ANALYSIS OF THE REACTIVE POWER FLOW AND VOLTAGE PROFILE IN THE NIGERIAN NATIONAL 330KV GRID

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ABSTRACT

The reactive power flow in the Nigerian National 330KV Grid is reported in this paper. A FORTRAN computer program employing the Gauss-Seidel iterative technique is developed and used to evaluate the load flow of the national grid with a total of eighteen busbar case studies. It is found that the Shiroro-Kaduna 330KV transmission lines were overloaded and consequently exhibits unsatisfactory receiving end voltages at Kaduna, Kano, Jos, and Gombe 330KV loadbuses.

As a result of the study a reallocation of the reactive power sources in the Nigerian National 330KV Grid is suggested. This suggestion included the provision of shunt capacitors banks of values up to 97.50Mvar at Kano, 99.60Mvar at Gombe and 70.00Mvar reactor bank at Ajaokuta.

LIST OF SYMBOLS AND ABBREVIATIONS

ΣP_g	Total power generated by the station
ΣP_j	Total power consumed by the loads
ΣE_j	Total energy consumption by the loads
ΣP_{loss}	Total power losses in the network and auxiliary equipment
ΣE_g	Total Energy Consumption at the generating Station
ΣE_{loss}	Total energy dissipated in the network
ΣQ_g	Total reactive power at the generating station
ΣQ_c	Total reactive power of the compensating devices
ΣQ_{tr}	Total line charging of the transmission lines
ΣQ_l	Total reactive power of the loads
ΣQ_{loss}	Total reactive power losses
P	Active (real) power, KW
Q	Reactive power, Kvar
C	Capacitance
NEPA	National Electric Power Authority
MW	Mega watt
Mvar, Mx	Mega volt Ampere Reactive
GS	Generating station
SS	Substation
TS	Transmission station
KV	Kilovolt
Q_{min}	Minimum Mvar capability
Q_{max}	Maximum Mvar capability
n	number of busbars
V_i	Voltage magnitude at bus i
V_k	Voltage magnitude at bus k
V_{MAG}	Voltage magnitude
$V_{ANG(o)}$	Voltage angle expressed in degrees
ΔV_{MAG}	Difference in voltage magnitude
$\Delta V_{ANG(o)}$	Difference in voltage angle expressed in degrees
P_i	nominal real power at bus i
Q_i	nominal reactive power at bus i
Y_{ij}	Line admittance between buses i and j
P	Iteration count
*	Complex conjugate
P.U.	Per unit
ε	Precission/convergence index
Line	Line number
δij	Line flow between buses i and j
$\delta loss,ij$	Line loss between buses i and j
$Vs\angle\theta s$, $V_t\angle\theta t$, $V_r\angle\theta r$, $V_g\angle\theta g$	Polar unit voltage in pdar form
$a_{sr}\angle\phi sr$	Per unit transformation ratio in Polar form
r_{sr}	per unit series resistance
X_{sr}	per unit leakage reactance
q_{sr}	per unit reactive power flow from s to r
q_{rs}	per unit reactive power flow from r to s
$g_{sr} = Y_{sr}/(r^2_{sr} + X^2_{sr})$	Conductance
$b_{sr} = X_{sr}/(r^2_{sr} + X^2_{sr})$	Susceptance
a	Step up transformer tap ratio
QGs	Reactive power output of generator entering bus s
b_g	Susceptance of step up transformer (inverse of series of leakage

	reactance-not shown in figure)
ΔQflow	difference in reactive power flow
ΔQloss	difference in reactive power loss
FB	From bus/sending end bus
TB	To bus/receiving end bus.

1.0 INTRODUCTION

The power system chosen for this analysis is the interconnected network of National Electric Power Authority (NEPA) of Nigeria. The network serves the major load centers throughout the country. The grid spans approximately 800Km in the North to South of the Country and about 350 to 410Km in the East to West directions of the country. In effect, the grid covers approximately an area of about 520,000 square kilometres with a population of about 88.5 million people.

As at the time of study, NEPA has a total generating installed capacity of 5798MW from 71 units as seven major generating stations[1]. The energy source for the Nigerian power system are oil, gas for thermal generation and swift-flowing rivers for hydro-generation [2]. The thermal stations find favourable locations in the oil rich fuel abundant areas down-south in Sapele, Afam and Delta. Egbin power station is reasonably far from oil wells, but sited near energy consuming centre such as Lagos. The hydro station are naturally located up-north in Kainji, Shiroro and Jebba. There are also few other small stations located at Ijora, Ajaokuta, and Calabar.

At the transmission level, NEPA grid contains 4971 Km 330KV transmission lines and 4841 Km of 132 KV subtransmission lines[3]. While the peak load of 2,500.42MW occured on February 7, 1994. This maximum value is just about one-third of the total installed capacity. Inspite of this apparent surplus supply, NEPA is not able to conveniently cope with consumers' electric energy needs[4]. Many reasons have been proffered for this problem and one of them is the reactive power despatch problem which is worth investigating.

For efficient and stable power supply, both the real and reactive power balances as well as their energy balance are desirable[5]. The real power balance can be expressed as:

$$\Sigma P_g = \Sigma P_j + \Sigma P_{loss} \quad \text{.....1}$$

Equation (1) is complemented with the energy balance which determines the future consumption of fuel in the system and takes the form :

$$\Sigma Eg = \Sigma Ej + \Sigma E_{loss} \quad \text{.....2}$$

Like the active power, the reactive power of a power system must be balanced. The reactive power balance can be expressed as :

$$\Sigma Q_g + \Sigma Q_c + \Sigma Q_{tr} = \Sigma Q_t + \Sigma Q_{loss} \quad \text{..... 3}$$

The main difference between the reactive power balance and the real one is that the excess of reactive power in one part of the power system cannot always compensate for the same shortage of power in the other part. This is explained by the fact that the transmission of reactive power over long distances increases the following losses[6].

1. Active power loss during the period of maximum load demand in the generated output
2. Energy loss leading to increased expenditure of fuel in the system
3. Voltage drop in the system especially during maximum load demand period
4. Reactive power loss, and
5. Introduces high losses in the generators, transformers, switchgears, and busbars.

Because these losses have to be reduced to a barest minimum so as to enhance system stability, the reactive power flow control is very essential in power system operations.

This paper examines the reactive power flow and related characteristics of the Nigerian National 330KV Grid. Some of the additional objectives of the study include the following:

1. To identify buses where poor voltage regulations may contribute to system instability.
2. To determine the optimum locations and the various sizes of reactive power sources for satisfactory system operation.
3. To minimise system losses so as to improve the economic index of the National Grid.

The investigations were made by using existing FORTRAN digital computer program with necessary modifications. The Gauss-Seidel technique employing the polyphase admittance matrix is used in solving for the optimal reactive power despatch problem. The study is expected to show whether or not the Nigerian National 330KV Grid at the peak loading condition is satisfactory. In the light of these findings, necessary

modifications or adjustments are carried out by means of generator reactive currents and other control devices present, to minimise system losses, improved system voltage profiles, and enhanced system stability will be suggested.

In particular, the reactive power flow in the Nigerian National 330KV Grid will be thoroughly investigated and necessary suggestions for implementation made.

2.0 NODAL EQUATION AS A BASIS FOR LOAD FLOW STUDIES:

The nodal voltage techniques are the basis for the formation of the bus admittance matrix, a vital tool for load flow studies. To formulate the bus admittance, $Y_{bus,}$ consider the circuit shown in figure 1, containing variable potential and current sources.

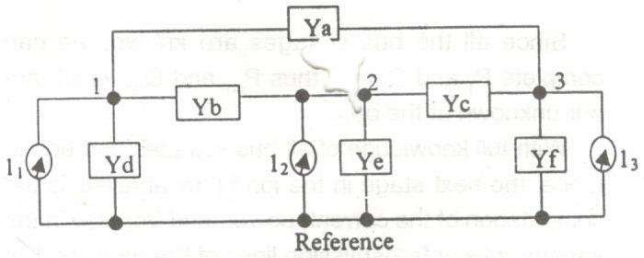


Figure 1: Circuit for Nodal Analysis

The nodal voltage equations are[7]

$$I_1 = (Y_a+Y_b+Y_d)V_1-Y_bV_2-Y_aV_3$$

$$I_2 = -Y_bV_1+(Y_b+Y_c+Y_e)V_2-Y_cV_3 \quad \text{.....4}$$

$$I_3 = -Y_aV_1-Y_cV_2+(Y_a+Y_c+Y_f)V_3$$

where $V_i = V_{1ref}$ = node voltages and i = 1,2,3

Equation 4 is expressed in matrix notation as follows:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} (Ya + Yb + Yd) - Yb - Ya \\ -Yb\ (Ya + Yc + Ye) - Yc \\ -Ya - Yc(Ya + Yc + Yf) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad \text{.....5}$$

or more concisely as :

$$I = [Y]\ V \quad \text{.....6}$$

Expanding this to the general case of i-node network, a set of hybrid equations based on a nodal analysis becomes:

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ \cdot \\ I_1 \end{bmatrix} = \begin{bmatrix} Y_{1i} & \ldots & Y_{1i} \\ Y_{21} & \ldots & Y_{2i} \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ Y_1 & \ldots & Y_{ii} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ V_i \end{bmatrix} \quad 7$$

The coefficient matrix of equation 7 may be referred to as the bus admittance matrix and is expressed as:

$$Ybus = \begin{bmatrix} Y_{11} & \ldots & Y_{1i} \\ Y_{21} & \ldots & Y_{21} \\ & & \\ Y_n & \ldots & Y_{ii} \end{bmatrix} \quad 8$$

Upon examining the relationship in equation 8 above, the following rules for finding the elements of the Y_{bus} matrix[8] are deduced.

1. The diagonal element Y_{ii} is obtained as the algebraic sum of all series admittance (those between buses) and shunt admittance (neutral bus) incident to bus i.
2. The off-diagonal element $Y_{ik}=Y_{ki,}$ are obtained as the negative of the admittance connecting nodes i and k.

In the case of π- representation of transmission circuits, the shunt susceptance would be included in the nodal admittance term as would the admittance of shunt reactors or the shunt elements of equivalent circuits as those representing tapped transformer.

3.0 METHOD OF SOLUTION

A number of load flow programs have been written for digital machines. They differ in some ways mainly by solution techniques and sophistication. In general, the less sophisticated programs will give satisfactory results that are of immediate value although more sophisticated ones will have increased accuracy.

Load flow equations in the Gauss-Seidel form are formulated, incorporating the generator buses whose reactive powers are to be maintained within prescribed limits.

For this iteractive technique, the complex voltage per phase at any bus i is given by :

$$(V_i)^{P+1} = \frac{1}{Yii}\left[\frac{(Pi - jQi}{(Vi)P} \sum_{k=1} YikVk^{p}\right] \quad \ldots 9$$

$$k = 1$$

for i = 2,3,.....n.

Y_{ij}, Y_{ii} are the elements of the familiar Y_{bus} matrix obtained from the power system network of the area being modelled.

The value for V_i on the right hand side of equation 9 are the best previous values for the corresponding buses. Note that as V_1 is known as priori, computations need only be performed for buses 2,3,....., n. The real and imaginary components of V_i^{P+1} are then multiplied by the ratio $V_i/V_i(P+1)$, thus complying with the constant V_i. The phase of V_i is thus found and the iteration can proceed to the next bus. The process continues until the value of V^{P+1} at any bus differ from V^P by a specified amount called the precision index, that is:

$$V_i^{P+1} - V_i^P \ll \epsilon \quad \ldots\ldots 10$$

Where ε is the precision index. A precision index of 1.0×10^{-4} is used for the loadflow study reported in this paper.

Equation 9 applies only to load buses where real and reactive powers are specified. An additional step is necessary at buses where voltage magnitude is to remain constant and reactive power unknown. This is called the generator bus. At the generator bus i where Qi is not known, an approximation for Qi is initially necessary. The approximation is derived from equation 9 as follows:

$$Y_{ii}\, V_i = \frac{P_i - {}_jQi}{Vi^*} \sum_{\substack{k=1 \\ i \neq k}} Y_{ik}\, V_k \quad \ldots\ldots 11$$

$$P_i - {}_jQi = (Y_{ii} V_i + \sum_{\substack{k=1 \\ i=k}} Y_{ik} V_k)\, V_i^* \quad \ldots\ldots 12$$

$$Q_i = \text{Im}\,[(Y_{ii} V_i + \sum_{\substack{k=1 \\ i=k}} Y_{ik} V_k)] \quad \ldots\ldots 13$$

Where the symbol Im means, "Imaginary part of." The reactive power Q_i is evaluated by equation 13 for the best previous value at the buses. The generator operating characteristics require us to stay within the capability range of the reactive generation source at the bus in question. Should it fall outside, then from that iteration Q_i assume the limit value. With Q_i thus fixed the bus in effect becomes a load bus and equation 9 is used to find a new V_i. The components of the new V_i are then multiplied by the ratio of the specified magnitude of V_i to the magnitude V_i found by equation 9.

The result is the corrected complex voltage of the specified magnitude.

The slack bus power can be calculated as follows :

$$P_1 - j\,Q_1 = V_1^* \sum_{k=1} Y_{ik} V_k \quad \ldots\ldots 14$$

Since all the bus voltages are known, we can complete P_1 and Q_1 a thus P_{G1} and Q_{G1} which are our unknown at the bus.

With full knowledge of all bus voltages and admittance, the next stage in the load flow analysis is the computation of the current, power, and Var flow in the various links or transmission lines of the network. For the line connecting the two buses i and j, the line powers S_{ij} and S_{ji} measured at buses i and j respectively and both defined positive into the line are obtained.

$$S_{ij} = P_{ij} + j\,Q_{ij} = V_i\, I_{ij}^* = V_i (V_i^* - V_j^*) Y_{ij}^* + V_i^2\, Y_{pi}^* \quad \ldots\ldots 15$$

$$S_{ji} = P_{ji} + j\,Q_{ji} = V_j\, I_{ji}^* = V_j (V_j^* - V_i^*)\, Y_{ji}^* + V_j^2 Y_{pj}^* \quad \ldots\ldots 16$$

Knowing line flows, the final step in the load flow analysis is the computation of the line losses on the various transmission lines. This is simply:

$$S_{loss},\, ij = S_{ij} + S_{ji} \quad \ldots\ldots 17$$

This completes the load flow study.

4.0 STEADY-STATE COMPONENT MODEL

One of the most critical steps in the reactive power analysis is the modelling of the system components[10]. To this end the mathematical models 11,12,13 is

presented in this section.

4.1 THE SYNCHRONOUS GENERATOR

Typically, generators are connected to the transmission system through a step-up transformer. Such an arrangement is illustrated in figure 2.

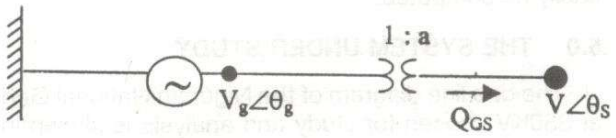


Figure 2: Circuit of a generator and step-up transformer

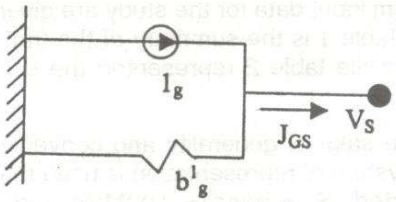


Figure 3: Norton is equivalent D.C. model for a regulating generator

The expression for the reactive power output of the generator at bus is :

$$Q_{Gs} = \frac{V_g V_s}{a}\cos(\theta_g - \theta_s)\, b_g - \frac{V_s^2}{a^2} b_g \quad \text{.....18}$$

The angular difference across the set-up transformer is typically small, thus

Cos $(\theta_g - \theta_s)$ can be assumed to be 1 with relatively little error. By taking advantage of this approximation and dividing both sides of equation 18 by V_s the ollowing reactive current' expression is obtained:

$$Q_{Gs}/V_s = V_g b_g/_a - V_s b_g/ a^2 \quad \text{.....19}$$

From equation 19 a Norton's equivalent circuit is derived and illustrated by figure 3. The terms of figure 3 are defined as follows:

$$I_g \cong V_g b_g/a \quad \text{.....20}$$

$$b'_g \cong b_g/a^2 \quad \text{.....21}$$

$$JG_s \cong QG_s/V_s \quad \text{.....22}$$

4.2 THE POWER TRANSFORMER

In order to introduce sufficient generality, the per phase model of a standard voltage transformer is shown in figure 4.

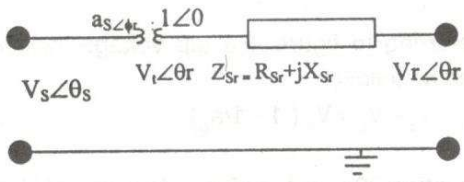


Figure 4: Transformer with Complex turn s ratio

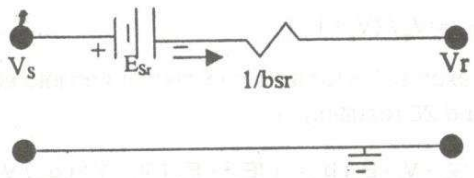


Figure 5: Linear Reactive model for a transformer.

The reactive power flow expressions viewed from both terminals are:

$$q_{sr} = \left[\frac{V_s^2}{asr2} - \frac{V_s V_r}{asr}\cos(\theta_s - \theta_r - \alpha_{sr})\right] b_{sr} - \left[\frac{V_s V_r}{asr}\sin(\theta_s - \theta_r - \alpha_{sr})\right] g_{sr} \quad \text{.....23}$$

$$q_{rs} = \left[\frac{V_r^2}{a_{sr}} - \frac{V_s V_r}{a_{sr}}\cos(\theta_r - \theta_s + \alpha_{sr})\right] b_{sr} - \left[\frac{V_s V_r}{a_{sr}}\sin(\theta_r - \theta_s + \alpha_{sr})\right] g_{sr} \quad \text{.....24}$$

It is a well known fact that angular differences across transmission circuits or transformers are typically small. In addition, the x/r ratio for transmission circuits and transformers is typically high. These observations permit equations 23 and 24 to be approximated to;

$$q_{sr} \cong \left[\frac{V_s^2}{a_{sr}2} - \frac{V_s V_r}{a_{sr}}\right] b_{sr} \quad \text{.....25}$$

and

$$q_{sr} \cong \left[\frac{V_r^2 - V_s V_r}{a_{sr}}\right] b_{sr} \quad \text{.....26}$$

From equation 26, it will be convenient to define a 'reactive current, F as follows:

$$F_{sr}\theta \frac{q_{sr}}{V_s a_{sr}2} \cong \frac{[V_s - V_r]}{a_{sr}} b_{sr} \quad \text{.....27}$$

$$F_{rs} \cong \frac{q_{rs}}{V_r} \cong \frac{[V_r - V_s]}{a_{sr}} b_{sr} \quad \text{.....28}$$

Referring to figure 4 a tap voltage increment is defined as follows:

$$E_{sr} \cong V_s - V_t = V_s (1 - 1/a_{sr}) \quad \text{..... 29}$$

Equation 29 is solved for a_{sr} in terms of V_s and E_{sr} giving:

$$a_{sr} = V_s / (V_s - E_{sr}) \quad \text{..... 30}$$

The expression for a_{sr} is now substituted into equation 27 and 28 resulting in :

$$F_{rs} = (V_s - V_r - E_{sr}) b_{sr} + 1 [E_{sr}^2 - E_{sr} (V_s - V_r)] b_{sr} / V_s \text{.....31}$$

and

$$F_{rs} \cong (V_r - V_s + E_{sr})b_{sr} \quad \text{.....32}$$

The second expression on the right hand side of equation 31 involves the difference of two second order terms, thus it may be neglected giving :

$$F_{rs} \cong (V_s - V_r - E_{sr})b_{sr} \quad 33$$

Equations 32 and 33 expresses the linear approximation of 'reactive current' flow viewed from both terminals of the transformer in figure 4. Note that the linear model of the transformer now resembles a circuit element with a series potential source representing the off-nominal transformer tap. The susceptance term, b_{rs}, now appears as a conductance term. The linear model is illustrated in figure 5.

4.3 THE TRANSMISSION LINE

The linear model for a transmission circuit is similar to that of a transformer but with E_{sr} set at zero. Line charging is included and represented by the familiar π-model. Figure 6 illustrates a transmission circuit where C_{sr} represents one half of the total line charging susceptance and appear as a negative conductance.

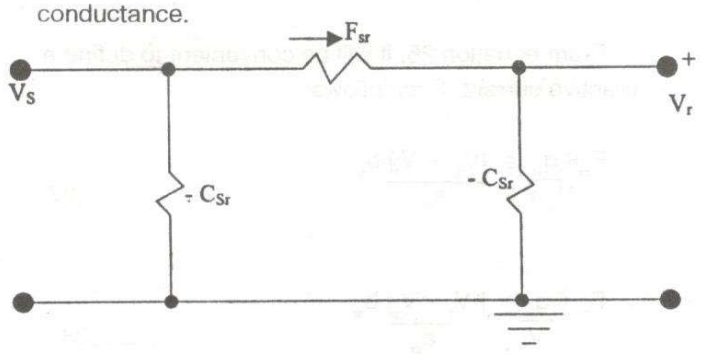


Figure 6: Linear Reactive model for Transmission circuit with line Charging.

Given the model for each component normally found in a modern power system, a single phase diagram of the system can be drawn and the corresponding net injected power equations as well as the interchange equations can be defined. As a result, the load flow studies for the power system network can easily be computed.

5.0 THE SYSTEM UNDER STUDY

The one line diagram of the Nigerian National Grid at 330KV chosen for study and analysis is shown in figure 7. It is a 26 bus system comprising seven major generator buses and 19 load points. The interconnections at lower voltage levels are regarded as loads. The system input data for the study are given in table 1 and 2. Table 1 is the summary of the transmission line data while table 2 represented the system bus data.

For the sake of generality and convenience, the per unit system of representation is used throughout. We selected: $S_3 \phi$ base = 100MVA and V_1 base = 330KV. The buses are numbered as indicated. They are not ordered consecutively. However, in more sophisticated studies as in larger systems, it has been shown that certain ordering of buses can produce faster convergence and solutions.[14]

The primary approach in this study is the solution of online load flow problem using the digital computer. The result gives the characteristics of the National Grid in steady state operation. For the purpose of this study, the following simplifying assumptions are made with regard to the National Grid :

1. All generators are connected directly to 330KV busbar
2. All generator transformers are lumped with their generators respectively
3. All shunt conductances are neglected

Note that the generator at bus 1 (Sapele Station) is selected as the slack bus. Actually, this is a tie to the neighbouring system. It is usually found that the choice of slack busbar affect the rate of convergence of the mathematical iteractive process. In some systems, Convergence can only be achieved by nominating the slack busbar at an unsuitable point in the system.[15] Note that δ at each bus is set to zero and the voltage at all non-generator buses 1.0. This is called a flat start, the voltage at generator buses will be held at the specified value unless a relative power limit is reached. Real and reactive powers are considered positive for watts and lagging vars generated or supplied and negative when received.

The following conditions were investigated:

1. Existing state of the NEPA 330KV Grid;
2. System changes: adding new reactor and capacitor banks (generating banks) to the existing NEPA 330Kv Grid.

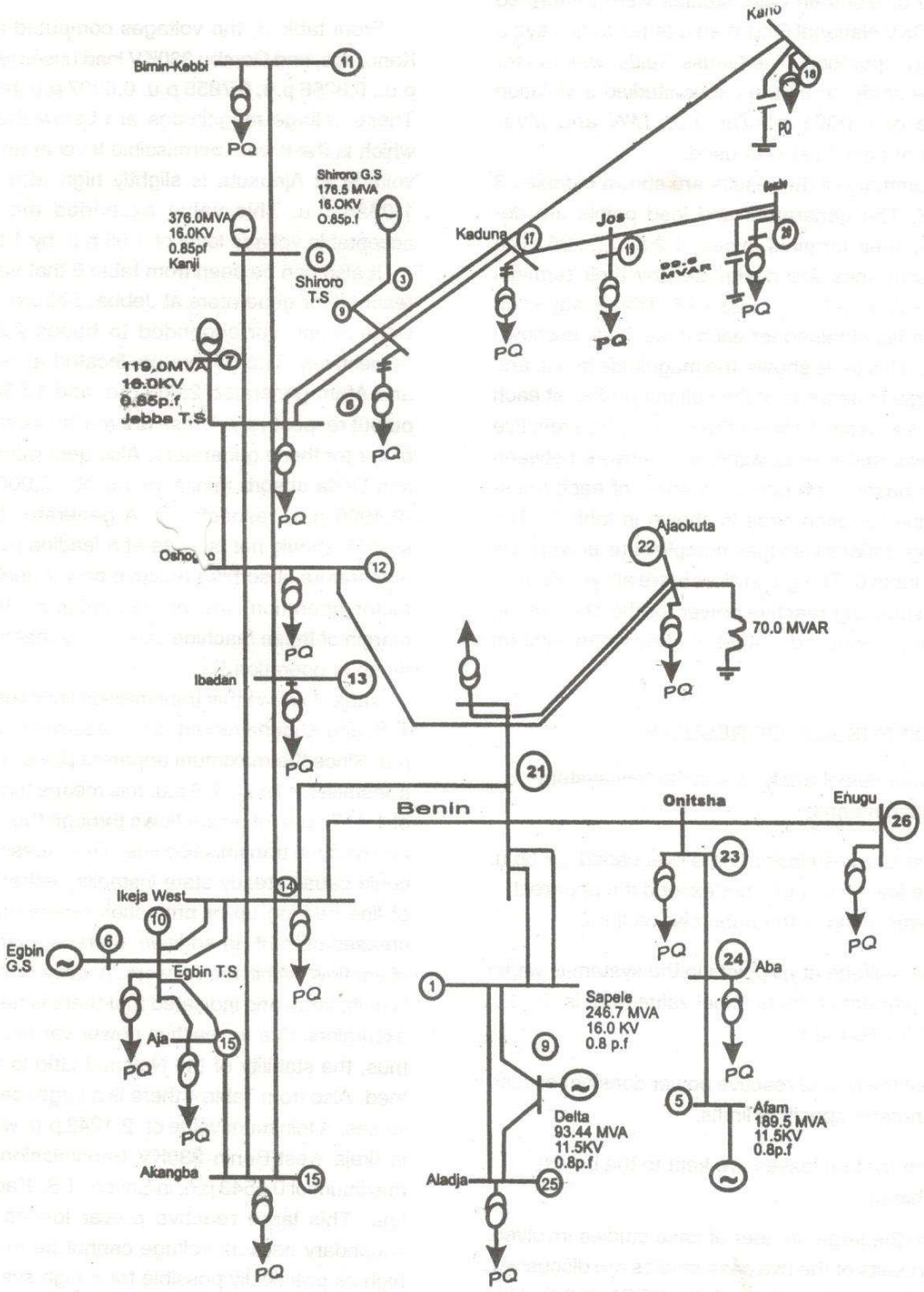


Fig. 7 The proposed locations of capacitor and reactor bank in the NEPA Grid (not drawn to scale)

6.0 COMPUTER RESULTS

A total of eighteen case studies were performed on the 330KV National Grid in an attempt to achieve a satisfactory operation. The Gauss-Seidel was run for each case study. In all the cases studied a violation tolerance of 0.0001 p.u.(or 0.01 MW and Mvar mismatch at each bus) was used.

The summary of the results are shown in tables 3 through 7. The generators and load points are described by their terminal buses, 1,2,3,.....,26. The transmission lines are designated by their terminal buses, 1 - 7, 1 - 21 .....,23 - 26. The steady state voltage profile obtained for each case study is shown in table 3. This table shows the magnitude in p.u. and phase angle in degrees of the voltage profile at each of the buses. Table 4 shows the steady state reactive power flows and losses within the network between the major buses. The percent loading of each transmission line for each case is shown in table 5. The generating stations with their complex bus powers are shown in table 6. The generators were allowed to pick the corresponding reactive power for the state of the load flow considered. Table 7 shows the system totals.

7.0 DISCUSSION OF RESULTS

For purposes of analysis satisfactory system operation means:

1. That no transmission line is overloaded, >7.6p.u. (the line flows does not exceed the apparent power rating of the transmission line).
2. That voltage at all points in the system is within ±5 percent of the nominal value (that is, $0.95 \leq |V_i| \leq 1.05$ p.u.)
3. That the flow of reactive power does not exceed generator specified limits.
4. That system losses are kept to the barest minimum.

Due to the large number of case studies involved, only the results of the two case studies are discussed, namely : the existing state of the NEPA 330KV Grid and the suggested NEPA 330KV Grid based on the recommendation arising from the study. Details of other case studies are reported in reference[16].

8.0 CASE STUDY ON THE EXISTING NEPA 330KV GRID

From table 3, the voltages computed at Kaduna, Kano, Jos, and Gombe 330KV load buses were 0.9025 p.u., 0.8268 p.u, 0.7858 p.u. 0.6397 p.u. respectively. These voltage magnitudes are below the 0.95 p.u. which is the lowest permissible level at any bus. The voltage at Ajaokuta is slightly high with a value of 1.0625 p.u. This value exceeded the maximum acceptable voltage level of 1.05 p.u. by 1.26%.

It also can be seen from table 6 that var limits are reached for generators at Jebba. Shiroro, Afam, and Delta which corresponded to buses 2,3,5, and 7 respectively. The generators located at Shiroro G.S. and Afam generated 2.600 p.u. and 1.5900 p.u. var output respectively. These are maximum rated values of var for these generators. Also generators at Jebba and Delta absorb minimum var of - 2.0000 p.u. and -2.4000 p.u. respectively. A generator in a power system should not operate at a leading power factor. Generators absorbing reactive power (leading power factor operation) are not desirable as the stability margin of these machines are easily reached in these mode of operation.[17]

Table 4 shows that transmission lines linking Shiroro T. S. and Kaduna recorded a line power flow of 9.0172 p.u. Since the maximum apparent power rating of the transmission line is 7.6 p.u. this means that an excess of 1.4172 p.u. of power flows through the Shiroro T.S. and Kaduna transmission line. The excess power flow could cause steady state instability either as a result of line heating up or protection operation due to increased current. In addition, there is a large quantity of var flow within the network. A value of 71.6479 p.u. is quite large and indicated that there is heavy voltage excursions due to reactive power var imbalance and thus, the stability of the National Grid is not guaranteed. Also from Table 4 there is a large reactive power losses. A minimum value of -2.1242 p.u. was recorded in Ikeja west-Benin 330KV transmission line and a maximum of 0.5543 p.u. in Shiroro T.S.-Kaduna 330KV line. This large reactive power losses mean that secondary network voltage cannot be maintained as high as practically possible for a high system loading during line outage. These effects show that the Nigerian National 330KV Grid once separated by a fault on sudden switching operation, without adequate care, becomes vulnerable and can easily collapse.

Considering again what constitutes a satisfactory system, the Nigerian National 330KV when operated under its present mode may be considered to be unsatisfactory. Recall that adding shunt capacitance would typically raise the system voltages whereas inductance normally lower the voltages. It is therefore necessary to add shunt capacitors and reactor at the most appropriate locations so as to restore the voltage levels.

In case studies 3-18, a number of possibilities were carried out with a view to improving the system operation. For instance the relatively large voltage deviations outside the permissible limits at Kaduna, Kano, Jos, Gombe, and Ajaokuta 330KV load buses are unhealthy for system operation. Also, excess line flows of 1.417 p.u. above the transmission line rating recorded in Shiroro T.S.- Kaduna line and its subsequent loss will mean partial collapse in the radial circuits supplying Kano, Jos, and Gombe. The 97.83% loading of Shiroro G.S.-Shiroro T.S. is too high. If the governors of the generators at Shiroro S. do not act in time to check drift in frequency due to loading, the generation from Shiroro G.S. may be lost. the general system may be worse for these possible outcome.

9.0 RECOMMENDED MODIFICATION TO THE 330KV NATIONAL GRID

The suggested NEPA 330KV Grid was obtained by adding shunt capacitor banks of values 97.5Mvar and 99.6Mvar to Kano and Gombe buses respectively and a shunt reactor bank of value 70.0Mvar at Ajaokuta bus.

From Table 3, it can be seen that all bus voltages are within tolerance with the highest bus voltage at Sapele (with a value of 1.05 p.u.) and lowest recorded at Kaduna load bus (0.9670 p.u.). These values fall within the 0.95 p.u.$\leq|V_i|\leq$ 1.05 p.u. permissible levels. Also, the voltage angles fell within $-90^0 < (\angle V_i - \angle V_j) < +90^0$ acceptable limits.The lowest voltage angle was recorded at Gombe with a value of -30.7214^0. The highest value of 0.5336^0 was registered at Delta. This goes to confirm that when the National Grid is operated in this mode, the security level would be guaranteed during contigencies.

As can be seen in Table 4, no transmission lines were overloaded. The highest percent loading of 95.67 occured along Shiroro T.S. - Kaduna 330KV line. Use of the recommended compensator schemes was also found to result in considerable reduction of the entire average loading of the Grid. For the uncompensated Grid, the total average loading was 32.507%. However, the compensated network recorded 30.674%.

Table 7 shows that the system losses were minimised. The real power losses reduced from 0.5975 p.u. to 0.4724 p.u. This resulted in a net of 0.1251 p.u.; about 20.84%. A big improvement in the reactive power losses was also achieved by the use of recommended compensator schemes. The reactive power losses decreased from - 14.9843 to - 16.9555 p.u. These values show that 1.970 p.u. (197.12 Mvar) of the reactive power in the Nigerian National Grid has been compensated. This represented 13.16%.

Furthermore, from Table 4 there is a major improvement in the reactive power flow picture in the National Grid. For uncompensated Grid, a reactive power flow of 10.4961 p.u. was found. When the Grid is compensated, the reactive power reduce to - 1.3543 p.u. representing a reduction of 11.8504 p.u. (or 112.90%).

10.0 SUGGESTIONS FOR IMPROVEMENT

In view of the escalating costs of constructing new generating plants and transmission lines it is imperative to optimise utilisation of existing facilities. Also, in order to achieve further improvement in voltage and eliminate system collapses consideration should be given to the following suggestions as outcomes of this research effort.

1. Reactive power support equipment as already identified should be installed. The shunt capacitor banks if installed at Kano and Gombe 330KV substations will regulate the local bus voltages while the reactor bank will reduce the voltage at the Ajaokuta 330KV load bus. A common feature of these control equipment relates to the fact that the bus voltage is strongly related to the reactive power injection at the bus.

Although not shown in the study, system stability and maximum extra high voltage transmission capability are normally improved upon by the use of switched series capacitors. In addition, switched series compensation decreases the fluctuation of load voltages by decreasing the angular swings caused by a disturbance.

2. The effects the reactive power flows have on generator operations are reflected in Table 6. Throughout the study, it was observed that Jebba and Delta

were absorbing vars to their minimum values. These phenomena are unhealthy for synchronous generator operations. Efforts should therefore be made to facilitate operation of some of the Jebba and Delta units as synchronous capacitors. This will provide reactive power compensation and improves the stability margins of these generating units.

3. There are at present no fast acting static var. compensator to automatically compensate reactive power flow as may be required for voltage regulation during peak load, light load or system distrubances. It is therefore recommended that thyristor controlled reactors and shunt capacitors at identified locations should be introduced. This will result to fast response time, flexibility of controls, continuous operation with virtually no maintenance, high reliability, and absence of inrush currents.

4. It is also recommended that instead of installing one reactor or capacitor at the identified locations two or more smaller ones equivalent in rating to the big one be installed. This will enable the compensating unit to be optimally used for voltage control especially at high load periods.

5. Arrangements on the provision of effective and reliable SCADA/EMS facilities at the National Control Center, Osogbo should be expedited. This will enchance remote control and monitoring of system parameters, over all Grid security, and more efficient Grid operations.

11.0 CONCLUSIONS

A method employing Gauss-Seidel technique has been used for the study of the reactive power flow and voltage profile in the Nigerian National 330KV Grid. As a result of this study, reallocation of reactive power sources in the Nigerian National 330KV Grid has been suggested.

The study has revealed that the installation of shunt capacitor banks of values up to 97.5Mvar and 99.60Mvar at Kano and Gombe buses respectively and a reactor bank of value 70.0Mvar at Ajaokuta bus were the most effective reinforcements. The proposed locations of these compensating units are shown in figure 1. When operated in this mode, the suggested Grid modification will operate satisfactorily with all bus voltages within tolerance, no transmissiion line is overloaded, low reactive power flows, low reactive power losses, etc and enchanced system stability.

To improve the analysis the impact of voltage constraints on the power system, it is clear that better operating tools need to be developed. These tools must take into account the changing system load as well as the changes in available energy.

Also, the study did not consider the saving in the cost of energy loss compared with the interest on, and depreciation in, the cost of additional capacitor and reactor installations for the same period. It is therefore suggested that an investigation into this should be undertaken.

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TABLE 1

SUMMARY OF TRANSMISSION LINE DATA IN P. U. ON SYSTEM BASES

P(Hz) = 50 BP (MVA)= 100 BV (KV) = 330 SRAT (MVA)= 76000

CSA (mm2)= 2x350 TYPES OF CONDUCTOR BISON

DB	FB	TB	Length	Series	Impedence	Shunt	Admittance
1	1	7	57.0	.00262	.01998	.0	.2666
*2	1	21	50.0	.00099	.00739	.0	.3928
3	1	25	63.0	.00248	.01861	.0	.2474
4	2	8	5.0	.00019	.00147	.0	.0196
5	3	9	5.0	.00019	.00147	.0	.0196
6	4	10	31.0	.00056	.00443	.0	.9632
7	5	24	25.0	.00098	.00738	.0	.0982
*8	6	8	81.0	.00153	.01197	.0	.6356
9	6	11	310.0	.01218	.09162	.0	1.2178
10	7	25	30.0	.00102	.00769	.0	.1022
*11	8	9	244.0	.00479	.03606	.0	1.9060
**12	8	12	157.0	.00210	.01528	.0	1.8348
*13	9	17	95.0	.00189	.01419	.0	.7544
*14	10	14	62.0	.00060	.00488	.0	.2296
15	10	15	77.0	.00303	.2276	.0	.3026
16	10	16	15.0	.00030	.00221	.0	.1180
17	12	13	115.0	.00424	.03232	.0	.4312
18	12	14	235.0	.00884	.06752	.0	.9712
19	12	21	231.0	.00970	.07380	.0	.9838
20	13	14	137.0	.00460	.03520	.0	.5400
*21	14	15	18.0	.00033	.00251	.0	.1332
*22	14	21	280.0	.00550	.04140	.0	2.2000
23	17	18	230.0	.00926	.07052	.0	.9410
24	17	19	197.0	.00809	.06089	.0	.8092
25	19	20	265.0	.01178	.08868	.0	1.1784
*26	21	22	195.0	.00383	.02882	.0	1.5320
27	21	23	137.0	.00538	.04050	.0	.5380
28	23	24	138.0	.00532	.04055	.0	.5410
29	23	26	96.0	.00362	.02718	.0	.3614

WHERE : THE NOTATION * DENOTES 2, NO TRANSMISSION LINES
THE NOTATION ** DENOTES 3 NO TRANSMISSION LINES

TABLE 2

SYSTEM INPUT BUS DATA

Bus No.	Type	Bus Voltage Magnitude (P.U.)	Voltage Angle (Degrees)	Bus Power P(MW) (P.U.)	Q(MVAR) (P.U.)	MVAR Power QMIN (P.U.)	Limit QMA (P.U.)
1	1	1.0500	.0	.0000	.0000	.0000	.0000
2	2	1.0000	.0	.9000	.0000	-2.0000	2.0000
3	2	1.0000	.0	1.5000	.0000	-1.2000	2.6400
4	2	1.0000	.0	2.2000	.0000	-2.6000	4.1200
5	2	.0000	.0	.7200	.0000	-1.4100	1.5900
6	2	1.0000	.0	2.3000	.0000	-3.0000	2.0000
7	2	1.0000	.0	.7000	.0000	-2.4900	3.4200
8	3	.0000	.0	.0790	.0593	.0000	.0000
9	3	.0000	.0	-1.0960	.8200	.0000	.0000
10	3	1.0000	.0	-.8000	.6000	.0000	.0000
11	3	1.0000	.0	-5640	-.4230	.0000	.0000
12	3	1.0000	.0	-1.4490	-1.0868	.0000	.0000
13	3	1.0000	.0	-1.3300	-9750	.0000	.0000
14	3	1.0000	.0	-3.3200	-2.4900	.0000	.0000
15	3	1.0000	.0	-2.2800	-1.7100	.0000	.0000
16	3	1.0000	.0	-9500	7125	.0000	.0000
17	3	1.0000	.0	-3.9000	-2.9284	.0000	.0000
18	3	1.0000	.0	-1.3000	9750	.0000	.0000
19	3	1.0000	.0	-6500	4875	.0000	.0000
20	3	1.0000	.0	-1.3280	.9960	.0000	.0000
21	3	1.0000	.0	-1.2420	.9330	.0000	.0000
22	3	1.0000	.0	-.2000	.1500	.0000	.0000
23	3	1.0000	.0	-.8600	.6450	.0000	.0000
24	3	1.0000	.0	2.6480	1.9800	.0000	.0000
25	3	1.0000	.0	.2000	.1500	.0000	.0000
26	3	1.0000	.0	.9000	.6750	.0000	.0000

WHERE : TYPE 1 DENOTES REFERENCE BUS
TYPE 2 DENOTES VOLTAGE CONTROL BUSES
TYPE 3 DENOTES LOAD BUSES

TABLE 3

COMPARISON OF BUS VOLTAGES

		Existing Grid		Suggested Grid		Differences	
Bus Number	Name of Station	VMAG	VANG(o)	VMAG	VANG(o)	ΔVMAG	ΔVANG(o)
1	Sapele	1.0500	0.0000	0.0500	0.0000	0.0000	0.0000
2	Jebba G.S.	1.0000	-2.2109	1.0000	-3.1632	0.0000	0.9523
3	Shiroro G.S.	1.0000	-8.5030	1.0000	-9.9962	0.0000	1.4932
4	Egbin G. S.	1.0000	-4.3555	1.0000	-5.1602	0.0000	0.8047
5	Afam	1.0000	-12.5052	1.0000	-13.3596	0.0000	0.8544
6	Kainji	1.0000	-1.0640	1.0000	-2.0147	0.0000	0.9507
7	Delta	1.0000	0.5336	1.0000	0.5336	0.0000	0.0000
8	Jebba T.S.	1.0026	-2.4864	1.0027	-3.4461	-0.0001	0.9597
9	Shiroro T.S.	0.9911	-8.8808	0.9969	-10.3759	-0.0058	1.4951
10	Egbin T.S.	0.9917	-5.0327	0.9912	-5.8250	0.0005	0.7923
11	Birnin Kebbi	1.0099	-4.1421	1.0099	-5.0931	0.0000	0.9510
12	Oshogbo	1.0076	-4.4367	1.0068	-5.2463	0.0008	0.8096
13	Aiyede	0.9863	-6.1901	0.9854	-6.9801	0.0009	0.7900
14	Ikeja West	0.9876	-5.6689	0.9867	-6.4254	0.0009	0.7565
15	Akangba	0.9839	-5.8837	0.9830	-6.6441	0.0009	0.7604
16	Aja	0.9899	-5.1441	0.9895	-5.9364	0.0004	0.7923
17	Kaduna	0.9025	-14.9226	0.9670	-16.2751	-0.0645	1.3525
18	Kano	0.8268	-21.5396	0.9829	-22.0684	-0.1561	0.5288
19	Jos	0.7858	-24.1482	1.0019	-23.7774	0.2161	-0.3708
20	Gombe	0.6397	-36.6873	1.0340	-30.7214	-0.3947	-5.9659
21	Benin	1.0439	-2.5537	1.0394	-2.7374	0.0045	0.1837
22	Ajaokuta	1.0626	-2.9930	1.0380	-3.0394	0.0246	0.0464
23	Onitsha	0.9968	-9.3671	0.9935	-9.9168	0.0033	0.3497
24	Aba	0.9865	-12.9067	0.9859	-13.7161	0.0006	0.8094
25	Aladja	1.0146	0.3107	1.0146	0.3107	0.0000	0.0000
26	Enugu	0.9793	-10.6988	0.9759	-11.2568	0.0034	0.5580

TABLE 4

COMPARISON OF TRANSMISSION LINE REACTIVE POWER FLOW AND LOSSES

Transmission line			MVar Flows			MVar Losses		
B/No.	From	To	Existing Grid	Suggested Grid	ΔQ flow	Existing Grid	Suggested Grid	ΔQloss
1	Sapele	Delta	2.5016	2.5016	0.0000	-0.1528	-0.1528	0.0000
2	Sapele	Benin	0.0928	0.4989	0.4061	-0.1362	-0.0827	-0.0535
3	Sapele	Aladja	1.8660	1.8660	0.0000	-0.1960	-0.1960	0.0000
4	Jebba G. S.	Jebba T. S.	-2.1340	-2.2084	0.0744	0.0003	0.0014	0.0011
5	Shiroro G. S.	Shiroro T. S.	5.3708	1.5026	3.8682	0.0620	0.0161	0.0459
6	Egbin G. S.	Egbin T. S.	1.0501	1.1653	-0.1152	-0.9091	-0.9079	-0.0012
7	Afam	Aladja	1.6337	1.7230	-0.0893	-0.0661	-0.0653	-0.0008
8	Kainji	Jebba T.S.	-0.7646	-0.7737	0.0091	-0.5859	-0.5853	-0.0006
9	Kainji	Birin Kebbi	-0.7763	-0.7764	0.0001	-1.1976	-1.1976	0.0000
10	Delta	Aladja	-1.9864	-1.9864	0.0000	-0.0744	-0.0744	0.0000
11	Jebba T. S.	Shiroro T. S.	-0.8778	-1.0385	0.1607	-1.5536	-1.5063	-0.0473
12	Jebba T.S.	Oshogbo	-1.5121	-1.4376	-0.0745	-1.7767	-1.7871	0.0104
13	Shiroro T. S.	Kaduna	5.1879	1.1295	4.0584	0.5543	0.0414	0.5129
14	Egbin T. S.	Ikeja West	0.4417	0.5437	-0.1020	-0.1972	-0.1988	0.0016
15	Egbin T. S.	Akangba	0.1063	0.1263	-0.020	-0.2833	-0.2834	0.0001
16	Egbin T. S.	Aja	0.5969	0.5972	-0.003	-0.1128	-0.1127	-0.001
17	Osogbo	Aiyede	0.3273	-0.3313	-0.0040	-0.3865	-0.3863	-0.0002
18	Osogbo	Ikeja West	-0.2376	-0.2334	-0.0042	-0.9542	-0.9530	-0.0012
19	Osogbo	Benin	0.9188	-0.8423	-0.0765	-1.0078	-0.9892	-0.0136
20	Aiyede	Ikeja West	-0.2666	-0.2625	-0.0041	-0.5237	-0.5224	-0.0013
21	Ikeja West	Akangba	1.1955	1.1761	0.0194	0.1186	-0.1183	-0.0003
22	Ikeja West	Benin	-2.1795	-2.0469	-0.1326	-2.1242	-2.0926	-0.0316
23	Kaduna	Kano	0.4815	-0.7618	1.2433	-0.4863	-0.7556	0.2693
24	Kaduna	Jos	1.2744	-1.0608	2.3352	-0.0635	-0.4971	0.4334
25	Jos	Gombe	0.8805	-1.0480	1.9285	-0.1027	-1.0416	0.9389
26	Benin	Ajaokuta	-1.5357	0.8020	-0.7337	-1.6855	-1.6518	-0.0337
27	Benin	Onitsha	0.06808	0.6485	0.0312	-0.1499	-0.1120	-0.0379
28	Onitsha	Aba	-0.1668	0.2389	0.0721	.0.4385	-0.4241	-0.0144
29	Onitsha	Enugu	0.3501	0.3533	-0.0032	-0.3228	-0.3201	-0.0027

TABLE 5

STEADY - STATE PERCENTAGE LOADING OF TRANSMISSION LINES

	Transmission Line		% Loading	
B/No	From	To	Existing Grid	Suggested Grid
1	Sapele	Delta	32.92	32.92
2	Sapele	Benin	87.18	94.30
3	Sapele	Aladja	24.56	24.56
4	Jebba G S	Jebba T S	48.50	49.92
5	Shiroro G S	Shiroro T. S.	97.83	64.78
6	Egbin G S	Egbin T.S.	39.83	39.96
7	Afam	Alaoji	26.36	26.67
8	Kainji	Jebba T. S.	28.44	28.64
9	Kainji	Birinin Kebbi	12.67	12.67
10	Delta	Aladja	26.35	26.35
11	Jebba T. S.	Shiroro T. S.	42.14	45.94
12	Jebba T.S.	Oshogbo	34.79	32.46
13	Shiroro T. S.	Kaduna	118.65	95.67
14	Egbin T. S.	Ikeja West	30.78	29.57
15	Egbin T. S.	Akangba	08.94	08.69
16	Egbin T. S.	Aja	14.79	14.79
17	Oshogbo	Aiyede	14.00	13.87
18	Oshogbo	Ikeja West	05.57	05.39
19	Oshogbo	Benin	13.91	14.13
20	Aiyede	Ikeja West	04.83	04.93
21	Ikeja West	Akangba	26.46	26.54
22	Ikeja West	Benin	34.82	35.21
23	Kaduna	Kano	18.65	20.03
24	Kaduna	Jos	32.10	29.64
25	Jos	Gombe	21.72	22.51
26	Benin	Ajaokuta	20.38	10.88
27	Benin	Onitsha	42.76	44.40
28	Onitsha	Alaoji	20.00	21.34
29	Onitsha	New Haven	12.77	12.78

TABLE 6

BUSBAR GENERATING CAPACITIES (P. U.)

B/No	Generating Station	Existing Grid	Suggested Grid
1	Sapele	-38.1522	-38.0116
2	Jebba	-2.0000[a]	-2.0000[a]
3	Shiroro G. S.	2.6400[a]	1.4918
4	Egbin G. S.	1.0427	1.1594
5	Afam	1.5900[a]	1.5900[a]
6	Kainji	-1.5414	-1.5506
7	Delta	-2.4900[a]	-2.4900[a]

a Var Limit Reached

TABLE 7

COMPARISION OF SYSTEM TOTALS

B/No	Parameter	Existing Grid	Suggested Grid	Difference
1	Real Power Generation P_a	9.5062	9.8669	-0.3607
2	Reactive Power Generation Q_a	-38.9109	-39.8210	0.9101
3	Real Power Load P_1	25.0960	25.0960	0.0000
4	Reactive Power Load Q_1	18.7985	16.1275	2.6710
5	Reactive Power Flows	10.4961	-1.3543	11.8504
6	Real Power Losses	0.5975	0.4724	0.1251
7	Reactive Power Losses	-14.9843	-16.9555	1.9712
8	Average % Loading	32.507	30.674	1.8330
9	Total capacitor banks MVar added	-	197.10	197.10
10	Total reactor MVar added	-	170.00	70.0