Available online at www.elixirpublishers.com (Elixir International Journal)

Electrical Engineering

Elixir Elec. Engg. 136 (2019) 53861-53866

ISSN: 2229-712X

Voltage Profile Improvement Using Static Var Compensator in Nigeria Power System

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ARTICLE INFO

Article history:
Received: 26 June 2019;
Received in revised form:
5 November 2019;
Accepted: 15 November 2019;

Keywords
Static Var Compensator,
Newton-Raphson,
Grid system,
Voltage violations,
PSAT.

ABSTRACT

The low voltage profile of the Nigeria grid results in poor voltage regulation in the network. The objective of this paper is to improve the voltage profile of the network using Static Var Compensator. The condition of the network was obtained through load flow technique. After performing load flow analysis, it was observed that some buses were violated that is, they were operating below the standard limit of 0.95 - 1.05 PU (313.5kV - 346.5kV). The Static Var Compensator is an important FACTS device which contains majorly a combined combination of the capacitor, inductor and the thyristor. The installation of SVC helped to improve the voltage profile of the affected buses to 1PU.

1. Introduction

The ordinary power flow or load flow problem is stated by specifying the loads in megawatts and mega vars to be supplied at certain nodes or bus bars of a transmission system and by the generated powers and the voltage magnitudes at the remaining nodes of this system together with a complete topological description of the system including its impedances. The objective is to determine the complex nodal voltages from which all other quantities like line flows, currents and losses can be derived. The model of the transmission system is given in complex quantities since an alternating current system is assumed to generate and supply the power to the loads. In mathematical terms the problem can be reduced to a set of nonlinear equations where the real and imaginary components of the nodal voltages are the variables. The number of equations equals twice the number of nodes. The non-linearities can roughly be classified being of a quadratic nature. Gradient and relaxation techniques are the only methods for the solution of these systems. The result of a power flow problem tells the operator or a planner of a system in which way the lines in the system are loaded, what the voltages at the various buses are, how much of the generated power is lost and where limits are exceeded. The power flow problem is one of the basic problems in which both load powers and generator powers are given or fixed. Today, this basic problem can be efficiently handled on the computer practically for any size of a system. In electric power system, significantly voltage change is affected by the load variation and the network topology changes. Voltage can drop considerably and even to a voltage collapse when the network is operating under heavy loading. When voltage drops highly, it will affect the phase voltage at the receiving end to become low, this case can affect performance of the equipment and possibly cause them damage [1]. Whereas when voltage collapse happens, it can operate under-voltage relay and other protection system, leading to extensive disconnection of load and thus affecting consumer loss. On the other hand, when the load level in the system is low, over-voltage can arise due to Ferranti effect. Capacitive over-compensation and over-excitation of synchronous machines can also occur [2]. Controlling voltage regulation is needed to inject or absorb reactive power to the network. Reactive power supports the buses which have voltage levels outside acceptable limits. FACTS (Flexible Alternating Current Transmission System) technology is used to maintain voltage profile when connected at the weakest bus by injection of current [3].

Static Var Compensator (SVC) is shunt connected static generators, whose outputs are varied so as to control specific parameter of the electric power system. The term "static" is used to indicate that SVC has no moving part.

2. Newton-Raphson Method

There are several methods of solving the resulting nonlinear system of equations. The most popular is known as the Newton-Raphson method which is an iterative technique for solving systems of simultaneous equations in the general form.

To set up the Newton-Raphson numerical method, we employ the power-flow expressions given by

$$P_i = \sum_{k=1}^{n} |\mathbf{Y}_{ik}\,\mathbf{V}_i\mathbf{V}_k| \cos(\theta_{ik} + \delta_k + \delta_i) \quad (1)$$

$$Q_i = \sum_{k=1}^{n} |\mathbf{Y}_{ik}\,\mathbf{V}_i\mathbf{V}_k| \sin(\theta_{ik} + \delta_k + \delta_i) \quad (2)$$

Let us assume that we have N buses and that all buses, except the slack bus (i = 1), are load buses with prescribed demands P_{di} and Q_{di}. Denoting the specified values $|V_1|$ and δ_1 for the slack bus, then each of the remaining buses in the network has the two state variables $|V_i|$ and δ_i to be determined by the power flow solution. The objective of the Newton-Raphson method is to produce values for $|V_i|$ and δ_i that will match the prescribed P_{di} and Q_{di} as determined from Equations (1) and (2). At each iteration of the method, new estimates of $|V_i|$ and δ_i for the non-slack buses (i = 2, 3, … , N) are generated. At the end of each iteration, the power mismatch is given by

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$\Delta P_i = P_{i,sch} - P_i$, (3)
$\Delta Q_i = Q_{i,sch} - Q_i$. (4)

Expanding equation 1 and 2 in Taylor's series result in the following set of linear equations given below:

$$\begin{pmatrix} \Delta P_2^k \\ \Delta P_n^k \\ \Delta Q_2^k \\ \Delta Q_n^k \end{pmatrix} = \begin{pmatrix} \frac{\partial P_2}{\partial \delta_2}^k \cdots \frac{\partial P_2}{\partial \delta_n}^k \frac{\partial P_2}{\partial V_2}^k \cdots \frac{\partial P_2}{\partial V_n}^k \\ \frac{\partial P_n}{\partial \delta_2}^k \cdots \frac{\partial P_n}{\partial \delta_n}^k \frac{\partial P_n}{\partial V_2}^k \cdots \frac{\partial P_n}{\partial V_n}^k \\ \frac{\partial Q_2}{\partial \delta_2}^k \cdots \frac{\partial Q_2}{\partial \delta_n}^k \frac{\partial Q_2}{\partial V_2}^k \cdots \frac{\partial Q_2}{\partial V_n}^k \\ \frac{\partial Q_n}{\partial \delta_2}^k \cdots \frac{\partial Q_n}{\partial \delta_n}^k \frac{\partial Q_n}{\partial V_2}^k \cdots \frac{\partial Q_n}{\partial V_2}^k \end{pmatrix} \begin{pmatrix} \Delta \delta_2^k \\ \Delta \delta_n^k \\ \Delta V_2^k \\ \Delta V_n^k \end{pmatrix} \quad (5)$$

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^k$ and voltage magnitude ΔV_i^k with small changes in real and reactive power ΔP_i^k and ΔQ_n^k. Elements of the Jacobian matrix are the partial derivatives of equations (1) and (2), evaluated at $\Delta\delta_i^k$ and ΔV_i^k or the voltage controlled buses, the voltage magnitudes are known. Therefore if m buses of the system are voltage controlled, m equations involving ΔQ and ΔV and the corresponding column are eliminated. Accordingly, there are n – 1 real power constraint and n – 1 – m reactive power constraints and the Jacobian matrix is of the order (2n – 2 – m) * (2n – 2 – m). J_1 is the order (n – 1) * (n – 1), J_2, is of the order (n – 1) * (n – 1 – m), J_3 is of the order (n – 1 – m) * (n – 1), and J_4 is of the order (n – 1 – m) * (n – 1 – m)

The diagonal and the off diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j\neq 1} V_i * V_j * Y_{ij} * \sin(\theta_{ij} - \delta_i + \delta_j)$$

$$\frac{\partial P_i}{\partial \delta_j} = -V_i * V_j * Y_{ij} * \sin(\theta_{ij} - \delta_i + \delta_j)$$

The diagonal and the off diagonal elements of J_2 are

$$\frac{\partial P_i}{\partial V_j} = 2 * V_i * Y_{ij}\cos\theta_{ii} + \sum_{j\neq 1} V_j * Y_{ij} * \cos(\theta_{ij} - \delta_i + \delta_j)$$

$$\frac{\partial P_i}{\partial V_j} = V_i * Y_{ij} * \cos(\theta_{ij} - \delta_i + \delta_j)$$

The diagonal and the off diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j\neq 1} V_i * V_j * Y_{ij} * \cos(\theta_{ij} - \delta_i + \delta_j)$$

$$\frac{\partial Q_i}{\partial \delta_j} = -V_i * V_j * Y_{ij} * \cos(\theta_{ij} - \delta_i + \delta_j)$$

The diagonal and the off diagonal elements of J_4 are

$$\frac{\partial P_i}{\partial V_j} = -2 * V_i * Y_{ij}\sin\theta_{ii} - \sum_{j\neq 1} V_j * Y_{ij} * \sin(\theta_{ij} - \delta_i + \delta_j)$$

$$\frac{\partial P_i}{\partial V_j} = -V_i * Y_{ij} * \sin(\theta_{ij} - \delta_i + \delta_j)$$

The approximate errors from (5) are added to the initial estimates to produce new estimated values of node voltage magnitude and angle for (i = 1,2,3) and (k = 1,2,……..,n).

$$|V_i^{k+1}| = |V_i^k| + \Delta|V_i^k| \quad (6)$$

$$|V_i^{k+1}| = |V_i^k| + \Delta|V_i^k| \quad (7)$$

Flexible Alternating Current Transmission System

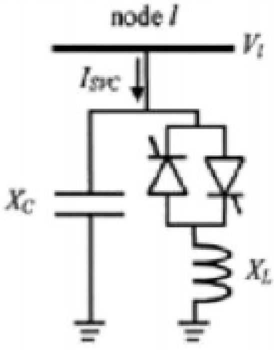

Fig 1. Static Var Compensator (SVC).

Static Var Compensators (SVCs) control specific parameters of the electrical power system (typically bus voltage). The control strategy with SVC is to keep the transmission bus voltage within a certain narrow limits defined by a controller droop and the firing angle $\propto$ limits ($90^o < \propto < 180^o$). With balanced fundamental frequency operation, an adequate transient stability model can be developed assuming sinusoidal voltages. This model can be represented by the set of p.u. equations;

$$[x_c', \propto']^T = f(x_c, \propto, V, V_{ref}) \quad (8)$$

$$B_e - \frac{\left(2\propto - \sin\propto - \pi\left(2 - \frac{X_L}{X_C}\right)\right)}{\pi X_L} = 0 \quad (9)$$

$$I_{SVC} - V_i B_e = 0 \quad (10)$$

$$Q_{SVC} - V_i^2 = 0 \quad (11)$$

Where $f(x_c, \propto, V, V_{ref})$ stands for the control system variables and equations respectively, V is the controlled bus voltage magnitude, V_i represents the TCR and the fixed capacitor voltage magnitude, V_{ref} is the controller point, X_{SL} is the droop, Q_{SVC} and I_{SVC} are the controller reactive power and current respectively, B_e is the equivalent susceptance of the TCR and the fixed capacitor combination, X_C and X_L corresponds to the fundamental frequency reactance of L and C, respectively.

In order words, the power flow equations for SVC are;

$$V - V_{ref} + X_{SL} I = 0 \quad (12)$$

$$B_e - \frac{\left(2\propto - \sin\propto - \pi\left(2 - \frac{X_L}{X_C}\right)\right)}{\pi X_L} = 0 \quad (13)$$

$$I_{SVC} - V_i B_e = 0 \quad (14)$$

$$Q_{SVC} - V_i^2 = 0 \quad (15)$$

For the power flow model to be complete, all SVC controller limits will be adequately represented. SVC limit is the firing angle $\propto$; i.e $\propto \epsilon [\propto_m, \propto_M]$; where $\propto_m$ is the minimum firing angle and $\propto_M$ is the maximum firing angle. V_{ref} is fixed at V_{ref}^0 until $\propto$ reaches a limit at which point V_{ref} is allowed to change while $\propto$ is kept at its limit value. Voltage control is regained when V_{ref} returns to V_{ref}^0.

In the above 41 bus 330kV network, Egbin is used as the Slack or swing Bus, with 13 other Generators buses, 27 loads buses and 63 Transmission lines.

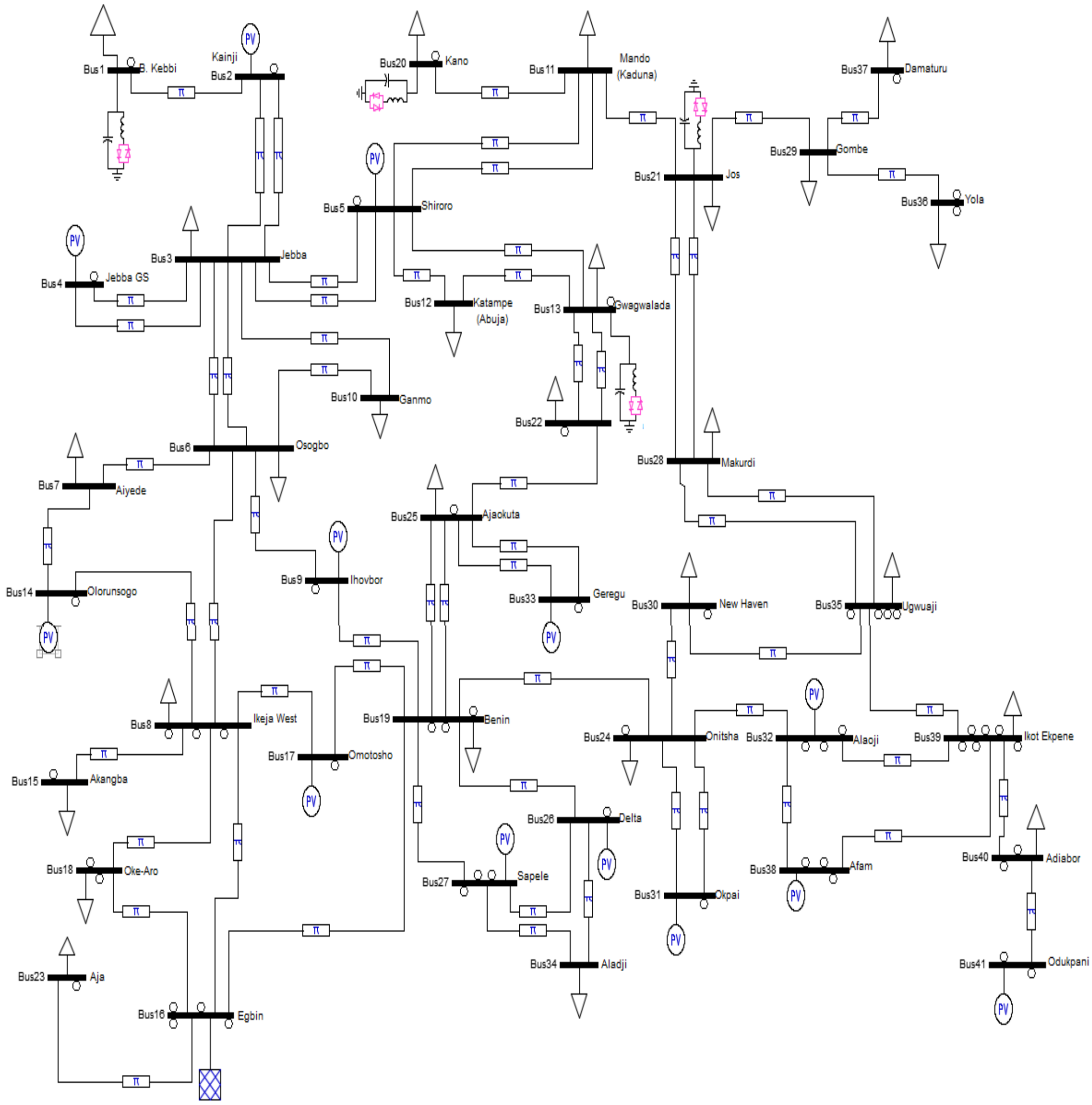

Fig 2.Modeled 41 Bus 330kV Nigerian Super Grid System – SVC connected.

Flexible Alternate Current Transmission System (FACTS) devices such as Static Var Compensator (SVC) is a device that can quickly and reliably control bus voltages. SVC devices will typically regulate and control the voltage to the required set point under normal steady state and thereby provide dynamic, fast response to reactive power following system violation such as under voltage or over voltage. The buses where the SVCs are connected are Kebbi, Gwagwalada, Kano and Jos.

3. Data and Simulation

The Simulation software used in this work is Power System Analysis Toolbox (PSAT). PSAT is a MATLAB toolbox for electric power system analysis and simulations. PSAT computational engine is purely MATLAB – based and the Simulink environment is used only as graphical tools. A comprehensive load flow analysis of the Network was carried out to pinpoint the weaknesses in the Network. Newton Raphson technique was employed to carry out this load flow analysis.

4. Results and Discussions

The results of the load flow analysis of the base case from the collected data of table 1 shows that there are voltage violations at some of the buses as shown in Table 2. These results are based on the Nigerian operating voltage range of (0.95 - 1.05 P.U) of 330kV.

Figure 3 shows the voltage profile of the network when SVCs were not connected to the network (Base Case) and also when SVCs are connected to the network. The standard operating range of voltages is between 0.95PU – 1.05PU (313.5kV – 346.5kV). The buses that fell below operating voltage are Birni-Kebbi, Gwagwalada, Kano, Jos, Makurdi, Gombe, New Haven, Ugwuaji, Yola and Damaturu. The Static Var Compensator was optimally connected to some buses that were below the operating voltage which are Birni-Kebbi, Gwagwalada, Kano and Jos.

5. Conclusions and Recommendation

This paper attempts to improve the voltage profile of the buses that are operating below the operating limit. In order to estimate the voltage profile, load flow simulation was performed on the network. From the result of the simulation, we observed a total number of ten violations. After strategically connecting SVCs we observed that the violated buses had been corrected.

In other to clear transmission lines violations, other options like application of FACTs (TCSC) and combination of the two are recommended.

Table 1. Bus Data for the 41-Bus Network

S/N	Bus Name	Nom. kV	Volt. Mag. PU	Actual Volt (kV)	Angle (Deg)	Load		Generation	
						MW	Mvar	MW	Mvar
1	B. Kebbi	330	1	322	0	162	122	-	-
2	Kainji	330	1	330	0	89	67	292	143
3	JebbaTs	330	1	339	0	260	195	-	-
4	JebbaGs	330	1.030	340	0	-	-	460	225
5	Shiroro	330	1	330	0	328	246	450	220
6	Osogbo	330	1	337	0	127	95	-	-
7	Aiyede	330	1	320	0	174	131	-	-
8	Ikeja West	330	1	325	0	847	635	-	-
9	Ihovbor	330	1	330	0	-	-	337	165
10	Ganmo	330	1	332	0	100	75	-	-
11	Mando	330	1	316	0	142	107	-	-
12	Katampe	330	1	319	0	303	227	-	-
13	Gwagwalada	330	1	326	0	220	165	-	-
14	Olorunsogo	330	0.961	317	0	157	117	266	130
15	Akangba	330	1	311	0	203	152	-	-
16	Egbin	330	1.012	334	0	-	-	0	0
17	Omotosho	330	1	330	0	262	196	304	149
18	Oke-Aro	330	1	320	0	120	90	-	-
19	Benin	330	1	333	0	144	108	-	-
20	Kano	330	1	305	0	194	146	-	-
21	Jos	330	1	324	0	72	54	-	-
22	Lokoja	330	1	320	0	120	90	-	-
23	Aja	330	1	318	0	115	86	-	-
24	Onitsha	330	1	329	0	100	75	-	-
25	Ajaokuta	330	1	320	0	120	90	-	-
26	Delta	330	1.012	334	0	-	-	480	235
27	Sapele	330	1.012	334	0	128	96	240	117
28	Makurdi	330	1	326	0	160	120	-	-
29	Gombe	330	1	302	0	68	51	-	-
30	New Haven	330	1	328	0	196	147	-	-
31	Okpai	330	1.012	334	0	-	-	400	196
32	Alaoji	330	1	330	0	227	170	240	117
33	Geregu	330	1	330	0	200	150	385	188
34	Aladja	330	1	330	0	210	158	-	-
35	Ugwuaji	330	1	328	0	175	131	-	-
36	Yola	330	1	302	0	26	20	-	-
37	Damaturu	330	1	302	0	24	18	-	-
38	Afam	330	1.003	331	0	534	401	580	284
39	Ikot Ekpene	330	1	328	0	165	124	-	-
40	Adiabor	330	1	328	0	90	68	-	-
41	Odukpani	330	0.994	328	0	-	-	360	176

Table 2. Bus Voltage Violations.

S/N	Bus No.	Voltage (kV)	Bus Violation type
1.	1	293.2535545	under voltage
2.	13	307.8620548	under voltage
3.	20	303.0401725	under voltage
4.	21	273.7928104	under voltage
5.	28	270.7862923	under voltage
6.	29	234.0070032	under voltage
7.	30	284.0169595	under voltage
8.	35	282.2990359	under voltage
9.	36	226.5181473	under voltage
10.	37	228.0053515	under voltage

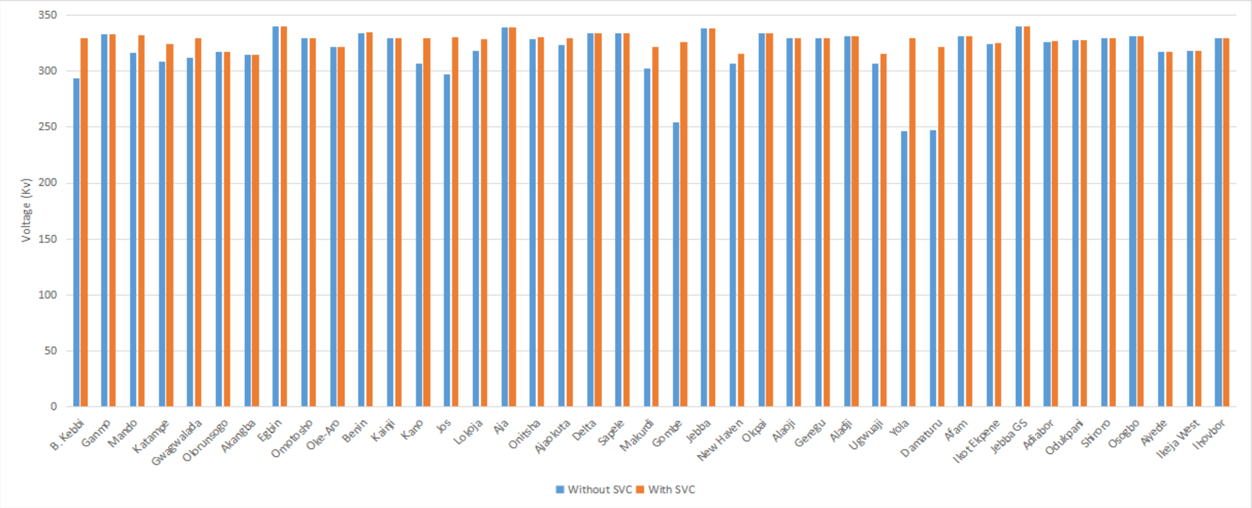

Fig 3. Voltage profile comparison before and after connection of SVCs.

Table 3. Voltage profile comparison before and after connection of SVCs.

S/N	Bus Name	Operating Limit	Without SVC (kV)	With SVC (kV)
1	B. Kebbi	313.5-346.5	293.2535545	330
2	Ganmo	313.5-346.6	332.8976567	332.8869819
3	Mando	313.5-346.7	316.4683475	332.4268952
4	Katampe	313.5-346.8	308.8993499	324.0376269
5	Gwagwalada	313.5-346.9	312.1427811	330
6	Olorunsogo	313.5-346.10	317.13	317.13
7	Akangba	313.5-346.11	314.6075441	314.5781556
8	Egbin	313.5-346.12	340.23	340.23
9	Omotosho	313.5-346.13	330	330
10	Oke-Aro	313.5-346.14	321.9000881	321.8723752
11	Benin	313.5-346.15	333.8093035	335.073108
12	Kainji	313.5-346.16	330	330
13	Kano	313.5-346.17	307.2163877	330
14	Jos	313.5-346.18	297.4608205	330.3049961
15	Lokoja	313.5-346.19	318.0531074	328.3109171
16	Aja	313.5-346.20	338.9083839	338.9083839
17	Onitsha	313.5-346.21	328.3518665	330.0745561
18	Ajaokuta	313.5-346.22	323.5701003	329.502789
19	Delta	313.5-346.23	333.96	333.96
20	Sapele	313.5-346.24	333.96	333.96
21	Makurdi	313.5-346.25	302.0607729	322.0995933
22	Gombe	313.5-346.26	254.2357306	326.4174834
23	Jebba	313.5-346.27	338.0659405	338.0623518
24	New Haven	313.5-346.28	306.9843271	315.4970011
25	Okpai	313.5-346.29	333.96	333.96
26	Alaoji	313.5-346.30	330	330
27	Geregu	313.5-346.31	330	330
28	Aladji	313.5-346.32	330.9198767	330.9198754
29	Ugwuaji	313.5-346.33	306.6313599	315.8016645
30	Yola	313.5-346.34	246.0995008	330
31	Damaturu	313.5-346.35	247.7152664	322.0131526
32	Afam	313.5-346.36	330.99	330.99
33	Ikot Ekpene	313.5-346.37	324.4247122	325.5987623
34	Jebba GS	313.5-346.38	339.9	339.9
35	Adiabor	313.5-346.39	326.4105323	326.6554664
36	Odukpani	313.5-346.40	328.02	328.02
37	Shiroro	313.5-346.41	330	330
38	Osogbo	313.5-346.42	331.3148039	331.294532
39	Aiyede	313.5-346.43	316.9951596	316.9678836
40	Ikeja-West	313.5-346.44	317.8800417	317.85097
41	Ihovbor	313.5-346.45	330	330

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