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Location of Shunt Compensation Device in Nigerian Power System

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Abstract -- The optimal location of shunt compensators to improve voltage stability and branch flows in Nigeria's 330kv network was investigated. The Nigerian bus system which operates at 330kV with 41 buses was evaluated for voltage drop index at load buses when active power value is varied at constant reactive power values. With the power varied from a base case through five steps of 10% increment, the result of the total voltage drop index ranked Yola, Omotosho and Maiduguri in descending order as the optimal locations for shunt compensation. Aided with this ranking, load flow analyses were executed for the individual and simultaneous shunt compensation at these buses. Each of the compensated cases, when compared with the base case bus, the tabulated load flow and bar chart results showed significant improvement due to the compensations. However, the singular and simultaneous compensation involving two of these three buses did not eliminate bus voltage violation in other buses as it is supposed to be. The best steady state operation recorded occurred when the trio of buses at Maiduguri. Omotosho and Yola were all shunt compensated with appropriately sized Static var compensation (SVC) for which no network bus had any form of bus voltage violation.

Indexed Terms: FACTS, TCSC, SVC, Voltage profile

I. INTRODUCTION

Human population growth matched by industrialization is in league to push up electrical energy demand, subjecting the electric power system network configuration and operation to excessive stress. Alleviating this stress for reliable system operation is an enormous challenge.

The general consensus among academicians, practitioners and policy makers is that direct access to the transmission grid is indispensable for competitive electricity market [1]. Yet, the combined synergy of operations by these independent entities is to optimize system security and ensure the sustenance of reliable supply.

Transmission lines' overloading, congestion and stress can occur as a result of network location concentration between generation and load. Ageing transmission facilities based on life-cycle may be strengthened by repairs and replacement of components, if its towers, transformers and conductors have sufficient evacuation margins to accommodate increase in demand. In

Contrast, systems with insufficient capacity margins pose unique operating challenges especially in the absence of effective expansion investment planning and evacuation. As population and industrialization grows, such power system deteriorates with demand exceeding evacuated power and the result is stress on transmission facilities, voltage instability and collapses.

The impacts of adding new, expanding or reinforcing existing transmission facility is long term remedy. For continued operation of an existing stressed electric power system, sustainable short- term measures are preferred.

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 capacity. It is currently incorporated in the implementation of Electric Power System Smart Grids. FACTS devices are of various types based on the desired functions. But to achieve increased transmission capacity

With economic considerations, FACTS types; the Static Vary Compensator (SVC) and the Thermistor-Controlled Series Capacitor (TCSC) are used for this study. According to [2], 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 neighboring influences on line power flows and bus voltages are indispensable. The mutual influences among the devices can arise possibly resulting to adverse interaction [3] [4]

The objectives of this study is to improve the branch voltage profile of the electric networks and improve the real power transfer capacity (load ability) of congested power system transmission lines at stable voltages using shunt FACTS devices. 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 in order to:

Generate a base case load flow result.

Determine the optimal location of SVC using

Voltage Drop Index.

- Install TCSC/SVC and perform load flow analyses for singular and combined shunt compensations.
- Determine the resultant effect on the overall voltage profile on account of the shunt compensation.

A. Flexible Alternating Current Transmission

Systems (FACTS)

FACTS technology is not a single high-power controller, but rather a collection of controllers, which can be applied individually or in combination with others to control one or more of the system parameters [5].

In general, FACTS controllers can be divided into four categories [6], namely: - Series, Shunt, Combine Series-shunt, Combine Series-Series. For the purpose of this study focused will be on series and shunt controllers which will be applied on transmission lines and buses respectively.

B. 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 [6] [7] [8] 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 [9][7][8]

C. Shunt Controllers

In practice, all shunt controllers inject current into the system at the point of connection. Variable shunt impedance connected to the line voltage can cause a current flow and hence can cause injection of current into the line. The reactive power injected can be varied by varying the phase of the current. It may be variable impedance, variable source or a combination of the two [7]. The examples are Static Synchronous Generator (SSG), Static VAR Compensator (SVC).

D. Description of Test Network

The test network is the Nigerian existing 330kV grid of 41 buses. The network contains 17 synchronous generators (thermal and hydro), 77 transmission lines and Load centers were used as shown in figure 1.0. While the one-line diagram is captured in that figure from NEPLAN simulator, the network data for generators, loads and transmission line parameters are given in the appendix table 4.0. As sourced from Transmission Company of Nigeria, TCN.

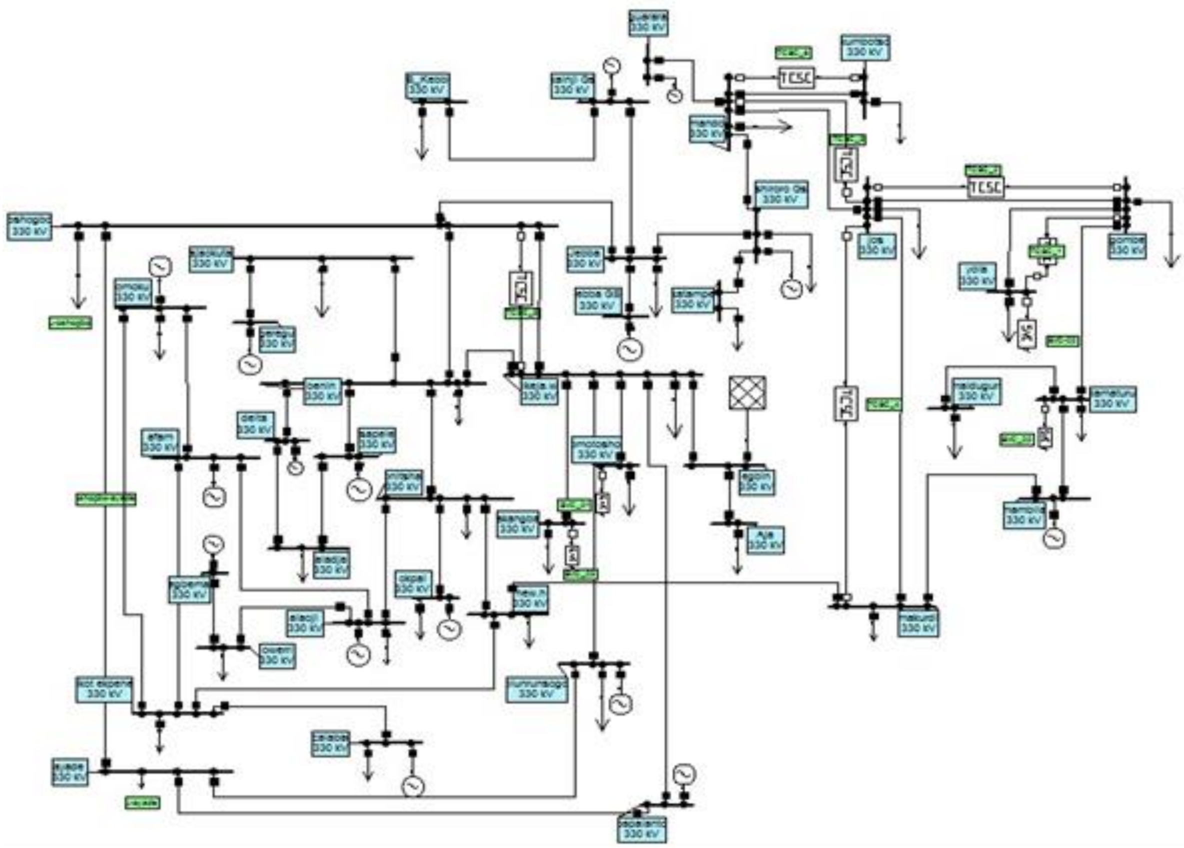


Figure 1.0 : One-Line Diagram of the Nigerian 330kV Test Network with 41 bus

II. METHODOLOGY

Two (2) Facts devices are used to regulate the weak bus voltage magnitude and phase angles, transmission line reactance, active and reactive power flow and transmission line loss reduction. This include TCSC and SVC FACTS devices. NEPLAN, being user-friendly simulation software with its modular concepts incorporates all aspects of electrical engineering with respect to transmission, distribution, generation and industrial electric power networks. Its proficiency for steady state power system analysis and interactive interface has made it a preferred choice for all analyses reported in this paper. To achieve the objectives of this paper, the following stepwise approaches (carried out using NEPLAN simulation software) were adopted and followed:

- Power system transmission network model was defined. A steady state balanced three-phased model was represented by a single-phase model.
- The base case network under review is a 41 Bus Nigerian Electric grid of 330kV.
- Bus admittance matrix of the transmission lines is formed with transformer admittances ignored.
- Load flow equations suitable for all electric network, including the test network is formed whose workability is tested using Mat lab codes for smaller network.
- The bus voltage magnitudes, power flows and line losses on the lines for the base case was determined using NEPLAN Simulator.
- The TCSC/SVC mathematical model for power flow/voltage regulation was incorporated into the load flow equations model.
- Simulation of the entire model was then carried out with NEPLAN to investigate the impact of the TCSC/SVC on the transmission line and at the buses.

A. Power System Transmission Model

- Voltage Expression: $V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k\neq i}}^{n} Y_{ik} V_k\right]$; $i, k = 1, 2, 3, \ldots n$

Where Yik is the admittance for the transmission line Between buses i andk

While Vi is the bus voltage at bus i and Vk is bus voltage at bus k.

r = the stage of load flow analysis after load increase

Total Voltage Drop Index (TVDI) Expression: $TVDI_i = \sum_r^s VDI_i^r$

For Power Flow

$$P_i = |V_i| \sum_k^n |Y_{ik}| \, |V_k| \cos(\theta_{ik} - \delta_i + \delta_k) \ ,$$

$$Q_i = -|V_i| \sum_k^n |Y_{ik}| \, |V_k| \sin(\theta_{ik} - \delta_i + \delta_k)$$

Where P_i is real power component of power in bus i and Q_i is reactive power component of reactive power in bus i

Mathematical Model of SVC for Reactive Power Flow.

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

Mathematical Model of TCSC for Active Power flow

- $P_{ik} = V_i^2 G_{ik} - V_i V_k (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik})$

- $Q_{ik} = -V_i^2 b_{ik} - V_i V_k (G_{ik} \sin \delta_{ik} -$

  Where P_{ik} real power at Bus k and Q_{ik} is reactive power at bus k.

Voltage Drop Index (VDI) Expression:

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

Where For s= number of percentage real power increase

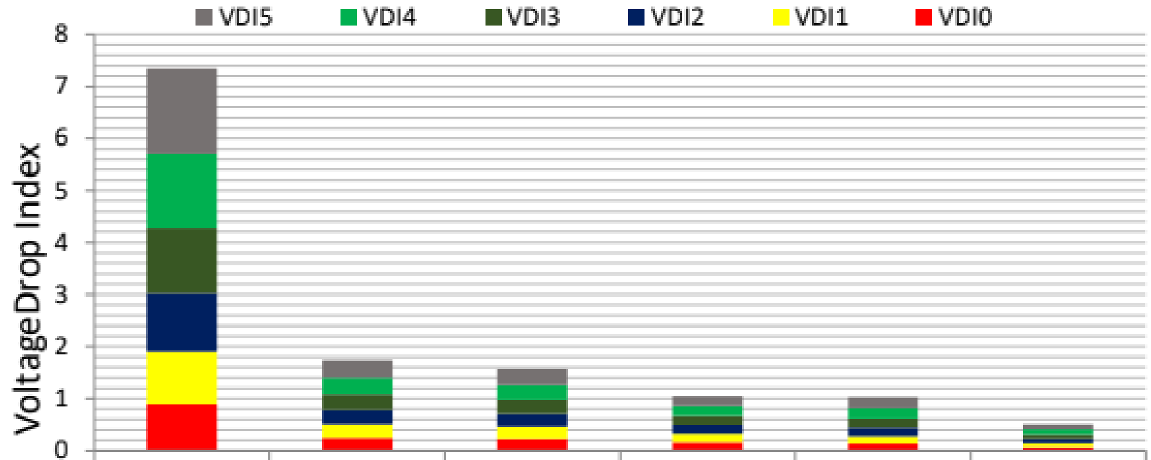
For N_{PQ} pure load buses in the network

III. RESULTS AND DISCUSSION

Optimal Compensation Location using Voltage Drop Index The load flow results of the 41bus system as active power at all pure load buses are increased through five steps of 10% each from a base case are presented in Table 1.0.

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 table 3.0: For each of the load flow case, the bus voltage profile is presented in a bar chart figure 2. The need for this increment is to observe the voltage drop profile as increase is made from the base case to 50% the total active 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.

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



	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

IV. CONCLUSION

The study has demonstrated the investigation of the ideal or choice location of shunt compensators to improve voltage stability and branch flows in 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.

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 was recorded when the trio of buses at Maiduguri. Omotosho and Yola were all shunt compensated with SVC. No bus in the network had any form of bus voltage violation as the least bus voltage was well within the prescribed limit

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APPENDIX

Table 1.0: 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 Makurc	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 Onitsha	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 2.0 Computation of VDI from bus voltage magnitude for increasing load real power

Load Bus Name	Voltage magnitude at Load Real Power variation						
	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 ekpene	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 3.0: 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

Table4: 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	OlunrunsogoGs	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 6.0: List of Bus bars

S/N0	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	OlunrunsogoGs	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	*