3	0.42	-21.94
Ajaokuta	Benin	1	Closed	Line	NO	44.398	6.74	-26.67
Benin	Onitsha	1	Closed	Line	NO	-72.891	0.37	-55.81
Benin	Sapele	1	Closed	Line	NO	-23.375	0.04	-21.46
Benin	Sapele	2	Closed	Line	NO	-23.375	0.04	-21.46
Benin	Sapele	3	Closed	Line	NO	-23.375	0.04	-21.46
Benin	Delta	1	Closed	Line	NO	-71.521	0.78	-15.08
Ajaokuta	Geregu	1	Closed	Transformer	YES	60.416	0	93.48
New Haven	Onitsha	1	Closed	Line	NO	-72.231	5.03	8.58
Onitsha	Okpai	1	Closed	Line	NO	-25.451	2.25	-39.49
Onitsha	Okpai	2	Closed	Line	NO	-25.451	2.25	-39.49
Onitsha	Alaoji	1	Closed	Line	NO	-104.72	3.25	-29.51
Jos	New Haven	1	Closed	Line	NO	-72.906	1.24	-97.07
Jos	New Haven	2	Closed	Line	NO	-72.906	1.24	-97.07
Okpai	Okpai Gs	1	Closed	Transformer	YES	58.553	0	109.45
Alaoji	Afam	1	Closed	Line	NO	-45.647	0.16	-5.11
Alaoji	Afam	2	Closed	Line	NO	-45.647	0.16	-5.11
Alaoji	Calabar	1	Closed	Line	NO	9.35	0.06	-32.01
Omoku	Calabar	1	Closed	Transformer	YES	-45.35	0	9.24
Afam	Afam Gs	1	Closed	Transformer	YES	130.175	0	131.47
Sapele	Sapele Gs	1	Closed	Transformer	YES	0.897	0	11.96
Sapele	Aladja	1	Closed	Line	NO	-47.492	0.1	-26.43
Aladja	Delta	1	Closed	Line	NO	-11.806	0.2	1.69
Delta	Delta Gs	1	Closed	Transformer	YES	54.771	0	103.1
Egbin	Egbin Gs	1	Closed	Transformer	YES	95.259	0	86.95
Egbin	Aja	1	Closed	Line	NO	-82	0.2	1.67
Egbin	AES	1	Closed	Transformer	YES	65.796	0	28.03
Total							52.11	-1116.87

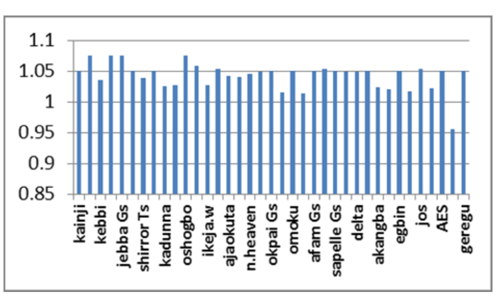
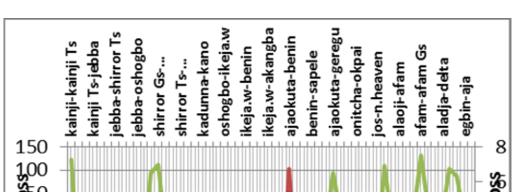


Fig. 9: Bar chart showing bus voltage magnitudes.



Legend: Upper trace – Reactive power loss
Lowe trace - Active power loss
Fig. 10: Active and reactive power loss

We observe that with the addition of the double circuit line from Jos to New Haven, bus voltage magnitudes at all nodes tended to the higher voltage limit, except bus 36 (Kano) which was slightly lower than 1.0pu. Busses 2 (Kainji), 4 (Jebba), 5 (Jebba GS), 11 (Osogbo), 12 (Aiyede), 14 (Benin), 24 (Sapele) and 33 (Jos) exceeded the maximum voltage limit of 1.05pu. Furthermore, active power losses dropped drastically by 28.4% to 52.11MW.

B. Effect of Adding Var Compensators alongside the Double Circuit Line from Jos to New-Haven

Following the extra-high voltages induced in the system after the addition of the double circuit line from Jos to New Haven, var compensators were added at various points in the grid to stabilise the voltage and bring it within limits.

Table 9: Bus records with var compensation following addition of double circuit lines from Jos to New Haven

Bus Nos .	Name	Nominal kV	PU Volt	Volt (kV)	Angle	Load MW	Load Mvar	Gen. MW	Gen. Mvar	Shunts
1	Kainji	13.8	1.05	14.49	6.35			480	69.32	
2	Kainji Ts	330	1.04619	345.243	-8.49					
3	Kebbi	330	1.00168	330.554	-17.55	180	75			
4	Jebba	330	1.04235	343.976	-10.4	120	58			-162.97
5	Jebba Gs	330	1.04256	344.045	-10.13					
6	Jebba Ps	13.8	1.05	14.49	2.87			420	61.16	
7	Shiroro Ts	330	1.03307	340.912	-17.76	240	108			
8	Shiroro Gs	13.8	1.05	14.49	-3.69			450	85.87	
9	Kaduna	330	1.02904	339.585	-20.35	180	98			
10	Katampe	330	1.02095	336.912	-20.77	250	80			
11	Oshogbo	330	1.04278	344.118	-12.24	180	90			
12	Aiyede	330	1.0256	338.447	-14.41	120	58			
13	Ikeja West	330	1.00352	331.163	-14.07	420	168			
14	Benin	330	1.02333	337.699	-8.33	200	75			-157.08
15	Ajaokuta	330	1.02612	338.621	2.17	90	38			
16	Onitsha	330	1.02557	338.437	-6.57	180	98			
17	New Haven	330	1.03437	341.341	-12.37	180	65			
18	Okpai	330	1.03726	342.295	-1.56					
19	Okpai Gs	13.8	1.05	14.49	12.45			450	78.13	
20	Alaoji	330	1.00767	332.53	-0.61	120	65			
21	Omoku	13.8	1.05	14.49	3.65			120	63.38	
22	Afam	330	1.00678	332.236	-0.14	150	90			
23	Afam Gs	13.8	1.05	14.49	15.29			480	142.48	
24	Sapele	330	1.02493	338.228	-7.97	75	38			
25	Sapele Gs	13.8	1.05	14.49	-3.28			150	51.05	
26	Aladja	330	1.02136	337.047	-7.3	77	34			
27	Delta	330	1.02254	337.437	-6.57	90	35			
28	Delta Gs	13.8	1.05	14.49	7.23			437	102.09	
29	Akangba	330	1.00028	330.092	-14.49	290	97			
30	Egbin	330	1.00218	330.72	-12.64	167	89			
31	Egbin Gs	13.8	1.05	14.49	0			393.02	129.22	
32	Aja	330	0.99773	329.251	-13.07	184	82			
33	Jos	330	1.04736	345.63	-17.4	150	50			
34	Calabar	330	1.01683	335.555	-0.12	80	36			
35	AES	13.8	1.05	14.49	-5.61			220	99.21	
36	Kano	330	1.00932	333.077	-28	240	105			76.41
37	Geregu	13.8	1.05	14.49	15.21			415	90.23	

Table 10: Line flows with var compensation following addition of double circuit lines from Jos to New Haven

From	To	Circuit	Status	Device Type	Transformer	Mvar To	MW Loss	Mvar Loss
Kainji	Kainji Ts	1	Closed	Transformer	YES	55.695	0	125.02
Kainji Ts	Kebbi	1	Closed	Line	NO	-75	3.59	-98.69
Kainji Ts	Jebba	1	Closed	Line	NO	-13.718	0.58	-29.72
Kainji Ts	Jebba	2	Closed	Line	NO	-13.718	0.58	-29.72
Jebba Gs	Jebba	1	Closed	Line	NO	14.874	0.12	-2.42
Jebba Gs	Jebba	2	Closed	Line	NO	14.874	0.12	-2.42
Jebba	Shiroro Ts	1	Closed	Line	NO	-30.718	2.79	-79.65
Jebba	Shiroro Ts	2	Closed	Line	NO	-30.718	2.79	-79.65
Jebba	Oshogbo	1	Closed	Line	NO	-22.941	0.27	-64.75

Jebba	Oshogbo	2	Closed	Line	NO	-22.941	0.27	-64.75
Jebba	Oshogbo	3	Closed	Line	NO	-22.941	0.27	-64.75
Jebba Ps	Jebba Gs	1	Closed	Transformer	YES	34.591	0	95.75
Shiroro Gs	Shiroro Ts	1	Closed	Transformer	YES	25.681	0	111.55
Kaduna	Shiroro Ts	1	Closed	Line	NO	-21.531	0.88	-32.62
Kaduna	Shiroro Ts	2	Closed	Line	NO	-21.531	0.88	-32.62
Shiroro Ts	Katampe	1	Closed	Line	NO	-40	0.79	-54.59
From	To	Circuit	Status	Device Type	Transformer	Mvar To	MW Loss	Mvar Loss
Shiroro Ts	Katampe	2	Closed	Line	NO	-40	0.79	-54.59
Kaduna	Jos	1	Closed	Line	NO	-19.084	0.62	-78.29
Kaduna	Kano	1	Closed	Line	NO	-28.595	3.8	-45.2
Oshogbo	Aiyede	1	Closed	Line	NO	-58	0.61	-43.13
Oshogbo	Ikeja West	1	Closed	Line	NO	-95.685	0.4	-100.74
Oshogbo	Ikeja West	2	Closed	Line	NO	-95.685	0.4	-100.74
Oshogbo	Benin	1	Closed	Line	NO	-85.762	0.81	-98.73
Oshogbo	Benin	2	Closed	Line	NO	-85.762	0.81	-98.73
Ikeja West	Benin	1	Closed	Line	NO	-17.652	2.09	-60.92
Ikeja West	Benin	2	Closed	Line	NO	-17.652	2.09	-60.92
Ikeja West	Akangba	1	Closed	Line	NO	-48.5	0.14	-5.5
Ikeja West	Akangba	2	Closed	Line	NO	-48.5	0.14	-5.5
Ikeja West	Egbin	1	Closed	Line	NO	-33.123	0.39	-21.16
Ikeja West	Egbin	2	Closed	Line	NO	-33.123	0.39	-21.16
Ajaokuta	Benin	1	Closed	Line	NO	22.057	6.9	-21.58
Benin	Onitsha	1	Closed	Line	NO	-30.698	0.28	-54.09
Benin	Sapele	1	Closed	Line	NO	-4.648	0.04	-20.27
Benin	Sapele	2	Closed	Line	NO	-4.648	0.04	-20.27
Benin	Sapele	3	Closed	Line	NO	-4.648	0.04	-20.27
Benin	Delta	1	Closed	Line	NO	-36.994	0.76	-14.04
Ajaokuta	Geregu	1	Closed	Transformer	YES	90.229	0	95.87
New Haven	Onitsha	1	Closed	Line	NO	-82.357	5.24	11.21
Onitsha	Okpai	1	Closed	Line	NO	-16.374	2.3	-37.67
Onitsha	Okpai	2	Closed	Line	NO	-16.374	2.3	-37.67
Onitsha	Alaoji	1	Closed	Line	NO	-86.617	3.17	-28.96
Jos	New Haven	1	Closed	Line	NO	-79.282	1.31	-94.74
Jos	New Haven	2	Closed	Line	NO	-79.282	1.31	-94.74
Okpai	Okpai Gs	1	Closed	Transformer	YES	78.13	0	110.88
Alaoji	Afam	1	Closed	Line	NO	-40.387	0.16	-5.02
Alaoji	Afam	2	Closed	Line	NO	-40.387	0.16	-5.02
Alaoji	Calabar	1	Closed	Line	NO	17.594	0.08	-31.52
Omoku	Calabar	1	Closed	Transformer	YES	-53.594	0	9.79
Afam	Afam Gs	1	Closed	Transformer	YES	142.478	0	133.25
Sapele	Sapele Gs	1	Closed	Transformer	YES	51.049	0	13.34
Sapele	Aladja	1	Closed	Line	NO	-38.724	0.09	-25.08
Aladja	Delta	1	Closed	Line	NO	-2.963	0.21	1.76
Delta	Delta Gs	1	Closed	Transformer	YES	102.087	0	107.04
Egbin	Egbin Gs	1	Closed	Transformer	YES	129.215	0	90.97
Egbin	Aja	1	Closed	Line	NO	-82	0.2	1.74
Egbin	AES	1	Closed	Transformer	YES	99.207	0	30.96
Total							52	-1003.47

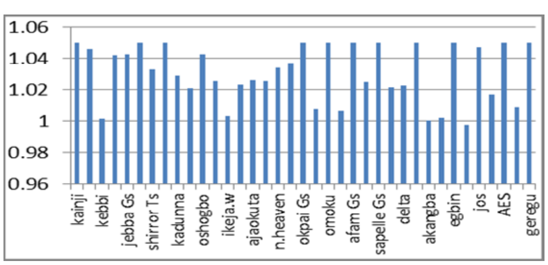
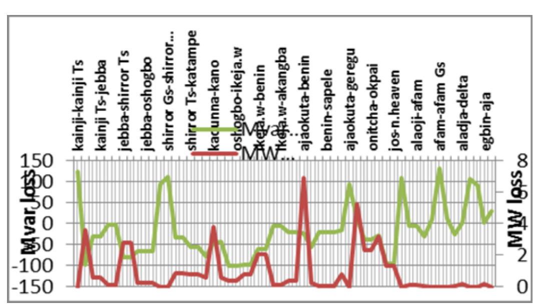


Fig. 11: Bar chart showing bus voltages with var compensation following addition of double circuit lines from Jos to New Haven



Legend: Upper trace – Reactive power loss
Lower trace - Active power loss
Fig. 12: Active and reactive power loss

Shunt reactors of 163MVar and 157Mvar were added to the circuit at Jebba (node 4) and Benin (node 14) to correct the extra-high voltages while a 76MVar shunt capacitor was added to the circuit at Kano (node 36) With these, the voltage magnitude at all nodes came within limits and the active power losses reduced further

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