Enhancing Loadability of Transmission Lines Using Series Compensation (Facts) Device in Nigeria Network

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Abstract -- This work studied the presence of reactive component of power in the transmission line which enhances congestion of the transmission line leaving little room for active power flow. The Nigerian Bus system operated at 330kV with 41 buses was used to evaluate voltage drop index for load buses as active power varied at constant reactive power values. The study is to improve the nodal voltage profile of the electric networks and improve the real power transfer capacity (loadability) of congested power system transmission lines at stable voltages using FACTS devices (SVC and TCSC). And to achieve this, load flow analysis was carried out at various load varying cases for the Nigerian bus grid system operated at 330kV using NEPLAN simulator. With power varied from a base case through five steps of 10% increment from the previous, the result of the total voltage drop index ranked Yola, as can be seen in descending order as the optimal locations for series compensation. Aided with this ranking, load flow analyses were executed for the individual and simultaneous series compensation at these buses. Each of the compensated cases when compared with the base case bus load flow tabular and bar chart results showed significant improvement due to the compensation.

Indexed Terms: FACTS, TCSC, SVC, LOADABILITY.

I. INTRODUCTION

Both Human population and industrialization growth has pushed electrical energy demand, subjecting the electric power system network configuration and operation to excessive stress. One of the major challenges prevalent in our (Nigeria) power system is the fact that the system thrives on what is being generated at the source in meeting up with the excessive load demand (reactive and active) without adequate compensation. And when there are much reactive loads on the power system without adequate compensation, the possibility of the systems operating near their thermal limits, transmission lines being congested and overloaded, losses in transmission lines, voltage violation at the buses, and eventual system collapse.

Alleviating this stress for reliable system operation is an enormous challenge. The ability to transfer active power from production sources to consumption or load centres during steady operating conditions is a major aspect of voltage stability. In meeting this challenge, innovations driven by economy, efficiency and security for high level of operational and component reliability have been made in the electric power sector with impacts that are both short and long termed. The general consensus among academicians, practitioners and policy makers is that direct access to the transmission grid is indispensable for competitive electricity market (Shmuel, 1998).

II. TRANSMISSION LINE LOADABILITY CONSTRAINTS

Power is transmitted when the line voltage causes current to flow in the conductors. In other words, the amount of power an individual line carries is proportional to the product of the current and the voltage. However, every transmission line is limited in the amount of power it can transmit by constraints on voltage and current. Flows of reactive power limit both the voltage and current capacity in a transmission line (John, 1989). The main constraints to power transfer capability of transmission lines according to Bakshi & Bakshi (2009) are:

- Thermal limits
- Voltage drop limits or regulation limit and,
- Stability limit

Again, transmission lines' overloading, congestion and stress can also occur as a result of network location concentration between generation and load.

Flexible Alternating Current Transmission Systems (FACTS) was developed and deployed as a sustainable short term measure to control system operation by ensuring voltage stability and increasing transmission line transfer capacity and it is currently incorporated in the implementation of Electric Power System Smart Grids. FACTS are of various types based on the desired function but to achieve increased transmission transfer capacity with economic considerations, a FACTS type; the Static Var Compensator (SVC) and the Thyristor-Controlled Series Capacitor (TCSC) is proposed. The SVC and TCSC have the same circuitry and component but defer by their mode of incorporation to the power system. The SVC is a shunt connected device and it is a variable shunt reactance, injecting or absorbing reactive power for voltage regulation and stability. The TCSC being a series connected device, is a variable reactance device placed in series to the transmission line with the ability to modify the line reactance and by extension the impedance thereby controlling the power flow through the transmission line. Its presence and operation provides an opportunity to relieve heavily loaded and stressed lines while increasing the transmission corridor or transfer capacity margin so that more power (real) can be transferred via the transmission line.

According to Glanzmann & Andersson (2005), in order to truly investigate singular or combined impacts of these devices in the steady state operation of the power grid into which they are incorporated, models that accurately capture their local and neighbouring influences on line power flows and bus voltages are indispensable. The mutual influences among the devices can arise possibly resulting to adverse interaction (Larsson, Rehtanz, & Westermann, 2004; Li, Li, & Zheng, 2001).

III. FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS (FACTS)

FACTS are recent technologies that employ high speed thyristors for switching in and out of transmission line components such as capacitors, reactors or phase shifting transformers to attain certain system desirable performance criteria (Wadhwa, 2013). The Institute of Electrical Electronics Engineering, IEEE defines FACTS as a power electronic based system and other static equipment that provide control of one or more ac transmission system parameters to enhance controllability and increase power transfer capability. FACTS devices are found to be very effective in the utilization of existing facilities of a transmission networks without sacrificing the desired stability margin (Rai, Arora, & Naimul, 2014). In other words, it can be effectively used for improved system stability limit, power flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability. Then according to Gönen (2014), the basic purpose is to minimize the bottlenecks in existing transmission systems and improve the availability, reliability, stability, and quality of the power supply.

In general, FACTS controllers can be divided into four categories (Kothari & Nagrath, 2003), namely, Series, Shunt, Series-Series and Series-Shunt respectively. For the purpose of this study, focus will be on Series and Shunt controllers respectively.

3.1 Series Controllers:

Series controllers inject voltage in series with the line. If the voltage is in phase quadrature with the line, the series controllers only supplies or consumes variable reactive power (Kothari & Nagrath, 2003; Singh, 2011; Essays, UK, 2013). They include SSSC, IPFC, TCSC, TSSC, TCSR and TSSR. They can be effectively used to control current and power flow in the system and to damp system's oscillations (Bakshi & Bakshi, 2009; Singh, 2011; Essays, UK, 2013).

3.2 Shunt Controllers:

In practice, all shunt controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage cause a current flow and hence represent injection of current into the line. The reactive power injected can be varied by varying the phase of the current. They may be variable impedance, variable source or a combination of the two (Singh, 2011). The examples are Static Synchronous Generator (SSG), Static VAR Compensator (SVC).

IV. THYRISTOR-CONTROLLED SERIES CAPACITOR (TCSC)

Thyristor Controlled Series Capacitor (TCSC) is one of the important members of FACTS family that is increasingly applied to long transmission lines of power system by modern utilities. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub- synchronous resonance (SSR); damping the power oscillation; and enhancing transient stability (Murali, Rajaram, & Reka, 2010).

TCSC is a series controlled capacitive reactance with a combination of TCR and a fixed capacitor which allow the capacitive reactance to be smoothly controlled over a wide range to provide continuous control of power on the ac line (Alok & Amar, 2013).

The main circuit of a TCSC model is shown in Fig.1

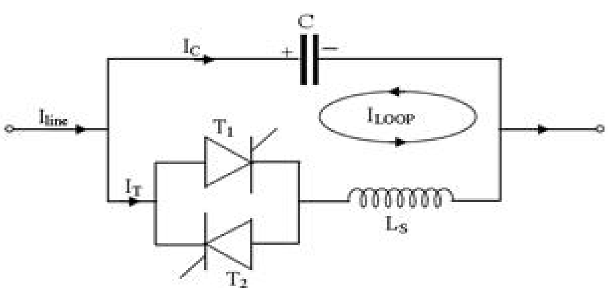


Fig. 1: TCSC Model (Baskshi, 2009)

According to Yu (2009), TCSC is used in power systems to dynamically control the reactance of a transmission line so as to provide sufficient load compensation. As part of the benefits, TCSC has the ability to control the amount of compensation of a transmission line, and as well, can operate in different modes. TCSC finds its usefulness in the network since power system loads are constantly changing and cannot always be predicted.

The modes of operation as cited by Yu (2009) include:

- Blocking mode: Thyristor valve is always off, opening inductive branch, and effectively causing the TCSC to operate as Fixed Series Capacitor (FSC).
- Bypass mode: Here, the thyristor valve is always on, causing TCSC to operate as capacitor and inductor in parallel, reducing current through TCSC.
- Capacitive boost mode: Forward voltage thyristor valve is triggered slightly before capacitor voltage crosses zero to allow current to flow through inductive branch, adding to capacitive current. This effectively increases the observed capacitance of the TCSC without requiring a larger capacitor within the TCSC.

TCSC allows for increased compensation simply by using a different mode of operation, as well as limitation of line current in the event of a fault. TCSC also has the capability of damping of sub synchronous resonance caused by torsional oscillations and inter-area oscillations. This feature promotes transfer of more power, and the possibility of connecting the power systems of several areas over long distances (Yu, 2009).

While the static VAR compensator (SVC) can be used for stability improvements, it is in general not well suited for increasing transfer capacity over congested lines. It is primarily used for reactive compensation of long transmission lines which is why it is proposed in this study.

To control power flow for increased transfer capability, the thyristor controlled series capacitor (TCSC) or the unified power flow control (UPFC) are best suited. The UPFC is the most versatile device and can be used in all areas, but it is also the most expensive (Shaffner & Anderson, 2002).

In addition to the above mentioned features of TCSC and SVC, the choice of TCSC/SVC was also based on the simplicity of the design, the implementation cost and the fact that SVC are mainly used for fast reactive power control and compensation of fast changing loads.

V. POWER FLOW MODEL MAXIMUM POWER TRANSFER OF TRANSMISSION LINE

The flow of active power (P) and reactive power (Q) through transmission system has influence on voltage magnitude and phase difference of voltage at terminals and voltage along the line (Bakshi & Bakshi, 2009). The receiving-end powers according to Sivanagaraju & Satyanarayana (2009) & Gönen (2014) as follows:

$$P_R = \frac{|V_S||V_R|}{|Z|}cos(\theta - \delta) - \frac{|V_R|^2}{|Z|}cos\,\theta \qquad (1)$$

Where, $\alpha = 0,\ \beta = \theta$, *for short lines.*

$$Q_R = \frac{|V_S||V_R|}{|Z|}sin(\theta - \delta) - \frac{|V_R|^2}{|Z|}sin\,\theta \qquad (2)$$

Similarly, sending-end powers are:

$$P_S = \frac{|V_S|^2}{|Z|}cos\,\theta - \frac{|V_S||V_R|}{|Z|}cos(\theta + \delta) \qquad (3)$$

$$Q_S = \frac{|V_S|^2}{|Z|}sin\,\theta - \frac{|V_S||V_R|}{|Z|}sin(\theta + \delta) \qquad (4)$$

Where,
PR is the receiving end active power,
PS is the sending end active power,
QR is the receiving end reactive power,
QS is the sending end reactive power

5.1 Mathematical Model of SVC for Reactive Power Flow.

$$SVC\ Expression{:}\ Q_{svc} = |V_i|^2\left[\frac{[2(\pi-\alpha)+sin\,2\alpha]}{X_L} - \frac{1}{X_C}\right]$$

5.2 Mathematical Model of TCSC for Active Power flow

- $P_{ik} = V_i^{\,2}G_{ik} - V_iV_k(G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik})$
- $Q_{ik} = -V_i^{\,2}b_{ik} - V_iV_k(G_{ik}\sin\delta_{ik} - B_{ik}\cos\delta_{ik})$

where Pik real power at Bus k and Qik is reactive power at bus k.

5.3 VDI Expression

$$VDI_i^r = \frac{\left||V_i|^{r+1} - |V_i|^r\right|}{|V_i|^r}\ ;\ i = 1, 2, 3, \cdots, n_{PQ}\ and\ r = 0, 1, 2, \cdots, s$$

Where For s = number of percentage real power increase for pure load buses in the network

r = the stage of load flow analysis after load increase and VDI is Voltage drop Index.

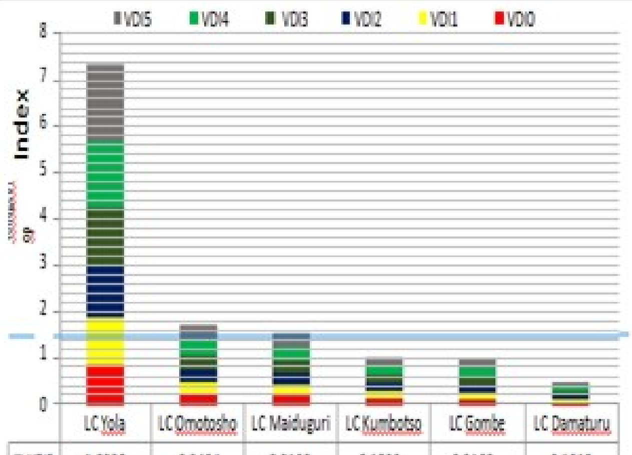
5.4

$$TVDI\ Expression{:}\ \ TVDI_i = \sum_r^s VDI_i^r$$

Where TVDI is total Voltage drop index.

VI. OPTIMAL COMPENSATION LOCATION USING VOLTAGE DROP INDEX

The load flow results of the 41 bus system as active power at all pure load bus are increased through five steps of 10% each from a base case are presented between below. The bus real power values for load flow analysis, computed VDI Magnitude for real power load and Load bus VDI in descending order results are presented below. For each of the load flow case, the bus voltage profile is presented in a bar chart after each table. The need for this increment is to observe the voltage drop profile as increase is made from the base case to 50% the active total load with equal percentage participation among the buses. However, the steady state behaviour of the network was also tested at 10% active load decrease from the base case. This analysis preceded subsequent load increases.



	LC Yola	LC Omotosho	LC Maiduguri	LC Kumbotso	LC Gombe	LC Damaturu
VDI5	1.6385	0.3424	0.3133	0.1893	0.2169	0.1019
VDI4	1.4315	0.32	0.2801	0.189	0.1958	0.0916
VDI3	1.2565	0.2977	0.2686	0.1782	0.1749	0.0916
VDI2	1.1229	0.2757	0.2465	0.1674	0.1644	0.0813
VDI1	1.0052	0.2644	0.2353	0.1671	0.1436	0.0711
VDI0	0.8908	0.2427	0.2241	0.1564	0.1332	0.0711

Load Bus Name

Figure 2 : Load Buses with significant Voltage Drop Indices

VII. RESULTS AND DISCUSSION

The result of this paper evaluates the series compensating devices using VDI method. This is then followed by the evaluation of the steady state performance of the network with respect to line voltage magnitude and branch flows with the insertion of series and shunt compensating devices which produces Yola branch as the prime location of series compensation as can be seen from the figure 2.

VIII. CONCLUSION

The paper has demonstrated and investigated an improved voltage transfer in a transmission line of a network. The Nigerian Bus system operated at 330kV with 41 buses was used to evaluate voltage drop index for load buses as active power varied at constant reactive power values was injected into lines at steps of 10% incremental values of the base case. Each of the compensated cases when compared with the base case bus load flow result showed significant improvement indicating that the compensation was worth it. The best steady state operation case recorded when the trio branches at Maiduguri. Omotosho and Yola were all series compensated with TCSC at varied reactive power at load buses. No branch in the network had any form of line voltage violation as the least line voltage was well within the prescribed limit.

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APPENDIX

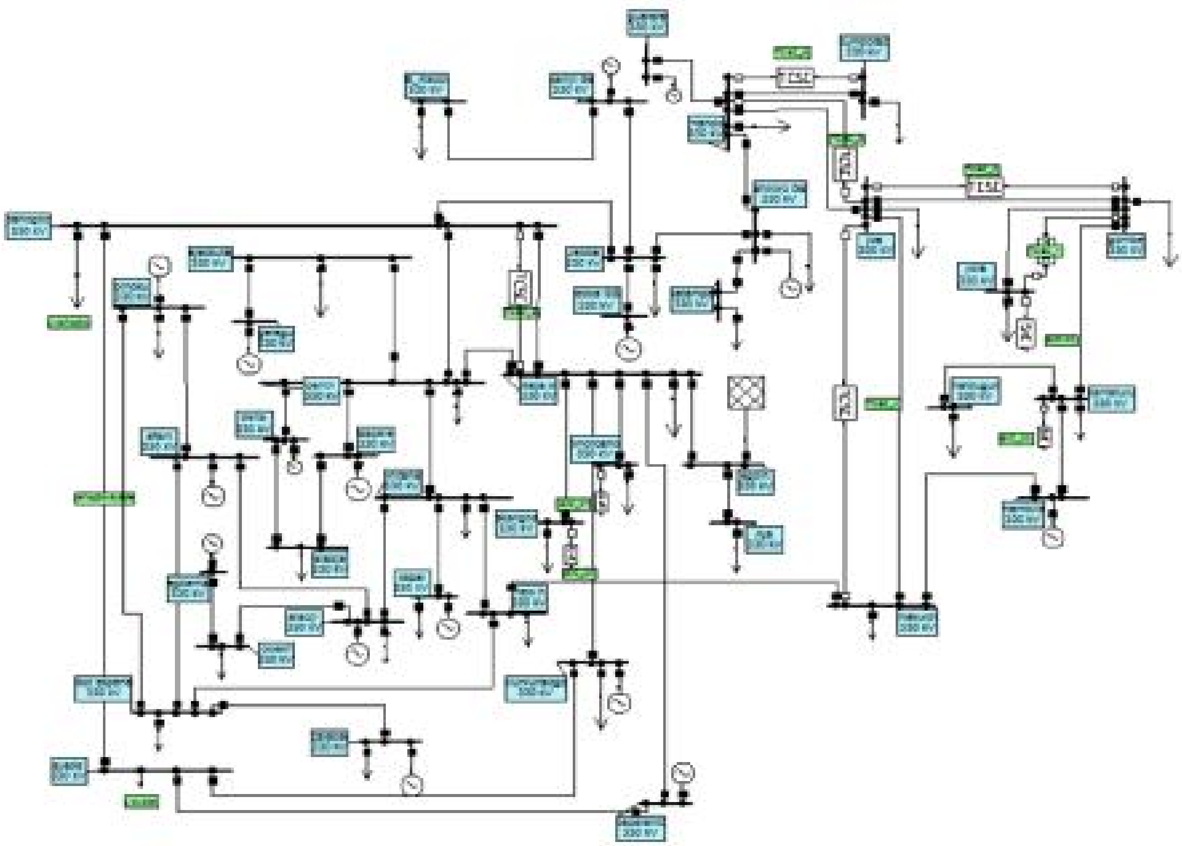

Fig. 3: One-Line Diagram of the Nigerian 330kV Test Network with 41 bus

Table 1: Load Bus Real Power Values for Load flow Analysis

Name	Base Case	10% Load Decrease	Real power Increment of 10%	20%	30%	40%	50%
LC Aja	355	319.5	390.5	426	461.5	497	532.5
LC Ajaoku	250	225	275	300	325	350	375
LC Akangb	270	243	297	324	351	378	405
LC Aladja	220	198	242	264	286	308	330
LC Ayade	239	215.1	262.9	286.8	310.7	334.6	358.5
LC B_Kebb	180	162	198	216	234	252	270
LC Benin	357	321.3	392.7	428.4	464.1	499.8	535.5
LC Damatu	230	207	253	276	299	322	345
LC Gombe	160	144	176	192	208	224	240
LC Ikeja.w	329	296.1	361.9	394.8	427.7	460.6	493.5
LC Ikot ek	240	216	264	288	312	336	360
LC Jebba	250	225	275	300	325	350	375
LC Jos	250	225	275	300	325	350	375
LC Katamp	250	225	275	300	325	350	375
LC Kumbo	250	225	275	300	325	350	375
LC Maidug	180	162	198	216	234	252	270
LC Makurd	200	180	220	240	260	280	300
LC Mando	160	144	176	192	208	224	240
LC New.h	256	230.4	281.6	307.2	332.8	358.4	384
LC Omoto	200	180	220	240	260	280	300
LC Onitsh	315	283.5	346.5	378	409.5	441	472.5
LC Oshogb	201	180.9	221.1	241.2	261.3	281.4	301.5
LC Owerri	280	252	308	336	364	392	420
LC Yola	180	162	198	216	234	252	270

Table 2: Computation of VDI from bus voltage magnitude for increasing load real power

	Voltage magnitude at Load Real Power variation							
Load Bus Name								
	D10%	BC		IN10%	IN20%	IN30%	IN40%	IN50%
LC Aja	99.95		99.95	99.95	99.95	99.95	99.95	99.95
LC Ajaokuta	99.92		99.92	99.92	99.92	99.92	99.92	99.91
LC Akangba	99.9		99.9	99.91	99.9	99.9	99.9	99.89
LC Aladja	99.97		99.97	99.97	99.97	99.97	99.97	99.97
LC Ayade	99.97		99.97	99.97	99.97	99.97	99.97	99.96
LC B_Kebbi	99.95		99.95	99.95	99.95	99.94	99.94	99.94
LC Benin	99.93		99.94	99.94	99.94	99.93	99.92	99.91
LC Damaturu	98.52		98.45	98.38	98.3	98.21	98.12	98.02
LC Gombe	97.62		97.49	97.35	97.19	97.02	96.83	96.62
LC Ikeja.w	99.95		99.96	99.96	99.96	99.95	99.95	99.95
LC Ikot ekpen	99.92		99.92	99.92	99.92	99.91	99.91	99.9
LC Jebba	99.97		99.97	99.97	99.97	99.97	99.97	99.96
LC Jos	100.71		100.6	100.6	100.5	100.4	100.3	100.3
LC Katampe	99.96		99.96	99.96	99.96	99.96	99.96	99.96
LC Kumbotso	95.89		95.74	95.58	95.42	95.25	95.07	94.89
LC Maiduguri	93.72		93.51	93.29	93.06	92.81	92.55	92.26
LC Makurdi	99.8		99.8	99.79	99.78	99.77	99.75	99.74
LC Mando	99.98		99.98	99.98	99.98	99.98	99.97	99.97
LC New.h	99.88		99.88	99.88	99.87	99.87	99.86	99.85
LC Omotosho	94.78		94.55	94.3	94.04	93.76	93.46	93.14
LC Onitsha	99.92		99.92	99.92	99.92	99.91	99.91	99.9
LC Oshogbo	99.92		99.93	99.93	99.93	99.93	99.93	99.92
LC Owerri	99.95		99.95	99.95	99.95	99.95	99.94	99.94
LC Yola	85.32		84.56	83.71	82.77	81.73	80.56	79.24

Table 3: Load Bus VDI in descending Order

Load Bus Name	VDI0	VDI1	VDI2	VDI3	VDI4	VDI5	TVDI
LC Yola	0.8908	1.005	1.123	1.257	1.432	1.639	7.346
LC Omotosho	0.2427	0.264	0.276	0.298	0.32	0.342	1.743
LC Maiduguri	0.2241	0.235	0.247	0.269	0.28	0.313	1.568
LC Kumbotso	0.1564	0.167	0.167	0.178	0.189	0.189	1.047
LC Gombe	0.1332	0.144	0.164	0.175	0.196	0.217	1.029
LC Damaturu	0.0711	0.071	0.081	0.092	0.092	0.102	0.509
LC Jos	0.0695	0.07	0.07	0.08	0.08	0.08	0.448
LC Makurdi	0	0.01	0.01	0.01	0.02	0.01	0.06
LC Benin	0.01	0	0	0.01	0.01	0.01	0.04
LC Akangba	0	0.01	0.01	0	0	0.01	0.03
LC New.h	0	0	0.01	0	0.01	0.01	0.03
LC Ikeja.w	0.01	0	0	0.01	0	0	0.02
LC Ikot ekpene	0	0	0	0.01	0	0.01	0.02
LC Onitsha	0	0	0	0.01	0	0.01	0.02
LC Oshogbo	0.01	0	0	0	0	0.01	0.02
LC Ajaokuta	0	0	0	0	0	0.01	0.01
LC Ayade	0	0	0	0	0	0.01	0.01
LC B_Kebbi	0	0	0	0.01	0	0	0.01
LC Jebba	0	0	0	0	0	0.01	0.01
LC Mando	0	0	0	0	0.01	0	0.01
LC Owerri	0	0	0	0	0.01	0	0.01
LC Aja	0	0	0	0	0	0	0
LC Aladja	0	0	0	0	0	0	0
LC Katampe	0	0	0	0	0	0	0

Table 4: List of Generation Stations

NUMBER	NAME	LOAD MW	LOAD MVAR	GEN MW	SWITCH SHUNT Mvar
1	Kebbi	150	60	-	-
2	kainjiGs	-	-	760	-
3	Jebba	350	195	-	-
4	shiroroGs	250	160	600	-
5	Oshogbo	201	137	-	78.27
6	jebba GS	-	-	578.4	-
7	Katampe	350	220	-	
8	Mando	200	125	-	77.83
9	Kumbotso	350	220	-	245.4
10	Jos	250	125	-	131.8
11	Gombe	160	95	-	144.4
12	Yola	160	90	-	-
13	Olunrunsog oGs	130	70	760	-
14	Damaturu	130	70	-	-
15	Maiduguri	200	150	-	188.6
16	Omotosho	300	188	-	254.8
17	Benin	157	80	-	77.14
18	Ajaokuta	100	55	-	-
19	GereguGs	-	-	414	-
20	SapeleGs	-	-	1020	-
21	Onitsha	115	42	-	-
22	DeltaGs	-	-	840	-
23	ikeja.w	429	248	-	505.2
24	Akangba	470	306	-	508.9
25	Papalanto	-	-	304	-
26	Aja	455	286	-	-
27	EgbinGs	-	-	1320	-
28	Aladja	82	45	-	-
29	AfamGs	-	-	702	-
30	AlaojiGs	360	218	1000	-
31	OkpaiGs	130	80	480	-
32	new.h	113	56	-	-
33	Ayede	139	61	-	-
34	MambilaGs	-	-	2600	-
35	GuararaGs	-	-	300	-
36	Makurdi	180	65	-	-
37	OmokuGs	185	79	150	-
38	Ikotekpene	140	0	-	-
39	CalabarGs	180	56	561	-
40	Owerri	180	75	-	-
41	EgbemaGs	-	-	338	-

Table 5: List of Bus bars

S/NO	NO. OF BUS	NAME OF BUS	TYPE	NO OF UNIT	INSTALLED CAP IN MW	NO AVAILABLE GEN
1	2	kainjiGs	Hydro	8	760	6
2	4	shiroroGs	Hydro	4	600	4
3	6	jebbaGS	Hydro	4	578.4	4
4	13	Olunrunsog oGs	Thermal	*	760	2
5	19	GereguGs	Thermal	3	414	3
6	20	SapeleGS	Thermal	10	1020	1
7	22	DeltaGs	Thermal	18	840	12
8	25	Papalanto Gs	Thermal	*	304	*
9	27	Egbin	Thermal	6	1320	4
10	29	Afam Gs	Thermal	20	702	3
11	30	Alaoji Gs	Thermal	*	1000	*
12	31	OkpaiGs	Thermal	3	480	3
13	34	MambilaGs	Hydro	**	2600	**
14	35	GuararaGs	Thermal	**	300	**
15	37	OmokuGs	Thermal	6	150	4
16	39	CalabarGs	Thermal	*	561	*
17	41	EgbemaGs	Thermal	*	338	*